Remixing Physical Objects Through Tangible Tools

by

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Abstract

In this document we present new tools for remixing physical objects. These tools allow users to copy, edit and manipulate the properties of one or more objects to create a new physical object. We already have these capabilities using digital media: we can easily mash up videos, music and text. However, it remains difficult to remix physical objects and we cannot access the advantages of digital media, which are nondestructive, scalable and scriptable. We can bridge this gap by both integrating 2D and 3D scanning technology into design tools and employing affordable rapid prototyping technology to materialize these remixed objects. In so doing, we hope to promote copying as a tool for creation.

This document presents two tools, CopyCAD and KidCAD, the first designed for makers and crafters, the second for children. CopyCAD is an augmented Computer Numerically Controlled (CNC) milling machine which allows users to copy arbitrary real world object geometry into 2D CAD designs at scale through the use of a camera-projector system. CopyCAD gathers properties from physical objects, sketches and touch interactions directly on a milling machine, allowing novice users to copy parts of real world objects, modify them and create a new physical part. KidCAD is a sculpting interface built on top of a gel-based realtime 2.5D scanner. It allows children to stamp objects into the block of gel, which are scanned in realtime, as if they were stamped into clay. Children can use everyday objects, their hands and tangible tools to design new toys or objects that will be 3D printed.

This work enables novice users to easily approach designing physical objects by copying from other objects and sketching new designs. With increased access to such tools we hope that a wide range of people will be empowered to create their own objects, toys, tools and parts.

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Chapter 1

Introduction

Those who do not want to imitate anything, produce nothing. -Salvador Dali

Digital fabrication has revolutionized the way products are designed and manufactured, and yet until only recently digital fabrication has remained in the world of high-end mass production. Digital fabrication comprises a combination of Computer Aided Design (CAD) software tools allowing engineers and designers to digitally define parts and models and Computer Aided Manufacturing (CAM) software to control Computer Numerically Controlled (CNC) fabrication machines, such as Milling Machines to cut 3D paths out of wood, plastic or metal. As McCullough explains, these tools “take images and turn them into things” [95]; with these tools essentially anything can be made. Because of its reliance on digital technology and software, and thanks to Moores Law, digital fabrication has gotten cheaper and faster at an ever increasing rate. Consumers can now purchase a 3D printer for what was the cost of a laser printer twenty years ago.

However the software tools and pipelines for designing objects and controlling CNC machines to fabricate them, remain complicated descendants of design tools made over 20 years ago.

At the same time there has been a resurgence in craft and do-it-yourself projects. Unlike the hobby shops in garages fifty years ago, and fueled by the Internet and mass media sharing, a wider audience has emerged as new producers in a digital age. Men, women, and children have embraced this new maker culture, taking up tools and crafts both old and new.

These new producers in the internet age have taken over other domains as well, from the written word (blogs), to moving pictures (video mashups, youtube), and audio (remixes, mashups). When we look closer, we see an overarching theme that new producers are not only creating from scratch they are looking at existing culture for inspiration. They have found new ways of creating and authoring that use the collective power of the internet as a source for raw material, allowing them to reinterpret culture in new and exciting ways. How will tools for the fabrication of physical objects take this into account?

In this thesis I seek to build new tools for these makers, crafters and children that enable them to be authors of objects in a new age of digital fabrication. No longer must design of objects be limited to industry. Design should not be done in a vacuum, but rather must embrace the physical world as a source for input, as opposed to merely output. In doing so, this thesis cuts across three themes: accessibility to new tools for fabrication, bringing the physical world into the CAD design process, and remixing physical objects.

1.1 Accessibility of Tools and New Audiences

Accessible CNC machines, that can cut, mill, or sinter 3D models, have the power to radically change how products are made, and the role end-users can play in being designers of their own products. One thread of this revolution has been FABlabs and hacker spaces where communities can gather to use shared digital fabrication tools to work on their own projects. Prof. Neil Gershenfeld has played a central role through his class "How to make (almost) anything," where MIT students are shown the basics of digital fabrication and given the opportunity to make anything they can dream [41]. However, Gershenfeld and his students have also set up FABlabs across the world for a few thousand dollars. With this model every small village around the world could afford tools that could be used to make almost anything.

There are also new CNC machines being developed for home use, such as the MakerBot, a 1,200 dollar 3D printer that can print 3D shapes out of extruded plastic [66]. CNC machines do not have to focus on hard manufacturing, they can also be used to create soft goods such as CNC embroidery machines that consumers can purchase to fabricate beautiful embroidered designs on fabric.

These new tools, combined with the ease of sharing information and skills on the internet, has set off a new revolution in craft and do-it-yourself technology. As more and more people in the western world move out of manufacturing industries and into the information workforce, they find themselves wanting more hands-on hobbies away from staring at the computer screen. Magazines such as MAKE, CRAFT and ReadyMade along with websites like Instructables, Makezine, and Ravelrey have given these "makers" and "crafters" a near unlimited source of projects and a forum to share their own designs and instructions [9, 79].

Beyond these adult hobbyists, children are also beginning to be encouraged by their parents to take a more hands-on approach to building and learning. One book, "Fifty Dangerous Things you should let your child do," explains activities for children, such as melting glass or whittling a figurine [141]. Gever Tulley, the author, also is the founder of Tinkering School, a summer camp where a group of children design a project - like a wooden roller coaster - and build it themselves, power tools and all. This type of hands-on learning has been lost, as schools have cut shop class and other industrial arts, to seek higher test scores and because of budget cuts. However for today's children to become the engineers and scientists of tomorrow, we need children to be engaged in the excitement of making things for themselves. Recent funding for Science, Technology, Engineering and Mathematics (STEM) through the NSF has highlighted this need or shows it is being recognized as an increasingly high priority.

As we look at the needs of these makers, crafters and children who wish to design, build and create through digital fabrication, they are very different from that of traditional engineers using CAD software to build airplanes or bio-medical machines. Their focus may not be on sub-millimeter precision, but instead on creativity. They may want to modify existing products they already own, make spare parts to repair them, or craft their own products.

Based on these differences we have highlighted a number of guiding principles for our tools. We will focus less on precision, and instead on speed, making these new interfaces "sketchy." Instead of forcing users to learn complicated new software tools, we will build upon skills they know like drawing or sculpting clay. In addition, we think that by moving the tools for design closer to the tools for fabrication, and setting them in the context of physical materials, they can be more accessible, as described in the next section.

1.2 Bringing the Physical World into CAD and Bringing CAD into the Physical World

CAD software allows designers and engineers to create models and parts that will be machined or manufactured to exist in the physical world. The entire purpose of CAD is to design something with enough specificity that it can be fabricated and transformed into a physical world instance of a digital ideal. Although the end goal is 3D physical form, the current CAD process divorces design from the physical world and traps it in the 2D screen.

In addition the actual design process is much different, and includes the physical world. Designers begin with rough, cheap, and fast physical prototypes to get an idea of form and function. Designers at IDEO created a mockup of a surgery tool in a few minutes during a meeting with clients, from spare parts around them, see Figure 1-1; this physical form allowed all the stake holders to better understand the design in a matter of minutes [18]. Frank Gehry famously designs many of his buildings quickly out of paper and cardboard, to more quickly find what works and what does not. The physical world affords play, exploration and fast movement when dealing with these prototyping materials. There is currently no easy way for digital design tools to allow for this type of physical, tangible sketching.

In the automotive world, scale is so important and so difficult to understand on the screen, that almost all designs end up being done at 1:1 scale models. First through tape drawing, where curves are placed on the wall, and then through full 3D clay models, see Figure 1-2.

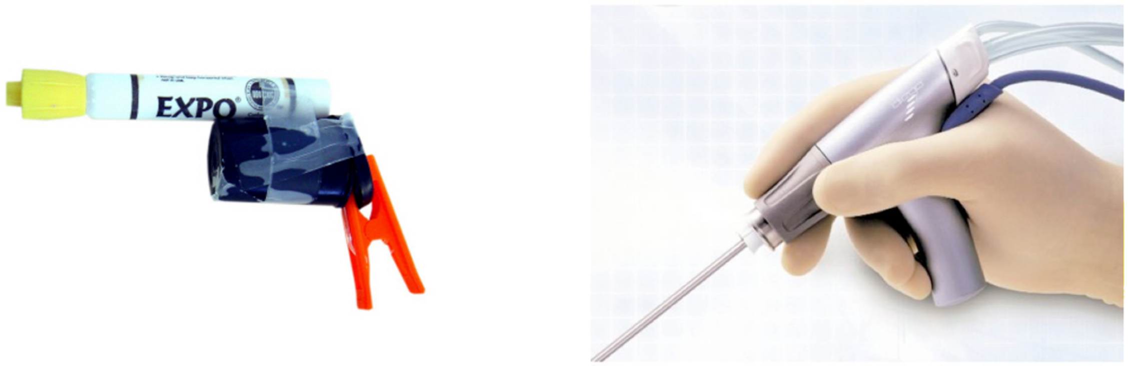


Figure 1-1: IDEO Surgical Prototype. Images courtesy of IDEO

Scale remains a weak point of the digital world, whereas it is invaluable in physical design processes.

(a) At Scale Clay Model

(b) At Scale Tape Drawing

Figure 1-2: Clay and Tape Car Mockups. Image courtesy Automotive Rhythms CC

Once prototypes have been made, designs often include parts from many different manufacturers, and although larger companies like McMaster Carr have CAD models for many of their parts, the vast majority do not. Thus designers and engineers must choose from 3D scanners, which are expensive and complicated, or the use of calipers and rulers, which are easily acquired but labor-intensive.

Finally, as a product is being designed, it often moves between the digital and physical, being 3D printed quickly to get a sense for the part or see how it fits in with others. But all changes must be done in the digital, even thought it might be easier to just sand a part down to make it fit.

The power of tangible thinking can also not be denied. Seymour Papert writes of the "gears of [his] childhood," and that through physical motion he was able to better understand the mathematics of differentials [107]. McCullough explains Henri Focillon's The Lide of Forms in Art argument that "art must be tangible." "Through the hand, authorship involves execution, and expression involves workmanship" [95]. But the digital world has much to offer as well.

This thesis seeks to explore a hybrid of digital and physical design, by embracing materiality, context and scale. By augmenting the physical space with digital design, we can move rapidly between physical and digital interaction, blurring this boundary. This allows for users to harness tangible thinking, and explore new designs with their hands. What if we could place parts directly into a CAD model where we want them, simply by pressing that part into the screen at its exact location and seeing it reappear in the digital world, see Figure 1-3? What if we could draw directly on the material we wish to cut, and have these lines etched into reality? This work seeks to explore more direct forms of scanning or copying, coupled with augmented projection, that can enable these interactions.

1.3 Remixing Physical Objects

In the last decade's proliferation of consumer-generated media, the remix has been a dominant force in music, images, and video. Lawrence Lessig describes this new "Read/Write" culture, where reading is not enough and "young people of the day add to the culture they read by creating and re-creating the culture around them" [90]. Technology has played the part of democratizing media, making it accessible, such that now anyone can be an artist.

When copying is difficult, its utility is limited to duplication. Once copying is easy, it is a creative tool. Copying becomes creation. Looking to other media, it was not until users

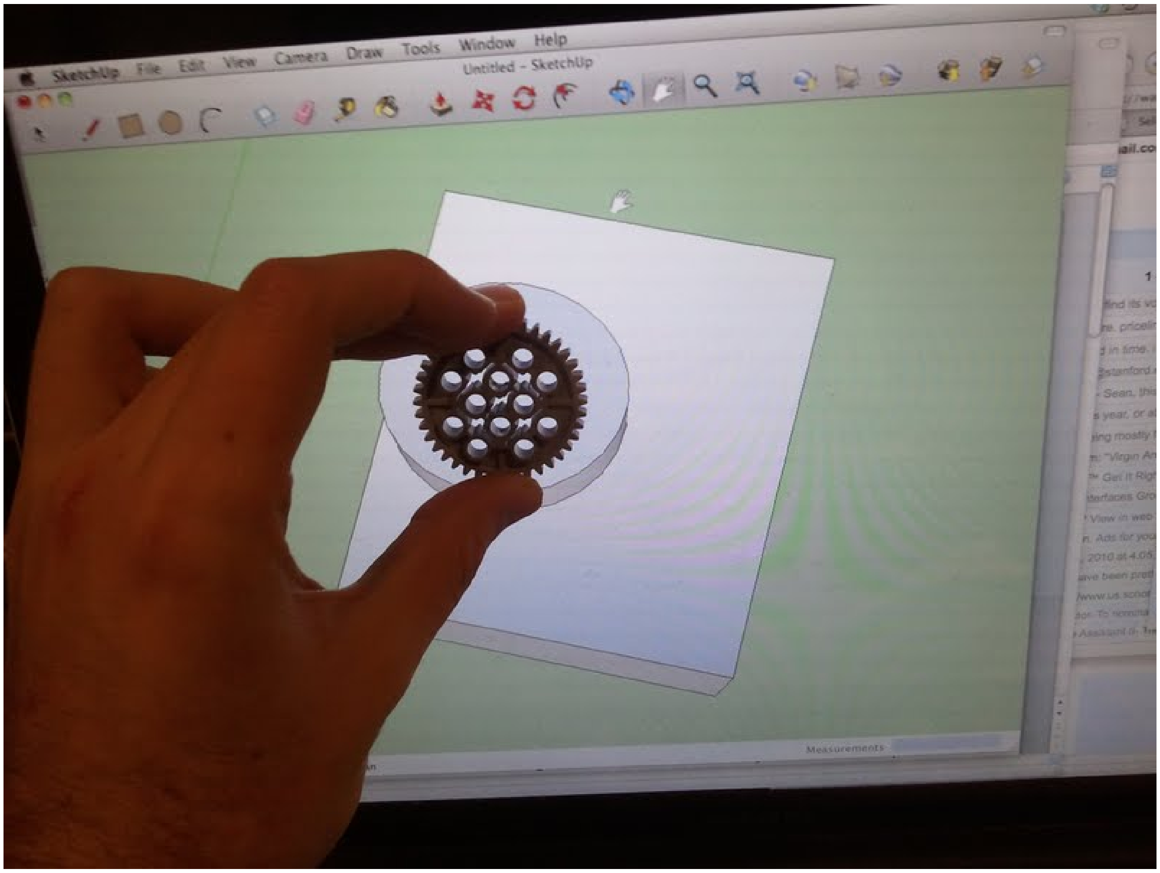


Figure 1-3: Bringing the Physical World into CAD

could copy easily that remixes became prevalent. When copying music required a 4-track, and physically cutting audio tape, few were mashing up songs. Software tools now make it easy, with beat matching and non-linear editing, with the result that music mashups are ubiquitous. By building tools that make it faster and easier to copy geometry from real objects, we hope to increase the creative potential for end-user designers.

To be sure there have been remixes of physical objects before. Marcel Duchamp pushed the boundaries of art through his assembled Ready-mades, re-contexutalizing found objects. More recently people have taken to Ikea Hacking; consumers will buy different parts from Ikea that originally were not designed to go together but then reassemble them in exciting ways [120]. However, Lessig explains that "collage with physical objects is difficult to do well and expensive to spread broadly" [90].

But the power of the digital world opens up new possibilities, and digital or augmented tools for remixing objects could allow for an exciting rise in popularity.

1.3.1 Why Remix Objects?

Customization

As Von Hipple points out in his work Democratizing Innovation, we live in a mass market world, but with heterogeneous users, with radically different needs [148]. Von Hipple focuses on "Lead Users," who are consumers of a product that does not fulfill their needs and take it upon themselves to modify it. There are many times consumers have needs for products that do not exist. Thus remixing has the ability to take useful parts of a number of products and combine them into one new problem-solving object. For example a connector that could combine Lego and Knex parts would be useful, but does not exist, and would very unlikely be made by these companies.

Expression

Lessig describes remix culture as a new kind of reading and writing that allows people to better express some creative drive. And similarly, remixing objects could allow for this individual creative expression.

Personalization and Craft

There may be a number of products that users feel very close to and have a strong connection with, that they wish to modify, and personalize, to make their own.

In addition we strongly associate things we built or designed as having a higher value. Craft is often just as much about the time and care that went into the object, as the final physical form. Here remixed objects have the ability for end-users to put their fingerprint on objects in their life, and make them more valuable through remixing.

Learning

Henry Jenkins explores that "More and more literacy experts are recognizing that enacting, reciting, and appropriating elements from preexisting stories is a valuable and organic part of the process by which children develop cultural literacy." Lessig writes "They learn by remixing" [90]. Should this not be the same for design?

Speed

If we design everything from scratch, we are not leveraging the hard work that many have done before us and shared with us. Objects and parts around you have an untold life, of hours and years of ideation and creation to come to life. Existing products can serve as a jumping off point for new designs. Remix can tap into this prior work and harness it for the end-users, making design, faster, cheaper and easier.

1.3.2 A New Kind of Design

Technology and new fabrication methods have made on-demand products a reality. However, we argue that Remixing Physical Objects is very different from Mass-Customization. Mass customization, for example Build-a-Bear, or designing Nike shoes online, allows end-users to explore inside a small design space which a team of designers has pre-created. Remixing opens up the design space radically, freeing users from constraints other designers may place on them, and instead allowing them to look to the world around them for inspiration and found parts.

1.3.3 The Design-Space of Copying Objects

What you copy, why you copy, and how you copy, matters. Here we hope to provide a better sense for the scope of our explorations in the design space of copying from objects in a CAD context.

What you copy

There is an infinite space of things to copy from, however because we are exploring object design we will limit this space to things you can copy from existing physical objects.

But even the space of copying from objects is too broad for this thesis to explore; you can copy geometry (shape or form), material properties, color schemes, functionality and many more parameters.

The two projects described in this thesis, CopyCAD and KidCAD focus on geometry creation, of shape and form. The space of copying geometry from existing objects is shown in Figure 1-4. It ranges from low-level copying of raw image data to high-level understanding of how objects work, so that mechanical functionality can be copied. We explore a fairly low level area, which is vectorization or surfaces but our systems have no real understanding of how those surfaces were designed, or linked, or fit together mechanically, as shown in the Figure.

The ultimate placement in this design space of copying geometry is based both on goals of the interface, but also on the technical ability of the system. Machine understanding of complex 3D mechanisms and design relations is still an active area of research. Here we focus on only low-level geometry as opposed to functionality, or parametric-based design, because of this limitation but also because these higher level concepts would make our tool much more complicated, and our goal is simplicity and ease of use.

Why you copy

There are many reasons why you would copy, and some of them are addressed previously by section 1.3.1 on "Why Remix Objects." However, what one wants to achieve from copying and how you use that copy deserves further exploration.

There is a continuum of "copying," along which there are many levels of how directly the copy stems from the original, see Figure 1-5. On one side, one can simply be inspired and

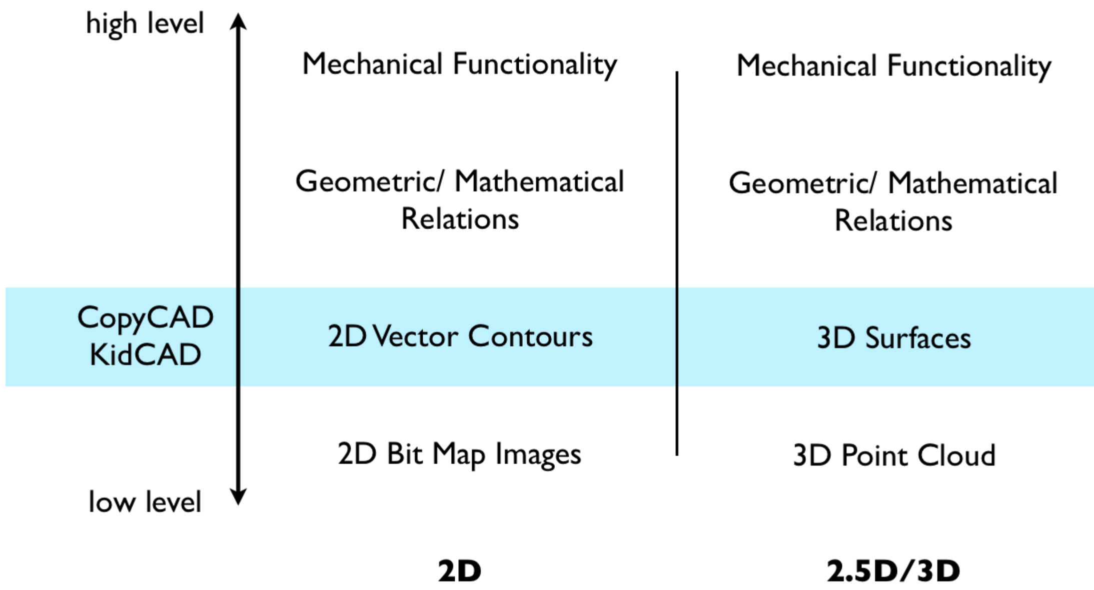


Figure 1-4: Design Space of Copying Geometry from Objects

no actual part of the new design can be traced back to the original, although it evokes a feeling of that original. On the other side is an exact 1:1 copy, a duplicate. However there is space in between as well.

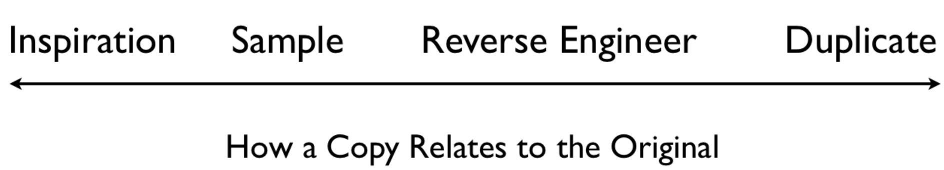


Figure 1-5: The Continuum of how a Copy Relates to the Original

This thesis seeks to explore "copying" through sampling, copying parts of objects and then combining them into something new, through a process of remixing. The individual part that was copied from the original object should be called a "sample" but throughout this thesis I will often refer to "sample" and "copy" interchangeably.

How you copy

The heart of this thesis is exploring how you can copy. How you can copy addresses the previous theme of bringing CAD into the physical world and visa versa, in section 1.2.

Figure 1-6: The Original Copy and Paste

Copy and paste metaphor is ubiquitous in today's computing systems. However, it too had to be designed and invented, and popularized. Larry Tesslar, while working at Xerox PARC on text editing software based on Douglas Englebart's NLS GUI system, ended up refining and defining cut/paste and copy/paste interactions [98]. Cut and paste comes from the real world of layout, editors would literally cut out text or images, and then paste them where they would want them. The computer opened up the possibility to extend this to copy, to make a copy of something and put it somewhere. But in many ways this copy was built for digital interactions that could not make sense for the real world; how would you copy something, make that copy disappear and then reappear where ever you wanted. It takes the metaphor from the real world of cut and paste, but it was built for digital GUIs. It uses abstraction to divorce it self from the real world, and in make it more useful, simple and intuitive for GUIs.

However, if our goal is to bring CAD into the physical world, to make it a more tangible experience, then the metaphor of Cut/Copy/Paste may not be the best solution. When exploring how to "Copy and Paste" in a tangible way, we have instead chose the metaphor of imprinting, both from clay and from letter press. Imprinting is more direct, and the object that is being imprinted becomes a tool, as opposed to an operand. In many ways this "toolness" gives the user more direct control as opposed to the indirectness implied by GUI commands.

One of the projects described in this thesis, CopyCAD, focuses on a 2D metaphor for imprinting, similar to letter press. In CopyCad the user takes the object they wish to copy, and positions it in the layout space, then it is imprinted into the model directly in that position.

KidCAD, a tool for children to remix toys, borrows the metaphor of stamping or imprinting into clay. Here the child takes the toy or object and presses it into the screen where it appears in that exact location.

The other reason that imprinting is a more apt metaphor, is that imprinting produces a lossy copy. Cut and paste, implies moving the same object around, and the world of digital copy and paste, when copying from digital to digital, is also a lossless process. But imprinting is less precise. And our systems for copying geometry in CopyCAD and KidCAD are lossy because the move from the analog world of atoms to the digital world of bits.

However, what is important is how copying is situated, and with CopyCAD and KidCAD, it is more direct and faster than with existing tools like 3D scanners or digitizing arms.

1.4 Tangible Tools for Remixing Objects

In order to explore these three themes, we have developed tangible tools for remixing physical objects. Our hypothesis is that integrating tools for scanning 2D and 3D geometry into design tools can empower novice users to remix physical objects and become authors and designers. By building tools that make it faster and easier to copy geometry from real objects, using a direct and embodied interface, we hope to increase the creative potential of end-user designers.

Through two projects, CopyCAD and KidCAD, we have explored the design space of tools built for easily integrating real world geometry and remixing it. CopyCAD is an augmented 2D CNC milling machine that allows crafters and makers to interact directly on the material that they will cut. They can copy found objects, and edit and modify them through a projected sketch-based interface, machining a final 2D part out of wood, plastic or cardboard. KidCAD is a tangible 2.5D interface for children to remix their toys. By taking the metaphor of stamping objects into clay, we allow children to intuitively and directly copy 3D shapes from existing toys, modify them at a 1:1 scale, and finally 3D print a new toy of their own design.

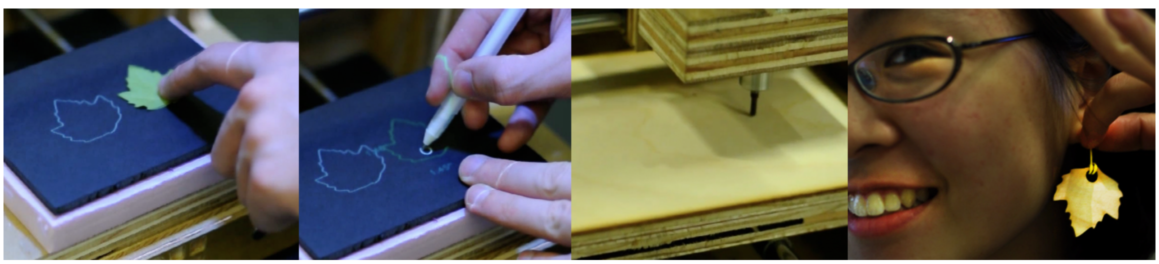


Figure 1-7: Making Leaf Earrings with CopyCAD

Through an iterative design process we have researched user needs, built and evaluated multiple prototypes, to come to these two final designs; this process represents the heart of this thesis. Further evaluation highlights how users can create new objects with these tools and how the tools effect their notions of authorship. Finally we reflect on these tools and point towards new directions for design and remix.

1.5 Thesis Roadmap

Chapter 2 and Chapter 3 provide a context for this thesis, reviewing the history and state of the art of commercial digital fabrication as well as related work in the Human Computer Interaction field.

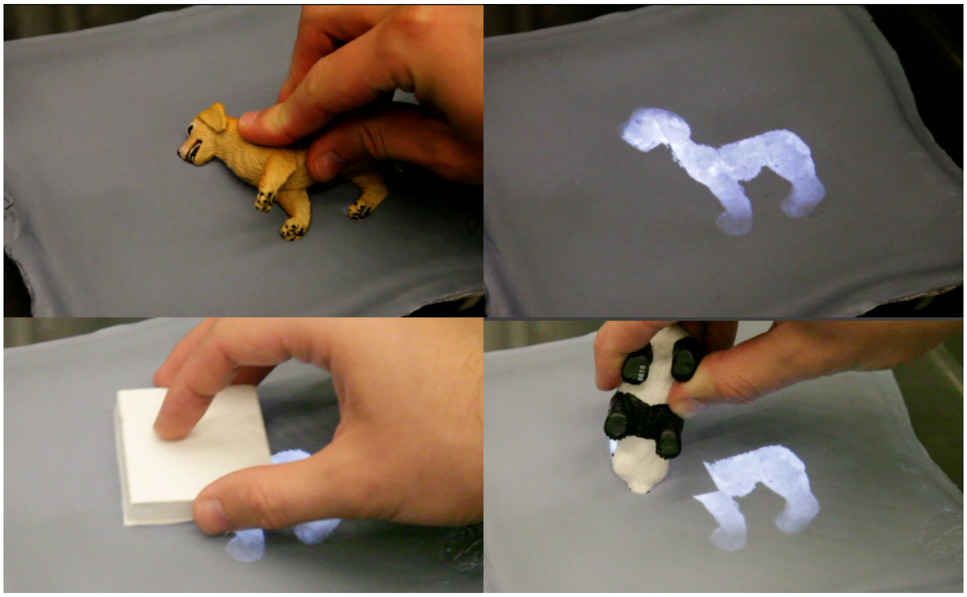


Figure 1-8: Remixing Toys with KidCAD.

Chapter 4 introduces the CopyCAD system, and describes our motivating background research, design principles as well as the implementation of the CopyCAD system. Chapter 5 presents a preliminary evaluation of CopyCAD and explores its use as a Creativity Support Tool.

Chapter 6 describes the KidCAD system for remixing toys. A novel, deformable 2.5D input device, deForm, is introduced in Chapter 7 and serves as the basis for the KidCAD system. Chapter 8 outlines the KidCAD software system. Chapter 9 presents a preliminary evaluation of the KidCAD system.

Chapter 10 provides a discussion of tangible tools for remixing physical objects, and reflects on the CopyCAD and KidCAD systems. New directions are outlined in Chapter 11 that point towards future 3D interactions and higher level copying of geometry. Chapter 12 concludes this thesis, summarizing its contributions.

Chapter 2

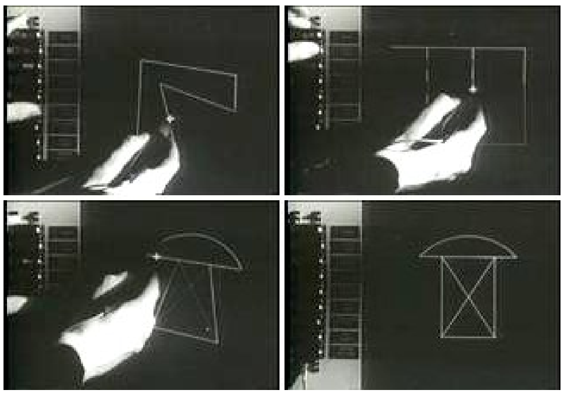
Background

This chapter provides a brief overview of digital fabrication technology and history which includes Computer Aided Design (CAD), Computer Aided Manufacturing (CAM) and Computer Numerically Controlled (CNC) machines.

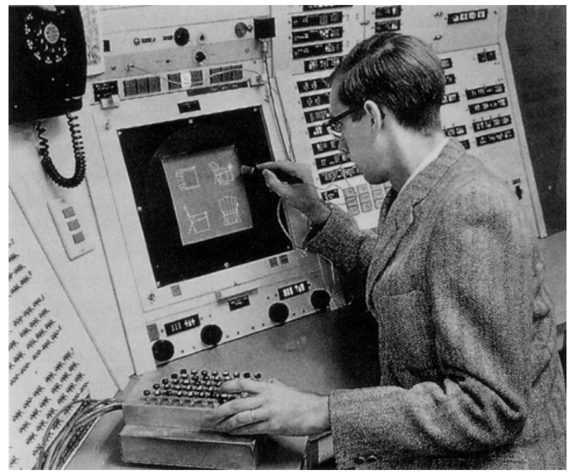
2.1 Computer Aided Design

Computer Aided Design is the process of using the computer to augment traditional drafting to describe parts, assemblies and their relations for domains such as engineering, product design, and architecture. CAD increases the accuracy and ease with which draftsman define and layout their designs, easing repetitive tasks. But the power of computing is best displayed by leveraging Object Oriented paradigms and hierarchical models, resulting in Parametric CAD systems. CAD systems can support classes of objects with relational parameters so that changes in one dimension will affect all other linked dimensions.

CAD has been around since the beginning of interactive computer systems. Ivan Sutherlands work on Sketchpad introduced the world to the possibilities of CAD, building upon traditional drafting techniques, and far surpassing them [136]. The Sketchpad system utilized a lightpen, allowing draftsmen to draw lines and interact directly with the digital CAD model. In addition commands could be issued to constrain geometry to certain relationships, such as making all selected lines parallel



(a) Sketchpad's Graphical User Interface



(b) Sketchpad

Figure 2-1: Ivan Sutherland demonstrates Sketchpad

CAD tools improved and have now become the dominant means for all drafting and design in architecture, engineering and product design. Improvements such as 3D modeling, solid modeling and Finite Element Analysis have made production simulation a reality, allowing engineers to predict how a part will behave in a mechanical assembly and anticipate how it might fail [157].

Commercial CAD software products are large programs, that are expensive and require training. An example is Solid Works, a entry to mid-range CAD software program which costs $3995 [4]. These systems often have a similar interface layout, dominated by 1 large 3D view of the current part. These systems allow for direct interaction using a mouse and keyboard.

More recently, simpler CAD systems aimed at consumers have been released, such as Google Sketchup [42]. These consumer-oriented CAD tools have far fewer advanced features, but provide a more direct and transparent interface.

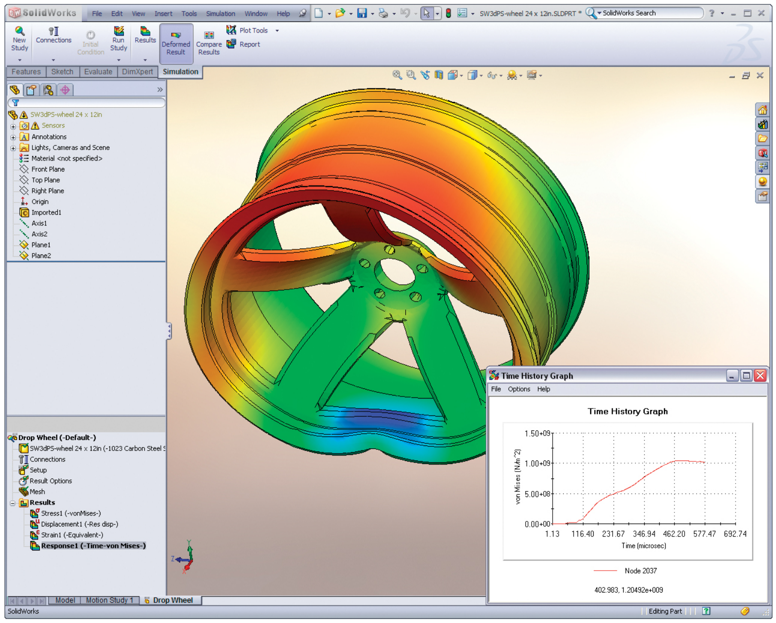


Figure 2-2: Finite Element Analysis simulation in Solidworks helps engineers understand how parts will fail when a force is applied.

2.2 Computer Aided Manufacturing

One of the greatest benefits of digital CAD models is a result of the prevalent Computer Aided Manufacturing (CAM). Once a part is fully described in a CAD software package, it can easily be machined on a CNC machine. This allows engineers to have their designed parts be manufactured or prototyped exactly as they are designed, with very tight tolerances.

Before a part can be machined on a CNC tool, it must be translated into 3D tool paths and machine code, to relay relevant coordinates and intended speed and feed to the CNC machine. This process is done in a CAM software tool, such as FeatureCAM [3]. These tools translate years of experience in machining standards into data files for a robotic tool.

2.2.1 CNC tools

There are a wide range of CNC tools that span traditional machining tools, such as machine mills and lathes, to newer rapid prototyping technology such as laser-cutters and 3D printers

[157]. CNC machines often operate by moving a machine tool around a 2D plane, or a 3D space, along a series of linear actuators, usually one linear actuator per axis of movement. This allows the computer control software to place the machine head at any known position in the machine's 2D or 3D coordinate space. The tool can then be moved to any other point, and can remove or add material along its path.

Some of the first CNC machines were converted manual mills and lathes. Mills and lathes work by spinning a cutting tool or part, respectively, at high speeds and moving the cutting tool across a part made out of wood, metal or plastic, to remove material [157]. A lathe spins the part being machined, and thus creates rotationally symmetric parts, for the most part. Manual mills and lathes have manual rotational wheels that control the location of a cutting tool or a part, and early CNC lathes simply added motors to these controls. CNC mills can machine intricate parts quickly, because the computer can control the mills at a much higher speed, with high precision. CNC mills and lathes are used in prototyping, but also in full scale manufacturing for high end items such as medical devices.

Another class of CNC machines are more often used for rapid prototyping, creating fast prototypes out of materials and processes not often associated with the final means of manufacturing a product. One example for prototyping 2D parts is the laser-cutter [21]. Laser-cutters operate like pen plotters, the machine moves the laser cutting head around a 2D plane to create vector lines and curves. Laser-cutters can cut through wood and plastic, while higher-powered models can even cut through metal. Laser-cutters work by using a highly focused, high-energy laser beam to burn through material.

So far discussed are subtractive CNC machines, which removed material to create a physical form. 3D printers use an additive manufacturing process, laying material down one 2D layer at a time to eventually build a 3D part. 3D printers were designed for rapid prototyping purposes, to see if a part was the right size or functioned properly, within a shorter time period than traditional machining would allow, and at a lower cost than tooling for final manufacturing [157]. 3D printers can even print working mechanisms that do not need to be assembled, with the help of soluble support materials which can later be dissolved leaving only the mechanism. For example Peter Schmitt 3D printed a working grandfather clock as a singe piece that did not need to be assembled [32]. There are many different methods for 3D printing ranging from Fuse-Deposition Modeling (FDM), which melts materials like ABS plastic into a thin filament that can be laid down layer by layer, to Selective Laser Sintering (SLS), which uses a laser to sinter a powder into a solid material layer by layer. Many 3D printed parts are not sufficiently durable enough to be used in final products.

2.2.2 Consumer access to CNC machined parts

Beyond FABLabs and hacker spaces [41], local collective machine shops with digital fabrication tools, there are a number of other alternatives for consumers to access fabrication tools. One option available to consumers is to send the part out to be manufactured elsewhere. Websites like Shapeways [2] and Ponoko [111] have made this process as easy as uploading a CAD file and selecting what material the part should be made out of. The part is then machined or 3D printed at one of Shapeways' or Ponoko's manufacturing centers and then mailed back to the user, with one or two weeks lead time. These websites also serve as online market places where other consumers can purchase designs submitted by other users.

In addition the cost of CNC machines is declining rapidly, such that entry level or do-it-yourself kit machines are accessible to hobbyists, through companies such as MakerBot Industries [67].

Chapter 3

Related Work

This thesis, through CopyCAD and KidCAD, builds off of much work in Human Computer Interaction research, primarily prior work on Design Tools or Creativity Support Tools. The goal of Creativity Support tools is to "develop improved software and user interfaces that empower users to be more productive, and more innovative" [128]. This broad research area focuses on technology to enhance creativity and creative expression. Through an understanding of modern conception of Creativity, such as Csikszentmihalyi's work [27, 28], this research area seeks to imbue software and interaction with methods that can help channel user's creative potential. A good overview of the design principles of Creativity Support Tools can be found in Mitchel Resnick's 2005 report [117].

More specifically, our work is directly influenced by past research in sketch based CAD systems, CAD for children, Tangible Design tools, augmented reality CAD systems, and tangible tools for remixing media. In addition, we were inspired by work on example centric design. This prior work has taken design tools in many direction, and our work builds on as well as synthesizes many of these themes.

3.1 Sketch-Based CAD systems

The origins of CAD systems came from the traditional pen and pencil drafting, so it is no surprise that the first interactive CAD system, SketchPad, would utilize a pen as input [136]. As time went on these sketching systems became more sophisticated and a number of trends have recently emerged that move beyond 2D sketching. A good overview of these themes can be found in Computational Support for Sketching in Design: A Review by Gabe Johnson, et al. [71]. Many of these systems rely on pen based input coupled with co-located display, found in tabletPCs as well as Wacom Cintiq tablets, which make pen based input closer to traditional drawing, but add the advantages of interactive Creativity Support Tools, such as backtracking. In addition, a new class of large interactive multitouch touch surfaces have become popular, allowing multiple users to interact with multiple fingers at once [45, 114].

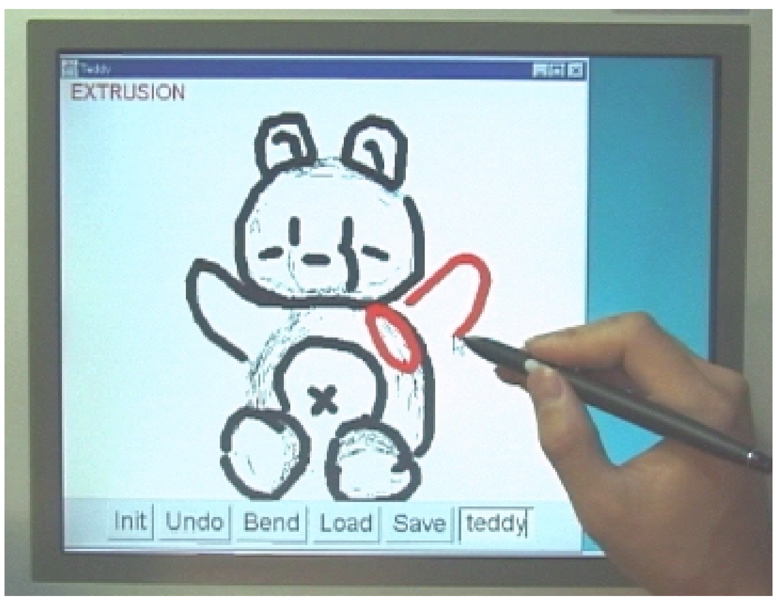


Figure 3-1: Teddy allows users to design 3D models with 2D sketches.

One theme has been transforming 2D sketched input on a flat surface into 3D geometry. An early system that has paved the way for much later work was Teddy by Takeo Igarashi, et al [64]. Teddy allowed users to sketch 2D shapes that were then inflated to 3D forms, and established a language for adding, editing and removing geometry through sketched curves.

More recently, ILoveSketch and EverybodyLovesSketch by Seok-Hyung Bae, et al have taken many of the design patterns used by traditional industrial designers in perspective sketching, and applied them to interactive software to create highly useable 3D sketching [10,11]. The use of sketched reference lines for perspective, along with the focus on quickly moving the object with the non-dominant hand are highlights.

Another trend in pen based systems has been Bimanual input. When sketching in the real world users ink with one hand, but use the non-dominant hand to position the paper or work surface. In addition, other tools such as a ruler will be used by the non-dominant hand in conjunction with the dominant hand [37]. In addition, car designers use two hands to design cars at scale using 2D tape drawing. Bill Buxton explored how these systems can be translated to the digital world [12]. More recently researchers have been exploring the possibilities of using both pen and touch at the same time to achieve many natural sketching interactions [59]

3.1.1 Sketching tools for rapid prototyping

A number of projects have focused on using sketching to more directly and quickly design for rapid manufacturing. There can be a close relationship between sketching and 2D CNC machining, as they both are 2D. Sketching can also provide a very direct means to describe changes to a design.

The Designosaur and the Furniture Factory are two projects that explore a link between sketching and rapid prototyping, in this case laser cutting [103]. The Designosaur allows children to sketch dinosaur bones that can then be cut out of wood and assembled to form dinosaurs, and provides an objected oriented model to organizing the designs. The furniture factory allows users to sketch 3D perspective drawings of furniture, which are turned into 2D panels which can be machined. The strength of these projects comes from abstracting design elements such as joints and press fits from the user, which are later added when the parts are machined.

Sketch Chair allows users to sketch chairs that can then be machined on a 2D CNC machine and later assembled [125]. Sketch Chair takes 2D sketched outlines and builds a 3D chair

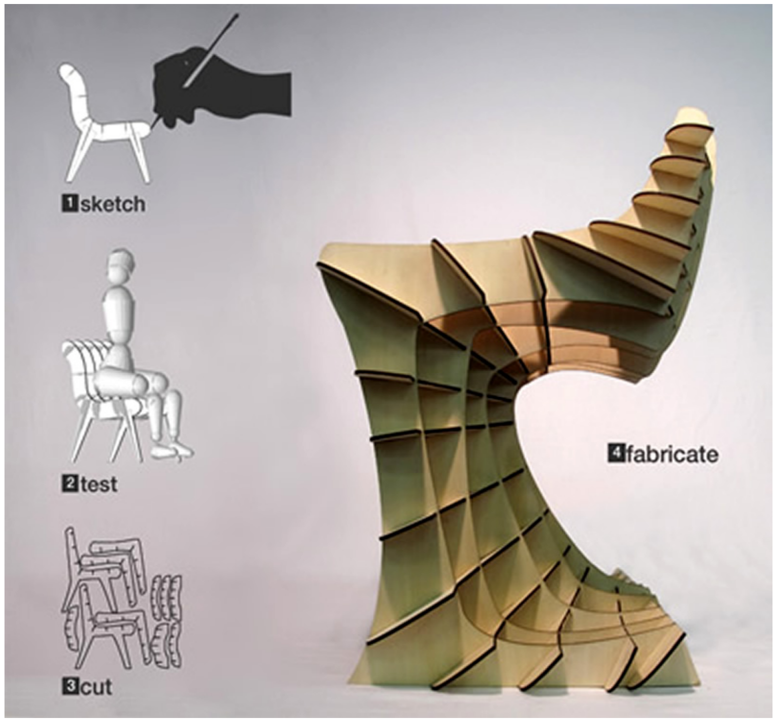


Figure 3-2: Sketch Chair allows designers to design chairs that can be easily cut and assembled with a CNC machine.

from that profile curve, as the chair is edited in 2D the 3D parametric model updates automatically. In addition, Sketch Chair uses physics simulations with digital human dummies to visualize if a chair will support the weight of a human, and how they will sit.

ModelCraft focuses on rapid iterative design [134]; it allows designers to sketch changes directly on physical rapid prototyped paper models and those changes are reflected back to the digital models. 3D paper craft models, which can be cut, folded and taped to form a 3D shape, are printed on special Anoto Paper. A digital anoto pen uses the paper to recognize where strokes are inked on the physical model. Users can edit, extrude or create holes in the models through a sketched gesture language directly on the physical model.

3.2 Tangible CAD Tools

Most traditional CAD systems have been limited to 2D GUI on-screen interaction. Researchers have begun to explore bringing CAD design into the physical 3D world through tangible interfaces. Instead of using a mouse or a pen to interact on a flat surface, these tangible design tools allow users to directly manipulate 3D forms to create digital CAD models.

A more formal definition of tangible interfaces, interfaces where the user can manipulate physical objects to change a digital model, can be found in Ishii's Tangible Bits [68]. Fishkin provides a good overview of many tangible interfaces and organizes them across level of embodiment and other axes [36]. The importance of Fishkin's work is that it clearly explains both tangible interfaces that are fully embodied, where input and output are fully coincident or collocated, as well as more "distant" tangible interfaces, where physical objects change a digital representation on a traditional screen.

3.2.1 Building Block Systems

Early work in tangible design tools focused on computerized building block type systems [5]. These systems allow users to build a model by arranging blocks that may represent walls, doors, or tables, on an electronic base that can actively sense which blocks are placed where. The blocks maybe shaped like the physical objects they represent or be more abstract. For the most part the physical interaction is mirrored in the digital world, but no digital information is sent back to the physical models.

John Frazer also explored these early tangible architectural tools. Some of his work managed to couple the tangible input with digital output by embedding LEDs into the building blocks, allowing the physical design to inform the user [38].

The URP project, built on top of the I/O Bulb platform, has an even stronger coupling between tangible blocks, or Phicons, and digital feedback by co-locating projected feedback around the tangible Phicons [144]. URP is an urban planning workbench where physical

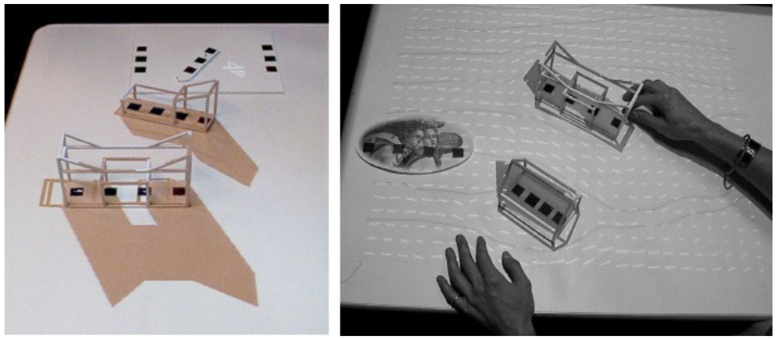


Figure 3-3: URP: A tangible urban planning work bench

models of buildings represent the digital models, allowing the user to easily move buildings around a proposed site. Physical models cast digital projected shadows, and a time dial allows users to see how the shadows change over the course of the day. In addition, wind simulations are projected around the buildings. This digital feedback allows designers to make informed decisions about the placement of buildings, and allows them to easily and quickly try alternatives simply by moving the buildings.

Other tangible building block systems harness co-located projected feedback to inform the user on suggested locations for blocks. CADCast uses projection on wooden blocks and a micro switch to show users step by step building instructions for LEGO or Other Block models [110].

Tangible building block systems can also provide feedback on a variety of different parameters other than placement alone. For example Senspectra allows users to build structures that can be deformed, and the level of deformation on individual vertices is displayed through color LEDs [82].

One limitation of many of these tangible building block systems is that the user must use only predefined pieces, which often contain electronics or patterns that can easily be tracked by the computer.

3.2.2 Tangible Sculpting

A number of interfaces have sought to bring the flexibility and malleability of sculpting with clay to the digital world. A number of software applications, such as Mudbox, allow users to manipulate "digital clay" on the screen with a mouse by deforming, adding or removing clay through mouse strokes [65]. However researchers have been working towards tangible input devices or systems that allow users to deform and manipulate physical forms to modify digital models.

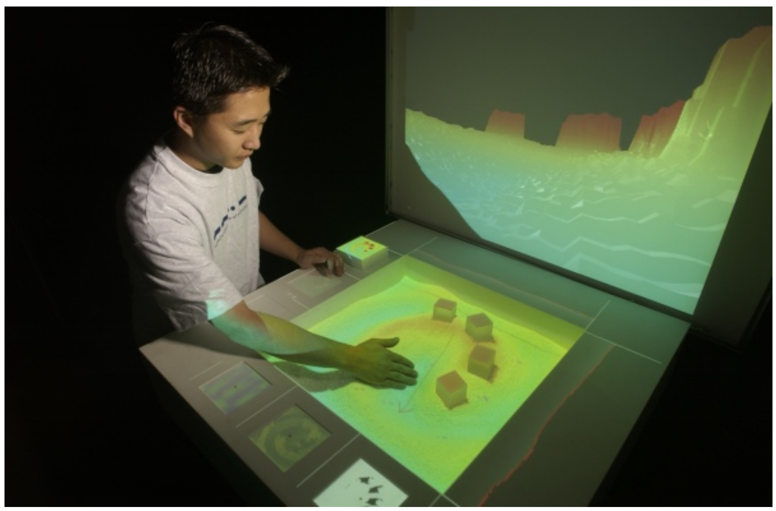


Figure 3-4: Sand Scape allows landscape designers to create 3D models by moving physical sand.

Illuminating clay and Sand Scape allowed land scape designers to manipulate a physical clay or sand models of landscapes with their hands [110]. These changes in these models were scanned in at 1 Hz using a 3D laser range finder. Projected digital feedback on top of the clay or sand could show the designer simulated water runoff or erosion patterns over time based on the current physical model. In this system the designers are limited to only mirroring the physical sculpture to the digital world, and thus are limited by the constraints of the physical world, for example no undo function, or loading and saving.

Other researchers focused on creating malleable or deformable input devices that would modify onscreen graphics, allowing them to have the physicality of input, but the flexibility of digital modification. Tovi Grossman used a bendable curve with embedded flex sensors called Shapetape along with a 3D position tracking of the curve to allow designers to create and modify 3D curves with two hands [43]. Research has also explored deformable materials with embedded sensors to detect deformations [133].

One other approach is to use passive deformable props along with active sensing of 3D hand position to approximate deformations on a 3D object; the tracked hand can press into the foam prop to sculpt onscreen graphics [127]. The passive deformable prop can also be tracked in 3D space and used to squash, stretch, or twist 3D models. The passive deformable prop gives haptic feedback and resistance to the user, mimicking the sensation of deformation. In this case, unlike Sand Scape, the foam prop returns to its normal state when the force of the hand is removed and is never truly deformed. A similar approach can be used even if the prop is deformed. For example, this system tracks a foam-cutting hot-wire tool, which cuts a known piece of foam. The changes in the foam block are interpreted based on the 3D movements of the foam cutting tool through the known location of the foam, and reflected back to the digital model [94]

3.2.3 Actuated CAD Design Tools

Many of the previous tangible design tools are limited by the fact that the computer cannot change the physical 3D form of the tangible interface, only the user can. An emerging trend is to couple tangible interfaces with actuation, to allow the interface to change its physical form. This results in a system where both the user and the computer can change the interface's physical state, and the physical state can easily be kept up to date with a digital model allowing for undo, saving and loading, and many other functions that so far have been relegated to the digital world.

AR-Jig uses a row of 12 actuated linear sliders, which the user holds in one hand [7]. The tool's position is tracked in 6 degrees of freedom in 3D space, and the user wears a head-mounted display to see the digital 3D model, see section for an overview of Augmented Reality. As the AR-Jig tool is moved around the digital model, the sliders change to physically represent a slice of the digital model. This slice can be deformed by the user by pushing and pulling on the physical sliders, to create a desired curve.

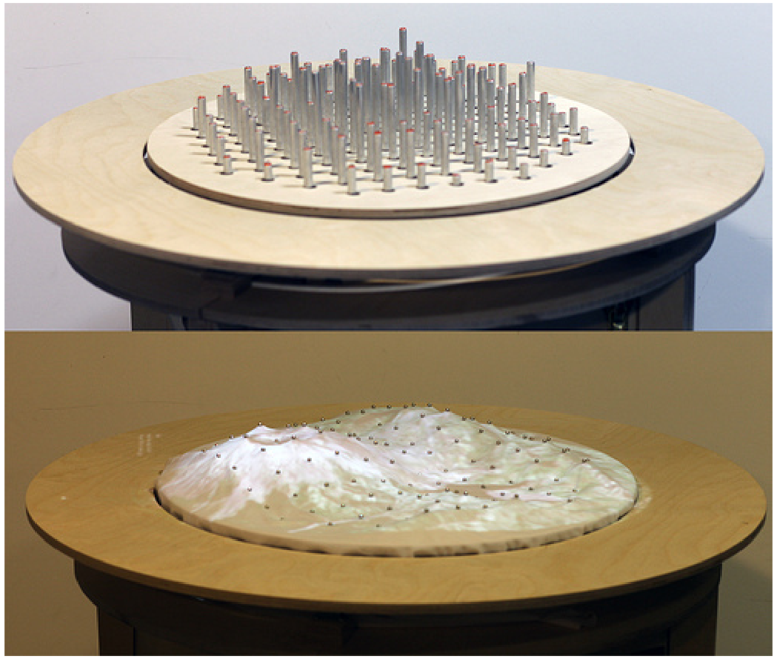


Figure 3-5: Relief, an actuated 2.5D shape display.

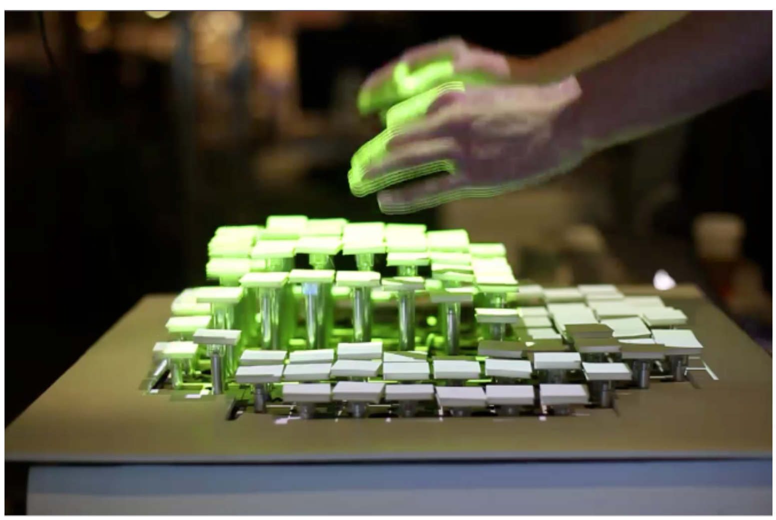


Figure 3-6: Recompose: 3D modeling with gestures and direct touch on an actuated shape display.

More recently Leithinger, et al, have created Recompose [14], a 3D modeling tool built on a 2.5D Shape Display, called Relief [88]. Relief uses a 12 by 12 matrix of linear actuators to create an arbitrary 2.5D surface that can be projected on. In Recompose users can directly modify the physical form by deforming it, but also use gestures to preform more complex functions.

3.3 Virtual and Augmented Reality Design Tools

Predating Tangible interfaces, Virtual and Augmented Reality have sought to immerse the user in the digital world, and often interact directly with their hands. Virtual Reality places the user into the digital world, replacing the physical, often through the use of a Head Mounted display, and allows them to interact often through data gloves or other 3D input devices [118]. Augmented Reality (part of Mixed Reality), on the other hand, overlays digital content in the physical world [97].

Both Virtual and Augmented Reality owe a great deal to Ivan Sutehrland, who in the explained that "Real and Synthetic objects will coexist" in the "Ultimate Display" [137]. In 1968 he created the first head-mounted 3D display and tracking system [138]. The system used two small CRT displays and mirrors to display 3D information directly in front of the user's eyes as they move around, tracked by a mechanical arm attached to the user's helmet. The displays would change content based on the location of the user in physical space, rendering the appropriate 3D scene from that vantage point in the digital model. The system also allowed for semi-transparent displays with the CRTs reflected off of glass to the users eyes, allowing the user to see both the real world and the digital 3D display at the same time.

Pierre Wellner ushered in a new era for Augmented Reality and Ubiquitous Computing, with his Digital Desk concept video [153]. Wellner used digital projection, as opposed to head mounted see through displays, to augment the physical world. This system would allow users to interact with digital information and the physical world at the same time. For example, users could copy numbers from a physical receipt into a projected digital spread sheet.

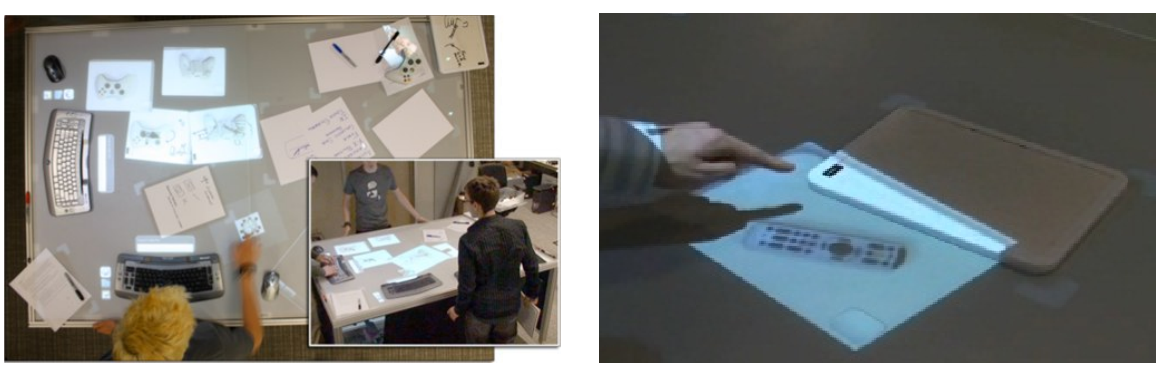
3.3.1 Virtual Reality Design Tools

Many Virtual Reality design tools offer users the ability to sketch 3D objects free form in 3D space. Users can move their hands and see 3D curves appear in the same locations through the use of a head mounted display. Surface Drawing was an early system that relied on this type of interface, however it added tangible tools to modify designs [126]. More recently FRONT, a design firm, developed Sketch Furniture, allowing them to sketch at a 1:1 scale in 3D space and then 3D print the results [39].

3.3.2 Augmented Reality Design Tools

Another class of design tools allowed users to interact with digital content overlaid on the real world.

The Ariel project augmented paper engineering drawings with digital projection [92]. Mackay explains, “Computer information (menus, multimedia annotations, access to a media space) is projected onto a drawing and users can interact with both the projected information and the paper drawing.”



(a) (b)

Figure 3-7: Pictionaire is an augmented design tool that allows designers to copy images of objects to easily sketch new designs.

Pictionaire allowed designers to easily copy images of objects on to a multitouch table directly where the objects are placed, so that they could be annotated, or traced for design work [48]. For example, a physical remote control can be copied and then that image can be quickly sketched over to design a new layout for the buttons. This quick copying of objects inspired our work greatly.

Using a Shader Lamp [113] approach to augmented reality, designers can digitally paint on physical 3D objects using 6 degrees of freedom tracked tools and a projection setup [86]. A number of tools can be used, for example digital stencils and spray cans for bimanual manipulation.

3.3.3 Augmented CNC machines

A number of projects have also sought to augment CNC machines. Most of these systems are for machine operators, and not for CAD design. One interface visualize forces on the cutting tool and machine commands, which are helpful for an industrial CAM operator [104]. Another system assists with simulating machining directly on a 3-Axis CNC machine [158]

Other systems have sought to make the CNC fabrication machines more interactive [154]. A number of systems described by Willis allow for direct manipulation of CNC machines through touch, sound, or mid air gestures. Often the only feedback is the output of the CNC machine.

3.4 CAD and Fabrication for Children

There have been many Creativity Support Tools designed for children with CAD in mind. More recently there has been a move towards more applied CAD tools for children that focus on fabrication. Michael Eisenberg has been a large proponent of CAD and fabrication for children [33–35]. He views these new opportunities in CAD and fabrication as "computational crafts" and embraces the constructionist belief that children can learn through doing [107]. Many of these tools rely on traditional mouse and keyboard interaction.

One such example of his philosophy is MachineShop, a tool for children to design wooden automata [15]. He and his students have also worked with cheaper media, such as paper.

Computer-Assisted Pop-Up Design, is an interactive system where children can easily design pop-up books which can be printed and easily cut [51].

Other systems focus on allowing children to create stuffed animals. Plushie, a system based on Teddy, allows users to draw 2D curves to create 3D shapes [99]. Users can then assign colors and different types of fabrics and print out templates that allow 2D patterns to be sewn into 3D forms once stuffed. Plushbot goes one step further, allowing children to design interactive stuffed toys with sewable electronics [62].

3.4.1 Tangible CAD Tools for Children

Researchers have also been working to create CAD tools that support tangible interaction. Posey is a pose-able hub and strut construction toy, which allows children to build different models in the physical world. These hub and strut parts are instrumented with sensors, and each part's position and orientation is relayed to the computer [151]. This allows children to create digital 3D models with tangible toys. A more abstract design tool UCube allows users to create 3D vertices through tangible interaction [84]. LEDs embedded into a grid of vertical rods can be turned on and off to signify the existence of a vertex. It is currently limited to a four by four by four pixel structure.

Mechanix allows children to design mechanical solutions to marble ball run problems that encourage the user to have a marble move from one point to another using gravity [140]. Projected graphics illustrate to the user where the marble should start and end, and mechanical elements such as wedges can be attached to the projection surface. These designs can be shared online, and possible solutions are suggested to users.

3.5 Tangible Remixing Tools

A number of Tangible Interfaces have been designed to allow children to, essentially, remix 2D photos or textures with input from the physical world. I/O Brush allows children to paint on a touch screen with colors and textures from the real world [122]. A special brush has embedded touch sensors and a camera; when the brush is pressed against an object it captures a photo. Users can then move the paint brush on a touch screen to paint with the associated image. This allows the “World to be your pallet.”

Figure 3-8: I/O brush allows children to paint with colors and textures from the real world.

TessalTable takes a similar approach, but allows users to copy parts of images or video from a digital pallet onto small tangible shapes by stamping [6]. These tangible shapes can be rearranged to form patterns. A projector then projects the image segments and video onto the tangible shapes.

The NeverEndingStorytellingMachine consists of two networked sketchbooks augmented with cameras and projectors, with the goal of remote collaborative storytelling [112]. Users can copy drawings or images of objects into the pages by pressing a capture button, which captures both the image and placement of objects on the page, and the pages are sent across the network to be projected on the other book.

3.6 Example Centric Design

Work at Stanford University's HCI Group has recently explored many facets of example-centric design. "Hacking Mashing and Gluing" outlines the notion of opportunistic design, that designers often build off examples in order to build quick prototypes [47]. However their work has also shown how to build interfaces to integrate examples in domains such as website design [49], embedded sensor design [46], and coding [17]. The most relevant work Bricolage allows users to copy the graphic design of one website and apply it to another, without affecting usability or changing content [78]. Also at Stanford, CAD tools based on data driven example sets suggest to users which model parts to add to their existing models [25].

Chapter 4

CopyCAD: An Augmented Milling Machine for Remixing Objects in 2D

4.1 CopyCAD

In this chapter, we introduce a novel technique for integrating geometry from physical objects into computer aided design (CAD) software. This technique allows users to copy arbitrary physical world object geometry into 2D CAD designs at scale through the use of a camera/projector system. This chapter also introduces a system, CopyCAD, that uses this technique, and augments a Computer Controlled (CNC) milling machine. CopyCAD gathers input from physical objects, sketches and interactions directly on a milling machine, allowing novice users to copy parts of physical world objects, modify them and then create a new physical part. We begin by providing background research on design practice motivating such a tool.

4.2 Background

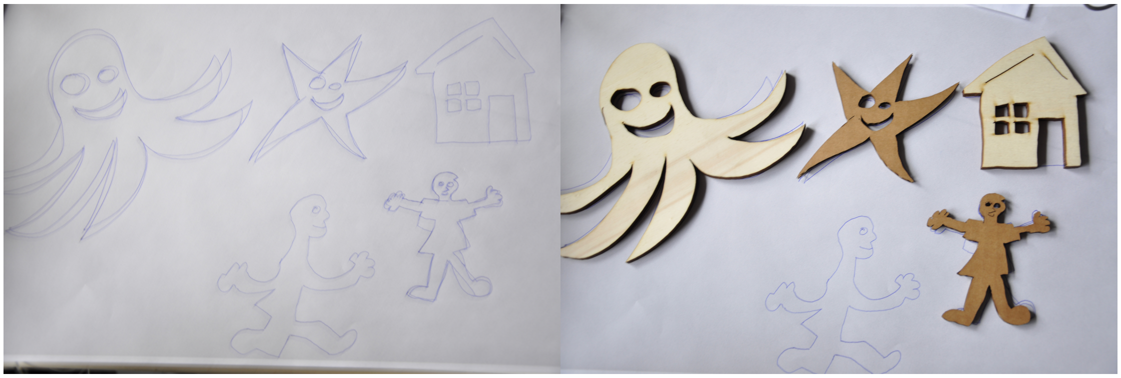
4.2.1 Proof of Concept Prototype

Initially we were interested in augmenting laser cutters with projected interfaces and the idea of directly interacting with CAD files on the material that would be cut. In order to gain insight into this problem space, in collaboration with Seth Hunter, we developed a proof of concept prototype to allow for this more direct style of interaction. We based our design around drawing directly on the material a designer wished to cut. A designer would simply use a pen to draw lines, curves or other strokes on the material, and once placed in the bed of the laser cutter, these lines would be cut by the laser.

To prototype this interaction we built on top of Anoto Pen technology. The Anoto pen uses a small camera inside of a pen coupled with specially paper that has a unique pattern on it, that blends in with the grey background of the paper. The pen is able to localize the strokes from the dot pattern viewed, and then store those strokes or send them over Bluetooth. The Anoto pen also has a traditional inking cartridge, so that strokes are visualized to the user. This provides a very natural inking experience, but also affords digital copying or digital interaction.

In our prototype, the user would attach a large sheet of Anoto paper to the wood, plastic or cardboard he or she wished to cut. Then the user could sketch directly on this paper, and the stroked lines would be sent over bluetooth to a program running on the laser cutter computer. The program would then export these strokes to DXF which could be interpreted by the lasercutter program. Then the user could place the material in the top left hand corner of the Laser Cutter bed, and the stroked lines would be cut exactly where they were drawn.

This initial prototype validated our concept of direct interaction on the material. However, we felt that there was a lack of more advanced interaction that might benefit novice designers greatly.



(a) Drawing shapes on anoto paper (b) Shapes cut out at 1:1 scale on a laser cutter

Figure 4-1: CopyCAD Proof of Concept Prototype

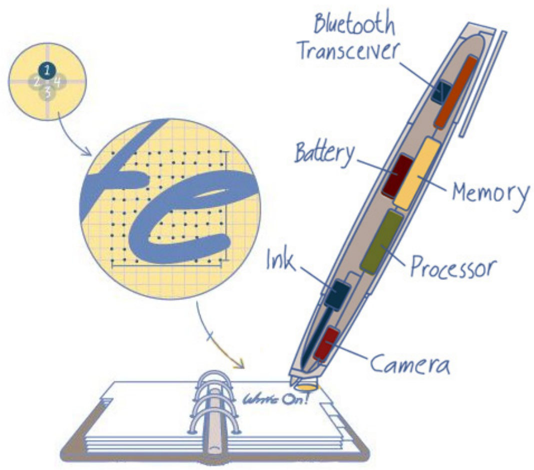


Figure 4-2: Anoto Pen Technology.

4.2.2 Background Research

In order to better understand how Makers and Crafters would want to use laser cutters and milling machines, we sought to interview people with experience using these tools. However, because many of these tools are not currently very accessible to this audience, we instead looked towards what issues, more advanced designers and CAD operators currently have with this technology, to find problem points and understand usage patterns. This type of exploration and learning from "Extreme" users is a common practice in design communities, and thus we felt it was a valid form of inquiry. We were particularly interested in learning about their design process, how they used digital fabrication in their pipeline, and how they worked with existing parts or designs from the physical world and brought them into the digital.

In order to better understand existing design process and problem space of CAD and digital fabrication we conducted three research inquiries. First we looked to prior research on design practice. Secondly, we conducted a survey of 36 professional and novice CAD users to gain insight into their process. Finally, we conducted in-depth interviews with 3 designers who were heavy users of digital fabrication technology.

Prior research on designers has highlighted use of examples in the design world. [Getting inspired!: understanding how and why examples are used in creative design practice] Designers draw off of examples found in blogs, websites, magazines for inspiration. However, a number of designers also have a plethora of physical objects around, both to inspire but also to integrate into prototypes. For example, at many IDEO branches they have tool chests filled with different mechanisms and materials to inspire designers, called Tech Boxes [20]. There has also been research into "opportunistic design," particularly for interaction designers [47]. Based on this prior research we wanted to investigate further how designers of physical objects, using digital fabrication tools, would exhibit this type of opportunistic design, by building off of existing parts and how this was represented in their work flow.

Survey of Novice to Expert CAD Users

We conducted a survey of CAD and Digital Fabrication practices, particularly relating to integrating existing parts into designs and also on digital fabrication work flows. Respondents were drawn from a MIT class on digital fabrication in addition to an advertisement placed on Facebook, targeting users who were interested in CAD. The survey can be found in appendix. A Total of 36 respondents completed the survey, 35 Males and 1 Female respondent. Over 55% would rate their expertise as proficient in CAD software, and over 60% use CAD software frequently. 60% were mechanical engineers, architects, or other professional users of CAD, and 40% were students. Respondents used various CAD software packages, Solidworks, Rhino and Illustrator were the top three. respondents also had the most experience using Laser Cutters (68% have experience using), then 3D printers (65% have experience using), and then 3D CNC milling machines (53% have experience using).

Digital Fabrication Practices

One area we asked respondents about was how often they translated their digital designs into physical prototypes. Almost 60% of respondents claimed to fabricate their designs on most projects, and 19.4% make physical prototypes multiple times per project.

On the whole these physical manifestations of digital designs were often "test mockups to verify the design" explains P26. What we found was that users could not fully understand if a designed part would work without bringing it into the physical world. This maybe because of functional constraints, but also more qualitative constraints like does this look right or feel right. For many users it was difficult to get a complete feel for what the object would be like without having it in the physical world.

These fabricated prototypes are a part of the process of design, but not always the end goal. One respondent explained that, "parts are often assembled into an experimental rig, with some parts being used for months and others being disposable, a new piece for each part." Another respondent explained that these fabricated prototypes are cognitive artifacts that help reflecting on ideas and thoughts. Ultimately they might end up as final object but most of the time they are intermediaries in a thought process.

However there was a realization that this moving in and out of digital and into the physical takes a lot of time. Some respondents were willing to spend the time but others tried to find other solutions. One respondent explained instead of 3D printing or machining he started with much lower fidelity prototypes. "Usually if I need to rapid prototype something, I use legos, knex, duct tape and whatever materials are around. I tend to avoid machining since it is time consuming."

Integrating Existing Physical Parts

We also asked respondents how they dealt with existing parts in their designs. "In reality no design happens in a vacuum," one respondent explained; they tend to build upon other people's designs and integrate off the shelf components.

Ideally there are CAD files or Data sheets available. respondents tended to look online first and only if they couldn't find CAD files or dimensions, create their own. Although large companies like McMaster Carr have CAD files and data sheets a lot of designers and engineers still tend to work with parts that don't, "We often do not have access to the CAD files for the parts of our robots, so I will measure and model them in order to integrate." Or even if they do the data sheets might not be complete. "Sometimes the measurements you need aren't shown on a datasheet and need to be calculated. Sometimes you're not sure what units are used for a diagram."

One architectural designer explained his problem of working with and restoring architectural ornaments. "I have made photographs of Victorian architectural ornaments, in order to add them into my drawings. Various means to convert into digital, but usually by hand and eye, though occasionally I have used raster-to-vector software. I am skilled at making measurements of the existing buildings I draw." Plans go missing or are lost over time, and so instead he has to measure and base off of photographs.

However, respondents explained that it takes a long time to input measurements with existing parts. "A new design process shouldn't have to be spent on drawing pre-existing parts. It should be more focused your new design. Wasted time = wasted money." 3D scanning in particular took the most time to use as reported by the respondents. But there can also be many errors in a more manual process. "If I can't find the CAD file used to make something I'll often have to make a best guess that sometimes requires redoing."

Interviews with 3 Expert CAD and Digital Fabrication Users

Following our larger survey we interviewed three expert CAD and Digital Fabrication users at the MIT Media Lab. Again we were looking for their process with Digital Fabrication and integrating existing parts or examples, and what problems they had with both.

The first respondent we interviewed had just been working on two projects, a digitally designed violin as well as some pottery experiments. He was working closely with a master violin maker, who had lent him a template for the Violin parts. The respondent was trying to copy and modify this design. He first put the template on the bed of a scanner, and scanned its shape. He explained there was no reason to 3D scan it as it would be useless to have that much data. After he had the image of the violin template, he then imported it into his CAD software and manually traced all of the curves, which took him a while. Then he attempted to machine this template on the shop bot, however it had a few errors, so he drew directly on the machined part to highlight the problems and then went back to his design to modify it using the physical part with sketched errors as a guide for fixing the digital model. It took him a number of revisions and physically machined parts to see how the digital model compared to his template, as shown in Figure 4-3.

Figure 4-3: Violin templates used to create violins.

In other projects, he often would build clay prototypes in the physical world to get a sense for size and fit. For example he was designing a hand grip. He quickly carved and moulded the grip out of clay and then 3D scanned it. However, he explained that 3D scanning is too much data. So he would go into the 3D model and draw over it, using the 3D scan as a guide.

The second user explained the benefits of finding models online, such as websites like turbo squid, however he was often hard pressed to find exactly what he wanted. Instead he would attempt to modify them to fit his needs, which was a very long and tedious process.

Our third respondent primarily used the shop bot and laser cutter for 2D milling, which he would then assemble. He highlighted the difficulty of visualizing how big or small a part will be, and how well it will fit in with the material he wanted to cut on. He always had small pieces of wood or plastic that he had previously used to cut other things out of and wanted to fit his new designs on these pieces. He found this process very tedious, and difficult to line up the digital design with the space on the material he wished to cut.

Conclusions from Background Research

From this background research we came to a number of conclusions that influenced our design of CopyCAD. Firstly, designers and engineers use examples, but even more they use found parts. They would like to have CAD files for these parts, however there are often no files to be found and the process for 3D scanning is too much information and a manual system takes a long time and leaves a lot to error.

Secondly, it is hard to visualize digitally if some things will be right, either for functionality or look; thus rapid prototypes are made. However, making a physical prototype takes time, often a lot of time. Once physical prototypes are made changes are sketched, or made, directly on these prototypes but have to be manually copied back to the digital parts.

4.3 Design Principles

From these interviews and surveys in addition with our knowledge of maker/crafters we devised a set of design principles for CopyCAD. Primarily we were interested in creating a hybrid, somewhere in between the virtual models and the rapid prototyped physical parts, that would address some of the problems we witnessed and make interaction more direct.

- Limit the need for creating geometry from scratch - Integrate existing parts form the physical world as tools
- Support many paths for input
- 1:1 Scale
- Situated and direct interaction on the material
- Build off of the flexibility of tools novice users already know, like drawing and sculpting
- Sketchy: Focus on speed as opposed to precision.

4.4 CopyCAD System

CopyCAD is an augmented 2D design tool for CNC machines. It allows users to copy both the object geometry and their locations in the bed of the machine. Users can copy many objects, add and subtract them, edit and draw new geometry all through a projected interface directly inside the bed. This system can scale to different machines and sizes, but our prototype was implemented on a small three axis milling machine. Because users can copy shapes from any physical material, CopyCAD allows for the transfer of skills to different domains and lends itself to different modalities. Someone who is good at sculpting can use clay as input, and someone who prefers sketching can sketch, and these skills can now be used as input for cutting out wood or other materials.

4.4.1 Scenario

Using CopyCAD, crafters can make jewelry comprised of shapes found around the house or outside. For example a crafter could find an interesting leaf on a nature walk. They could bring that leaf back to CopyCAD, copy the shape of the leaf. Then make a second copy of the leaf. Next they could draw a hole at the top of both leaf shapes. Finally they can press cut, and CopyCAD will mill the leaf shape and hole out of wood. They have just made leaf shaped earrings, see Fgure 4-4 .

CopyCAD can be used for more practical problems beyond artistic expression. For example there is a LEGO robot hobbyist who is working on a new robot. She needs a certain size cam for her linear actuation module. However, LEGO does not make cams let alone the one that she needs for her specific design, she was able to find one from a different manufacturer but it doesn't fit in with LEGO. So she can bring a LEGO gear to the CopyCAD machine, place it on the work area and copy the gear shape. Next she can delete the gear outline, leaving only the lego connector shape. Then she can bring the cam she needs and copy it with the lego connector in the middle, or she can draw the exact cam shape she needs around the lego connector shape. Finally she can start the cut command, cut the new Lego CAM out of plastic and get her robot going. See Figure 4-5 for a description of that process.

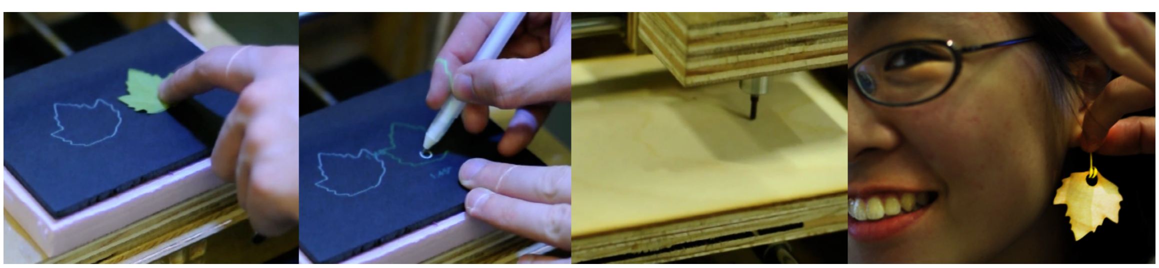


Figure 4-4: Making Leaf Earrings with CopyCAD

4.4.2 Interactions

Interaction with CopyCAD occurs through a multitouch projected interface directly on the bed of the milling machine. Shapes and pen strokes can also be captured as input through a camera mounted above the bed of the milling machine.

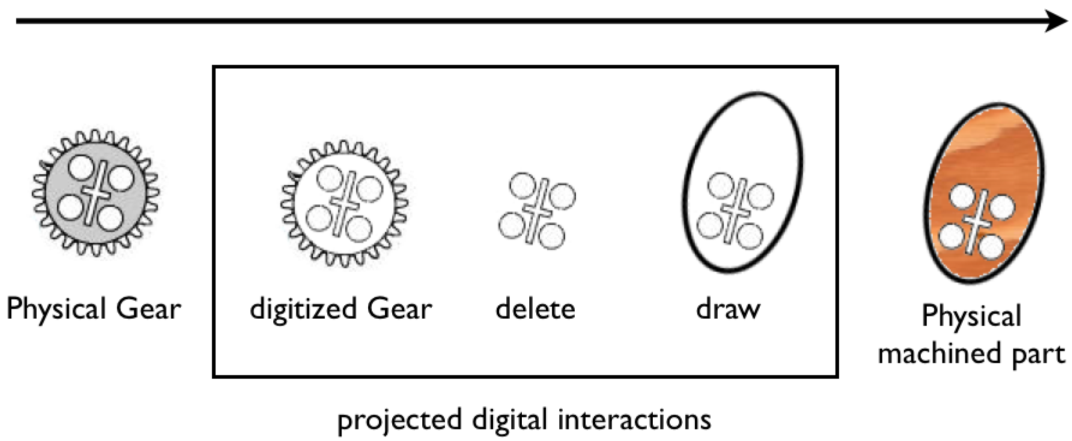


Figure 4-5: Making a Lego CAM

Projected Context Menu

Many CopyCAD functions, such as copying, deleting or cutting are triggered through a projected context menu to the left of the work area. These menu options change depending on whether or not physical objects are present and if digital outlines are selected.

Copy

First, users can capture 2D geometry from a physical object by placing it on the bed where they want the object to be copied and pressing a projected copy button from the context menu. The curves are extracted and projected in the same location where the physical object is initally detected. Users can copy from a wide variety of materials, however only the exterior outline and interior holes are copied.

Draw

Users can draw lines, curves and other strokes directly onto the material to be cut. After drawing the user can select the draw button to capture the drawn strokes. Then they can interact with the digital strokes using multitouch gestures.

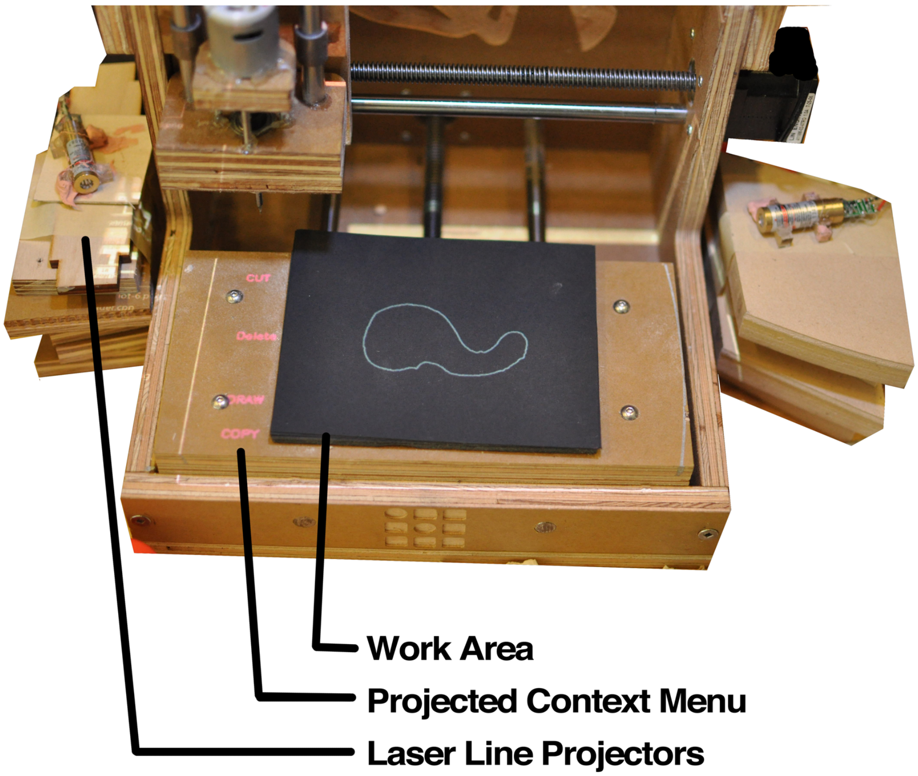


Figure 4-6: Projected Context Menus

Edit

Users select both copied digital objects, or individual curves, by touching them with their finger. Selected shapes appear in green, and measurements of its height and width are also projected.

Once a shape is selected, it can be translated, scaled, or rotated through multitouch gestures. To translate, one drags the shape, to rotate, one uses a two finger rotation gesture, and to scale, one uses a two finger pinching gesture.

Digital shapes can be deleted by selecting them and then pressing delete on the projected context menu.

Boolean Operations

Users can also use other objects to add and subtract geometry to their current designs, this enables users to delete portions of objects or combine two objects together. The user can place an object on top of projected objects, and then select add or subtract which applies boolean algebra to the new shape and the existing shapes. Our hope is that these tools will allow users to easily remix multiple objects in order to form new objects.

Locating Objects with Projected Feedback

Our system allows users to design through tangible thinking, users can move objects with their hands, place two objects close together and then copy to simultaneously create one new shape. Or users can use the projection to locate objects, and explore how new objects will fit in with their existing designs, as in Figure 4-7. This type of epistemic action allows users to more quickly try many alternatives.

Figure 4-7: Locating Objects with Projected Feedback

Machine

Once finished with their designs, users can press a button on the projected context menu to start cutting their design on the machine. Before the machine begins cutting the safety shield must be placed on top of the work area. Because the designs are projected directly onto the material that will be cut, one does not have to worry if there will be enough space on the material or can avoid areas of the material that they do not want to cut on.

Modify Machined Parts

Once parts are machined, they can be altered in the physical world. For example, sanding down a side to make it fit better. These modified parts can be copied back into the digital world with CopyCAD and then modified digitally as well.

4.5 Implementation

4.5.1 Hardware

The CopyCAD system is comprised of four main parts: a CNC milling machine, a web camera, a projector, and linux computer to run the software.

At the core of CopyCAD is a Mantis 3-axis milling machine designed by David Carr [1]. The machine can cut a variety of materials, such as wood, paper, fabric, and foam. This machine can be assembled for under $100 in parts. The machine uses three stepper motors and screw drives to control the linear movement of the three axes as well as a brushless dc motor to drive the spindle. Motor control boards control the three axes and the spindle, and these boards are interfaced over parallel port to a Linux computer running a realtime OS. This computer both creates the control paths for the milling machine, and instructs the milling machine in real-time where to go. This computer interfaces with our design computer over ethernet; the design computer runs the user interface and creates the designs, which it sends to the milling machine control computer along with commands to start and stop the machine.

The Mantis Milling machine is modified with an extended platform raised 20 inches from the work area. This platform holds both the web cam and the projector parallel to the bed of the machine.

The projector provides the user interface and visual feedback to the user on the machine bed. It is a 800 by 600 pixel, 200 lumen Micro projector made by dell. The advantage of this

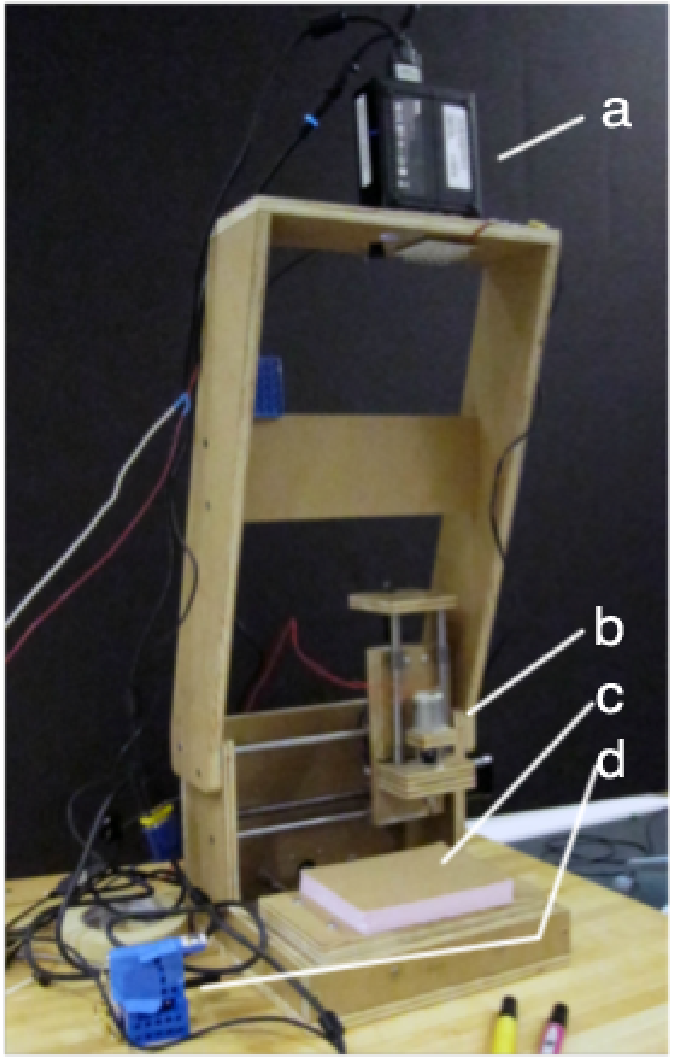


Figure 4-8: CopyCAD System

projector are that it is small, light and cheap but still much brighter than pico projectors, so that it can be seen indoors in the daytime.

The camera mounted above the bed provides two functions, capturing outlines of objects but also detecting multitouch gestures. The camera is a 640 by 480 pixel web camera made by Logitech, modified with a 16mm lens. The narrow lens combined with the camera being placed far away (20 inches) from the bed are used to minimize distortion of object capture. If a wide angle lens is used the sides of objects will be captured in addition to their outline as viewed from above. The camera is controlled using the Gstreamer control software, that allows for manual control of exposure so that camera settings can be loaded. A large five by five white LED array is mounted next to the camera to give constant illumination for objects to be scanned.

To better capture multitouch finger gestures we use an active laser multitouch system similar to [139]. Two green lasers with line lenses create an illuminated light plane and are used in conjunction with the camera to detect touch selections, see figure 4-9. Once an finger touches the surface of the bed, it is illuminated in green by the lasers and is easily tracked.

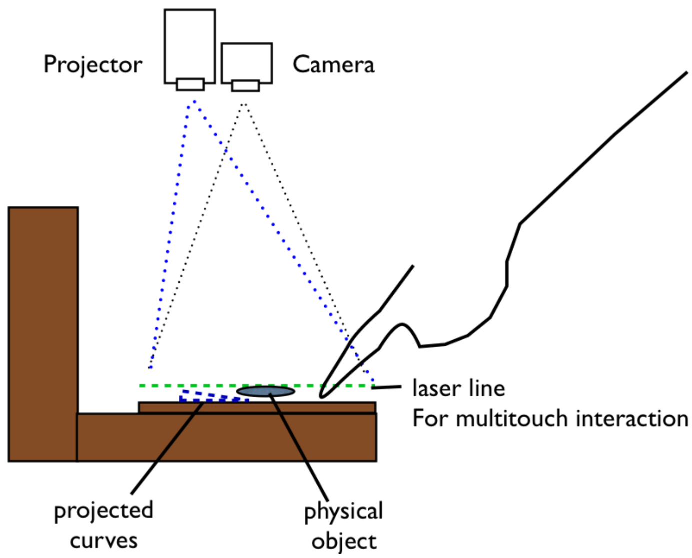


Figure 4-9: CopyCAD System Diagram

4.5.2 Software

The software was written using C and OpenCV. Each frame from the camera is analyzed and the system finds green colored regions, also known as blobs. First the image is transformed into HSV space, and is then segmented creating a binary image with all green pixels of a certain hue that matches the laser. These blobs are labeled and tracked using OpenCV's findcontours function. These blobs are then interpreted as finger touch points for multitouch interaction. A series of projected buttons are placed on the left hand side and the system tracks if these touch points enter and exit these button locations, in addition to the projected digital objects.

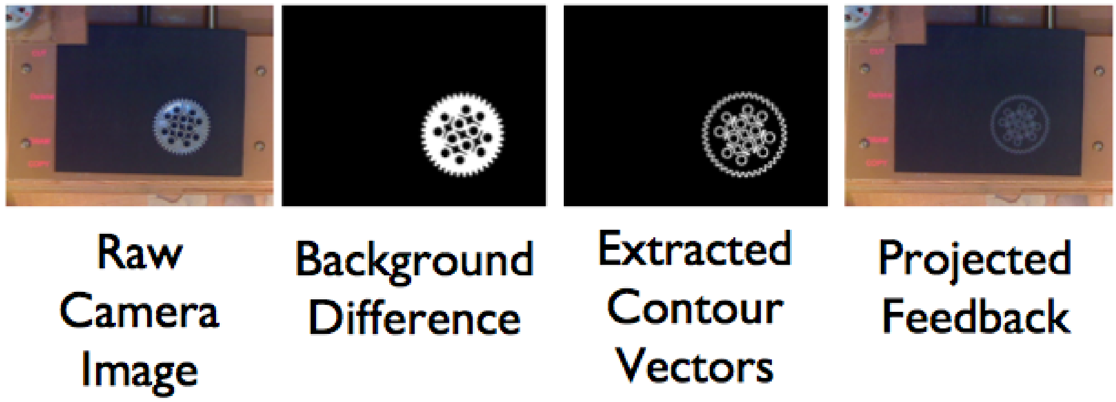


Figure 4-10: CopyCAD Computer Vision Pipeline

When a user selects the copy button, the projector projects a black image and the web camera saves an image. Next, simple image processing is performed to capture the interior and exterior curves of an object or sketched lines. Currently the system implements simple background subtraction to find the curves, see Figure 4-10. When a new material is placed into the work area the user zeros the system by pressing the "New" button. This takes a picture of the background material and saves it for later comparison. When the user selects the copy functionality, the system stops projecting so that the camera can take a clean picture. It currently takes 1.5 seconds to copy an object, but this speed could be increased and is mostly a function of projector and camera synchronization.

The copied curves are stored as vectors of 2D points, inside a tree based data structure based on their relative locations of curves. Once the user selects the cut operation, the curves are converted to a dxf file which is sent to a preprocessing program based on CAD.py. This program then sends the file to the milling machine control computer.

4.5.3 Accuracy

The system uses a 640 by 480 pixel camera and has a working space of 4 by 6 inches, for a resolution of approximately 100dpi. The milling machine far exceeds this. However this is enough resolution to copy a lego gear and have it still fit in with other lego parts once machined as shown in Figure [?]. Higher resolution web cameras or digital SLR cameras for high resolution stills could be used to increase resolution.

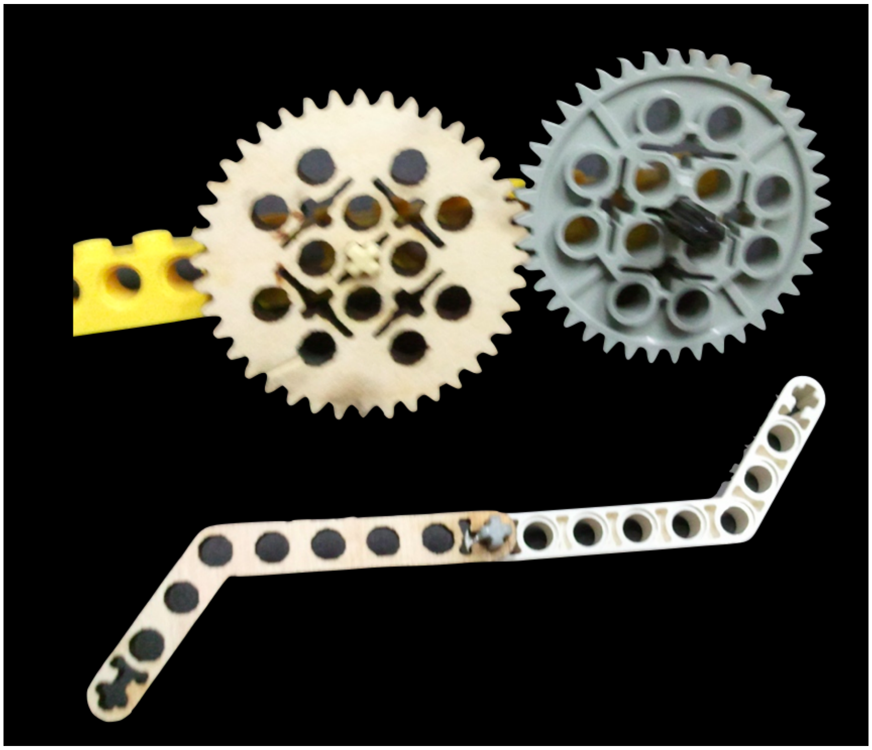


Figure 4-11: CopyCAD Accuracy

4.6 New Systems

Following initial evaluation of CopyCAD, described in Chapter 5, we built a new version of CopyCAD that leveraged our findings. Our goal was to the usability of the system and also to build a more flexible machine that could be used at a FAB lab.

4.6.1 From augmenting the machine to augmenting the material

Rather than focusing on augmenting the machine itself with a projected interface, for our next version we decided to augment the material. This allowed us to create two stations, one a design station where a user can bring a sheet of material and place it down and create designs, and another is a machine station where the user can bring the material he or she

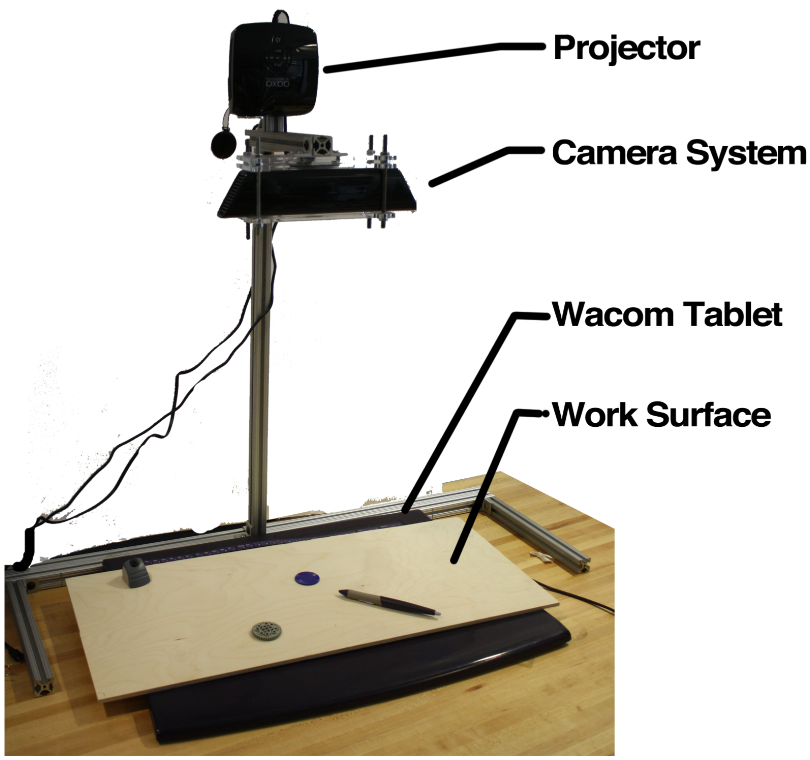


Figure 4-12: Second Version of CopyCAD

designed on and machine the design. This split allows for greater flexibility in a FAB lab because many people could be working at design stations simultaneously without occupying a milling machine or laser cutter. This also gave us more flexibility for input because the design station did not have to withstand the cutting of the material.

A tag placed on the material associates a digital file with both the design station and the machining station such that the digital design will follow the material.

4.6.2 Larger working area

We also increased the size of the working area to 10 by 8 inches, to allow for larger designs, something many users had worried about. We were limited to this size by the resolution of our new cameras which are 1024 by 768 pixel Point Grey Flea 2 greyscale cameras. We wanted to retain the same 100PPI spatial resolution. We also upgraded our projector to a

1024 by 768 pixel micro projector to obtain 100PPI projected resolution.

4.6.3 Higher resolution touch and pen input

One large problem with the previous system was the limited touch resolution that made selecting small shapes and interacting with them difficult. Instead for the new version we decided to opt for pen based interaction using a Wacom tablet as the basis. The wacom tablet's pen works 0.5 inches from the surface of the tablet allowing us to interact directly on material such as plywood or acrylic up to 0.5 inches thick. We use a Wacom Intous 2 18x12 tablet, which allows for multiple pen tools or mice at once.

4.6.4 Digital inking

Another limitation we addressed was the initial CopyCAD's use of real ink. Although users mentioned they enjoyed the flexibility of using different pens, they were concerned by the fact that they couldn't easily erase the strokes. With the wacom tablet in the new version, we can use the pen strokes from the tablet. This allows users to create digital strokes directly on the material.

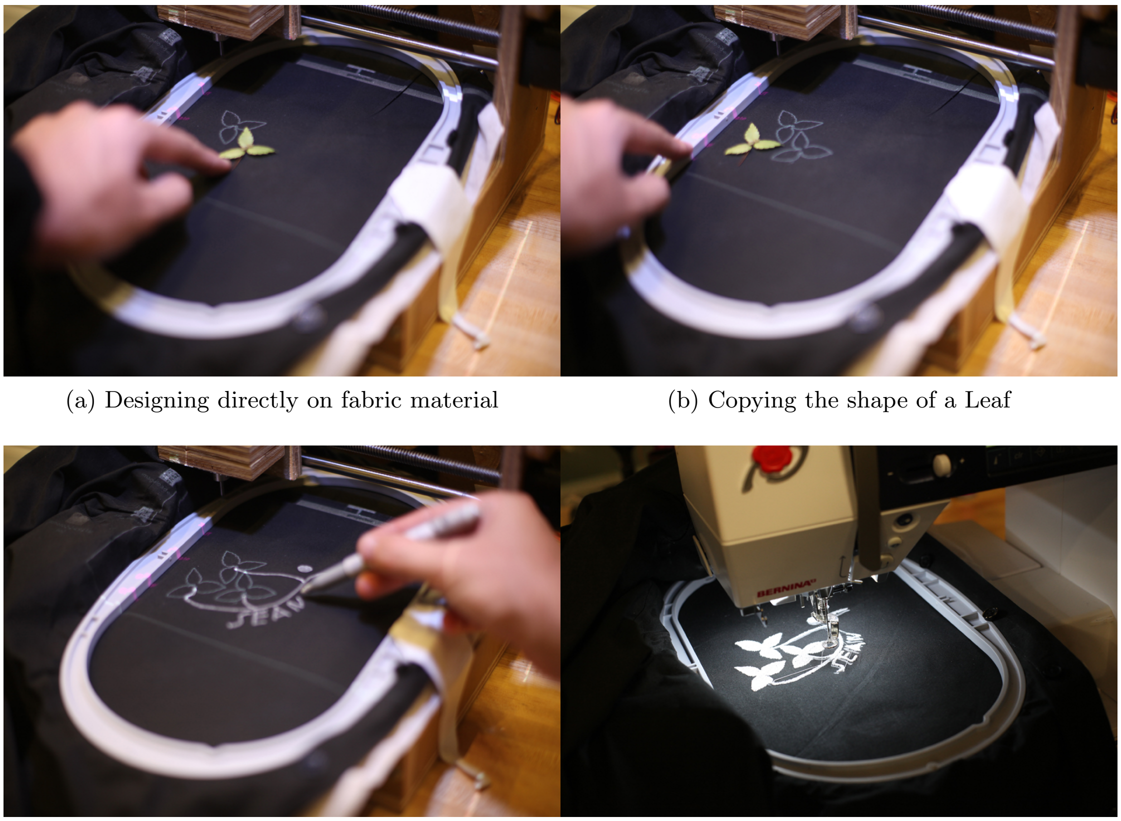
4.6.5 Tangible lenses

We wanted to keep the 1:1 nature of CopyCAD in the new version, however some users wanted the ability to zoom in to make smaller changes to designs. We added tangible lenses that can be placed on the work material to zoom in. This is a avery clear interaction, and allows users to easily know when they are zoomed in, at what scale and to easily return to the 1:1 interface.

The tangible lenses are tracked with the over head camera, using simple reactivision markers [74].

4.6.6 Extending CopyCAD to other CNC Machines

In addition to milling machines we wanted to explore using CopyCAD with other 2D CNC machines. We have built prototypes with CNC embroidery machines and CNC laser cutters. This style of direct interaction lends itself well to these other machines.



(a) Designing directly on fabric material

(b) Copying the shape of a Leaf

(c) Drawing more graphics

(d) Embroidering graphics on fabric

Figure 4-13: CopyCAD with CNC Embroidery Machine

4.7 Conclusion

We have shown an example of how novice users can easily copy physical world geometry and modify their designs through sketching and a projected touch interface. By placing the interface directly on the rapid prototyping machine or directly on the material to be cut, we have further closed the loop for designing physical objects. By allowing for easy integration of existing physical objects, we believe users will be able to explore the possibilities of digitally remixing physical objects. The following chapter provides a closer analysis of how the initial version of CopyCAD was used, and evaluates it as a Creativity Support Tool.

Chapter 5

Preliminary Evaluation of CopyCAD

We chose to evaluate CopyCADs use as a Creativity Support Tool, to find areas that could be improved upon and to better understand both crafters as a user population and how crafters would use the system. We evaluated the original CopyCAD system with three crafters during three different 1.5 hour-long lab based sessions. After a 10 minute introduction to the system, the participants had two 15 minute sessions to create jewelry designs, such as pendant necklaces or earrings, from found objects, clay and drawing input on the copyCAD system. Then they filled out a Creativity Support Index Questionnaire, a standard survey instrument for evaluating a tool across Exploration, Collaboration, Enjoyment, Effort, Immersion and Expressiveness [22]. Finally there was an interview about their experiences with the tool.

The copyCAD tool was created to support novice designers, such as crafters or makers. A call for participation was emailed out seeking participants that were interested in crafts and were not experts at traditional Computer Aided Design tools. Three participants were selected. R1 is a mid 30s female crafter, who knits and does some bead work. R2 is a mid 20s female crafter, who also knits and does some bead work and wire bending. R3 is a mid 30s female crafter, who knits. Female participants were not specifically sought out, however of 6 respondents 5 were women and scheduling conflicts left only 3 female participants. This maybe due to the gendered nature of the term "crafts" in modern American society.

5.1 Crafters as Users

In post study interviews one topic of discussion with the participants was the role that crafts played in their lives. We found it suitable to pull out some of these conversations earlier to attempt to portray some of the motivations and convictions of crafters. These findings may be useful for other researchers working on tools for crafters.

One interesting topic was the relationship to the artifact created through the craft. Unlike other hobbies, crafts often have a physical artifact that is the result of the work. Because the crafters played a direct role in creating the artifact, there is a strong emotional connection. As R1points out "When you make something, it is unique. You are imbuing it with some sort of personal caring or love. You can be more particular about [style choices] and can customize the fit or the size. It feels different to see a baby covered by a blanket you made it than a blanket you bought it."

There is a connection with the object that is clearly more significant than with other objects that may be purchased. However, how much does this value depend on the amount of time spent creating the object? Will tools that make crafts easier decrease the value of the artifact? This may be an important consideration for designers of creativity support tools. Indeed, R2 explains her dislike of software tools, "It is so much easier for me to just draw what I want than to use Illustrator to design it". This connection to the physical world must also be maintained to attract crafters.

Crafters also pride themselves on the time that they spend on their projects, as R1 also explained. "I am an intermediate plus knitter, the only reason I am is because I practice it. You become an expert just by doing it, it about knowing how to fix things and how to ask for help when it goes wrong." In some ways the time spent is a badge of honor. R2 told a story of how someone else was commenting on her craftwork. "See! It didn't take you long to do that she told me. And I though 'NO!' I spent for ever on it. But then I realized of course what she meant was this comes easy to you." If a tool for crafters helps them cut time down necessary, the crafters need other ways of claiming to be part of a tribe, or some sort of level of status. There is a delicate balance between making something easy to entry and making sure people feel like they can become part of a specific community. It shouldnt be as simple as purchasing the tool to gain entry.

From the interviews with crafters we infer that simply making a task extremely easy and fast may not be the best approach to building tools to support crafters.

5.2 Metrics for Evaluating a Creativity Support Tool

If speed and ease of use are not the most important qualities of a tool for crafters, what other metrics may be useful for creating a successful tool? Through prior research We tried to find better measures than speed or usability to evaluate creativity support tools. Exploration of alternatives has been shown to be strongly connected to successful design [31]. Design process, and the creativity process are often tied into an iterative loop, with one step being exploration of designs and then the next step being refinement or reflection, and then repeating [116]. Clearly this exploration of alternatives is an important thing to support.

Another important aspect of the creative process is Flow [28]. Flow is a state of immersion in work or activity where there is a singular focus on the task at hand. In tool design this seems to be connected with user engagement and at a simpler level break downs in usability that can pull the user out of a state of flow [22].

In tools to support musical performance an important measure is often expressiveness [73]. Beyond music, expressivity can represent the level of flexibility in a system to provide the user with options to make what they are doing their own [22]. For example drawing a line: a line could be defined as a connection between two points in space (not very expressive) or defined by someones stroke (more expressive). Tools can support expressivity both in original input and in editing and modifying existing content.

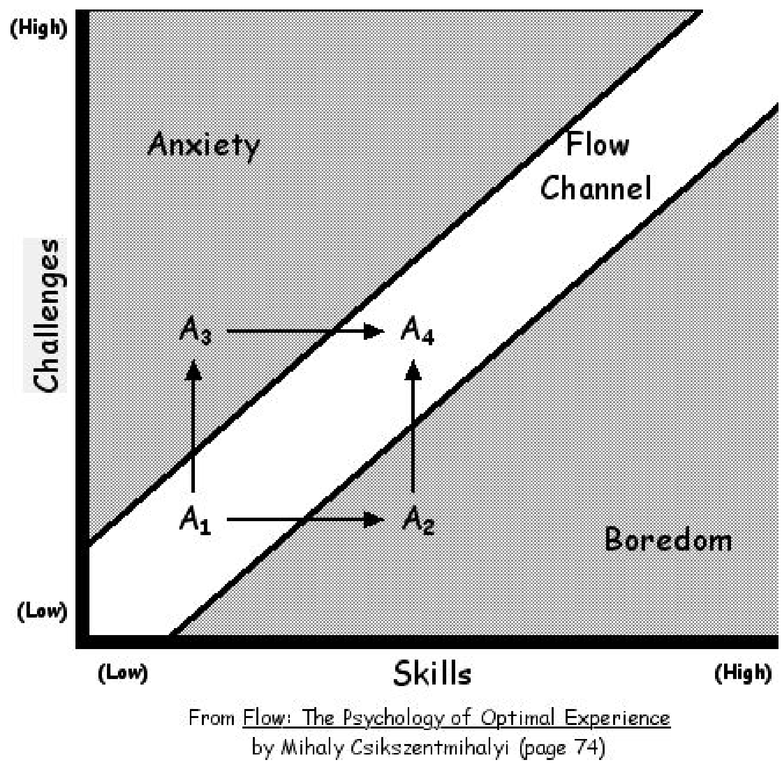


Figure 5-1: Csikszentmihalyi's model of Flow

Turkle and Papert describe the reality that different people can approach problem spaces in radically different ways, highlighting the "tinkerers" and "planners" [142]. Resnick argues for support for many different paths in tools, suggesting that these "hard" and "soft" approaches are both valid [117]. By supporting a number of ways to accomplish the same task more users may be able to use the tool in their own way.

In addition we believe that tools should promote users to feel empowered, and to feel that they can, with the tool, do more than they could before. This perception of increased self worth, or self-efficacy, is important in changing behavior on a larger scale. For example broadening access to careers in science and technology. Consequently, we consider that increased self efficacy in designing, as an important measure for creativity support tools.

Although these may not be the only measures with which to evaluate tools, we think they closely align with the goals of the CopyCAD project.

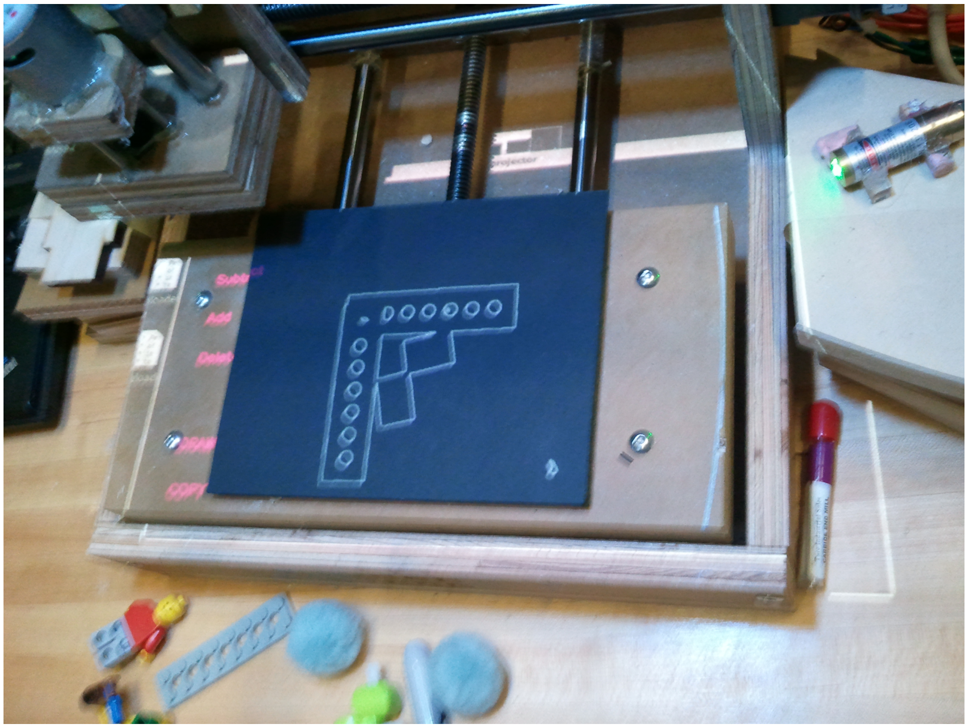


Figure 5-2: User 1 Design

5.3 Exploration

During the trials we observed that it was easy for users to explore many different shapes in their designs. Users combined shapes and drawings, often trying many different designs before cutting one out. They often used the projection coupled with physical objects in their hands to see how objects could fit in to their existing designs, a form of epistemic action [76]. This type of tangible thinking offloads computation from the brain into objects, because a cognitive advantage that our system enables because of its connection to the physical world this is possible.

In addition users found that the tool itself could provide means for exploring different designs, by allowing them to easily cut out new shapes and then tangibly explore with the new physical artifacts. “You are working from a combination of stuff you have and stuff you can have in five minutes. There is a focus on trying different combinations” remarked R2.

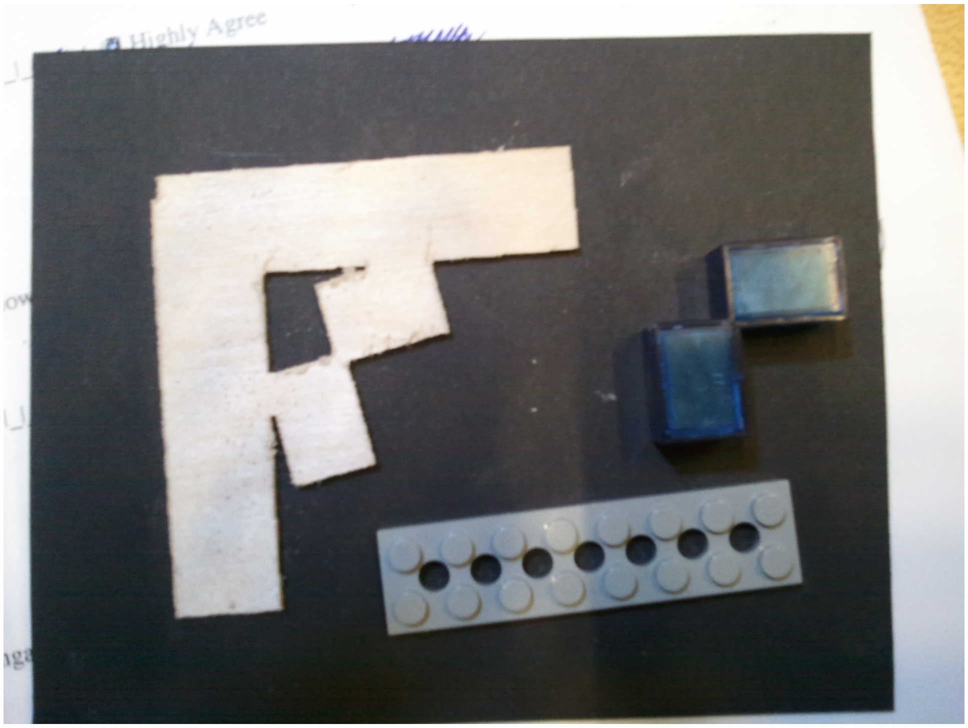


Figure 5-3: User 1's design machined out of wood

However there was less exploration inside the digital world due to the lack of editing tools. Most of the exploration was in the physical world. It was difficult for the users to explore many designs at once, often causing them to delete everything without a way to go back. User R2 also explained that for her the process was mostly delegated to the physical world instead of the digital."I think because for me a lot of the process is physical, and I don't know how they fit together. And this one is too bulky and maybe I need more silver. Its so tied to the actual materials I have on hand, and it's an iterative process."

These responses suggest better support for digital exploration would improve users' experience and designs. A better system for backtracking and exploring alternatives could be used. We propose keeping track of each step through small multiples onscreen, and allowing for branching. This way different alternatives can be explored and compared easily. And in addition other users felt at a loss for new ideas to explore. "There could be more feedback about the process of copying, and maybe suggested places to put things." Providing for more open-ended inspiration is an interesting area to explore in future work.

Figure 5-4: User 2 Design

5.4 Flow

Currently our system falls quite short in supporting flow. In observations, users had a hard time staying focused on the design mostly due to the fact that it was hard to select small objects with the finger based input. Often the items to be selected were much smaller than a finger. “You want to be more granular in what you can select. But it doesn’t mean you have to touch it.” R1 talking about break downs in selection with the touch interface and selecting small objects. These sorts of technical issues can bubble up and pull users out of flow, by making it difficult to complete complex actions. A more accurate pointing tool, such as a pen, could be used to allow for more fine selection. Or a system for disambiguating which small object was selected could be implemented [44].

But beyond smaller interface issues, staying in flow while using CopyCAD could be improved by expanding the scale that the tool can support. One user who was trying to design a piece of jewelry with a number of interlocking pieces explained “I was having to think more

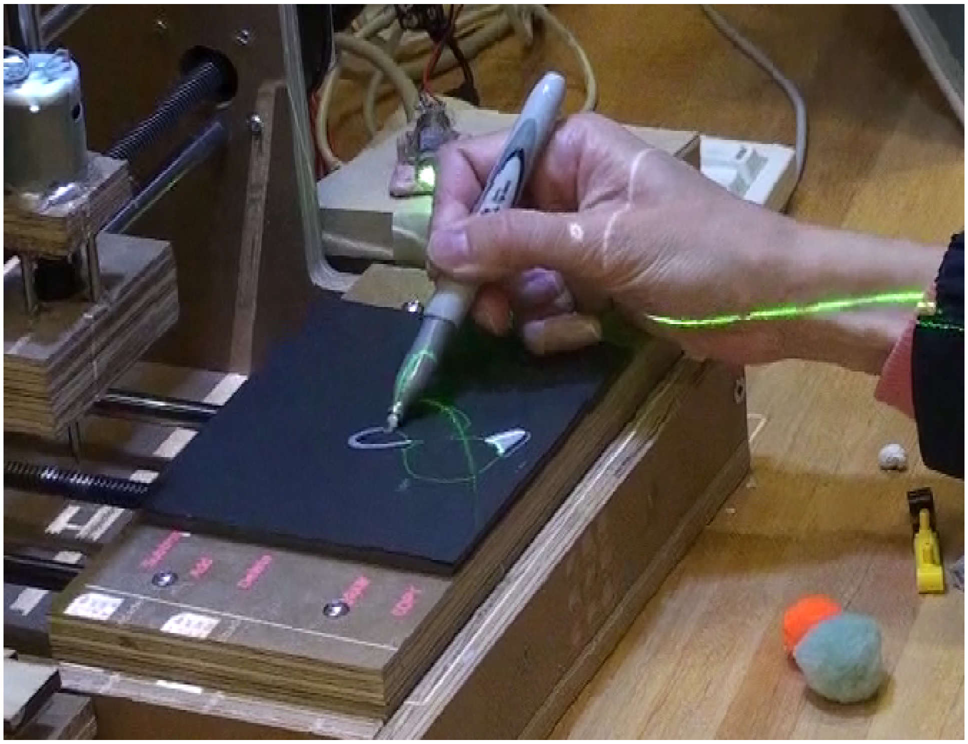


Figure 5-5: User 3 Drawing

about laying out in space. I was feeling the spatial orientation of many pieces was difficult to keep in my head." By supporting a way for users to easily visualize multiple designs at once we can reduce the cognitive load of users and hopefully allow them to better focus on the task of designing.

5.5 Expressiveness

Users rated the level of expression they were able to achieve with CopyCAD as high in a quantitative survey (two users rating it nine out of ten and the other giving it six out of ten). However, it is unclear how clear this term was to the users so it may have been more useful to compare it to other tools. In some cases their designs were very simple and close to the shapes that were copied, due to the lack of easy ways to modify the data. Because users were not able to easily change the shapes once they were copied, beyond scaling and rotating, adding ways to more easily manipulate existing curves easily could greatly expand

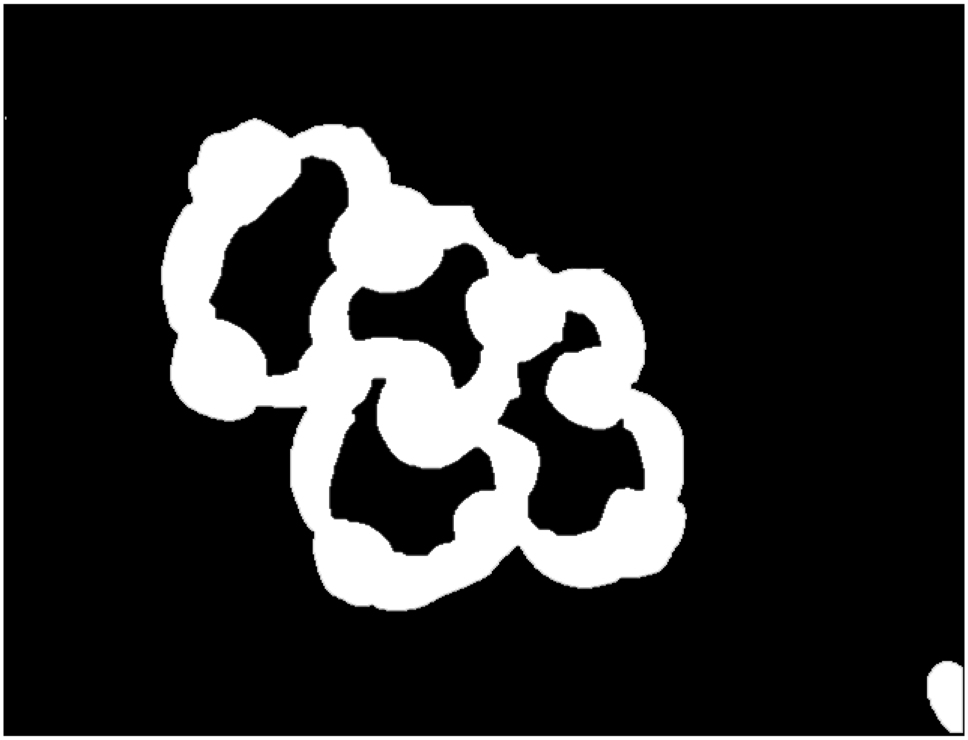


Figure 5-6: User 3 Drawing

expressitivity. For example, bending curves by pushing on them with multitouch finger input.

One area of expression that users seemed to enjoy was the ability to add and subtract shapes easily. This simple action of adding, seemed to add a lot of expressive capability. All but one of the designs created by users used adding, which one user really felt allowed them to take existing objects and "really make them my own."

One of the users wanted to tie their expression more tightly with the final material. The participant remarked, "it would be great if you could design for your material instead of design and then material...These are the lines that I am making. I am positioning it and oh, really I want the grain over here." Currently the user designs on a black surface in the same area that the material will be cut. Future versions could support input directly on the material that will be machined. For example this would allow users to design with the grain and capture areas that they find interesting.

Again one user expressed the need for more creative input. She explains, "if you could get the 3rd dimension then you could add so much more texture and character to it. It could be like drawing in the sand, more expressive... Maybe you could smudge. More of a tactile language. Should adding and subtracting be more like tearing, or pulling or pressing?" This would open the possibility of adding 2.5D input, to be able to sculpt in addition to draw.

5.6 Supporting Many Paths

Different interaction styles emerged in the study. One user, R3, preferred to draw most of her designs. R1 did not use the pen at all, and focused on copying multiple shapes into patterns, and on deleting parts of objects to make interesting new shapes. The tool seemed to support both planners and experimenters.

One of the users was quite pleased that she could use a variety of methods to input. "For me it's about how do you translate a medium that I am comfortable working in, into something that I don't yet have the skills for." This user preferred to use the pen for input. Another user expressed the advantages of being able to sketch with a real pen "Sure I could use that [traditional CAD tools], but if I was attempting to use say [Adobe] Illustrator to draw something that's going to take me a whole lot longer to draw than if I was really drawing."

5.7 Self Efficacy

In terms of supporting increased self efficacy of design, CopyCAD seemed to make a small impact in the users. One user explained that "I'd never used a rapid prototyping machine before. I would like to use another machine like this, it has piqued my curiosity. I don't have to learn a cad program, as a carving tool or an embossing tool." It was clear to many of the users that using these rapid prototyping tools could be easier than they believed previously, "it accomplishes something that I couldn't do alone." In addition one user was excited to now start designing buttons with the system, which she previously thought would be very hard to do. “It would be interesting to use it for buttons. It would be really cool because buttons are really expensive or really boring.”

We see significant obstacles in making rapid prototyping tools more accessible. One user explained her thoughts about starting to learn CAD, “I don’t have any programming experienceI feel like. Because I don’t know what I don’t know. I think it would take a long time to get to the place that I would want to be.” There still seems to be a stigma that rapid prototyping machines are very complex and require “programming.” I think that as more tools get out to people, this can change, but it will not be easy.

In addition wood working seems to be dominated by men. As one of the women in the study explained how she wanted to be able to make all the designs she saw in a magazine, she highlighted how the designer was a man. She remarked, “I had always been interested in the shop, you can see things in magazines, like , shelter magazine or like in dwell, made all of this furniture in. It’s super awesome. And you know it didn’t take him that long because he knows what he is doing.”

This gender standard also stays in the way of many crafters, who are often women, adopting rapid prototyping tools. The Lilly Pad Arduino has sought to make electronics “softer” and more approachable to women [19]. How can these rapid prototyping and CAD tools be made more approachable to women as well?

5.8 Conclusions

In evaluating CopyCAD through a pilot study we have highlighted several areas for improvement. Beyond making these improvements, we believe that thinking more about what crafters want out of a tool would provide valuable insight. We must explore how craft support tools different from creativity support tools. We must strive to develop new tools which can easily integrate into existing communities as opposed to displacing current practices. Many questions remain unanswered and this work begins to provide strategies for thinking about challenges and solutions. In the coming years, we expect increasing numbers of tools to support makers and crafters, and CopyCAD can provide some insight for future designers working to bring digital fabrication to crafters.

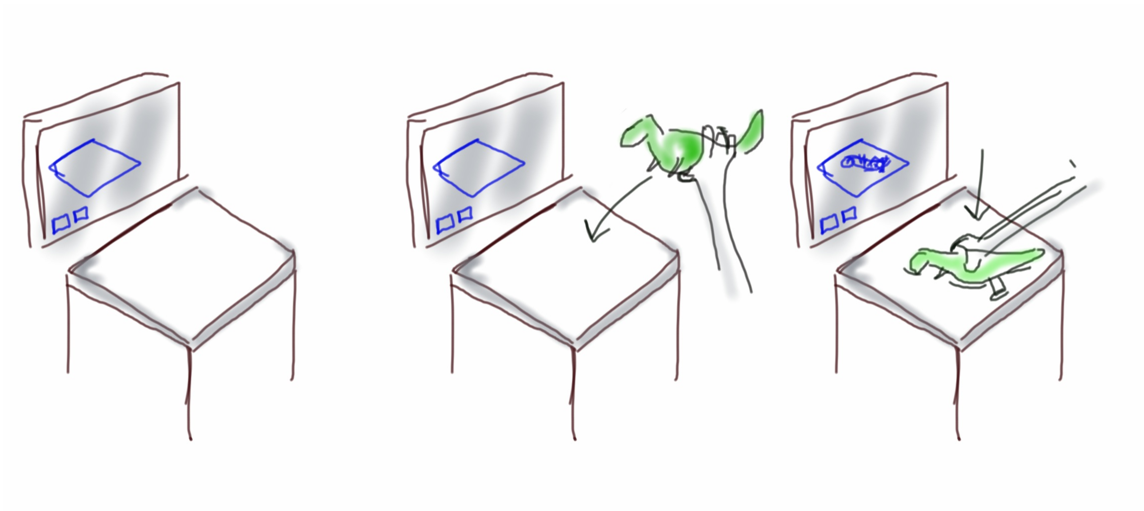
Chapter 6

KidCAD: A tangible interface for Remixing Toys

KidCAD is a tool for children to remix toys and objects using a deformable 2.5D realtime input device. The system uses a metaphor similar to that of sculpting with clay, where children can stamp physical objects into the system and see the deformations it creates directly projected on the gel surface. By pressing an object into the gel it is 3D scanned. The system allows for adding, subtracting and erasing geometry using everyday objects, finger input, and tangible tools. Finally, once the user is done creating an object it can be 3D printed.

The KidCAD system works by using the deForm input device, described further in Chapter 7. This input device provides high-resolution realtime scanning of geometry as well as 2D greyscale texture. deForm also provides a malleable gel surface that users can deform, which provides passive haptic feedback to mimic the experience of sculpting. Projection directly on the gel surface, provides input/output coincidence, and allows users to easily locate and modify 2.5D geometry. Users can easily use two hands to manipulate their designs. KidCAD allows users to deform their geometry using any found object, such as toys or even traditional wooden sculpting tools.

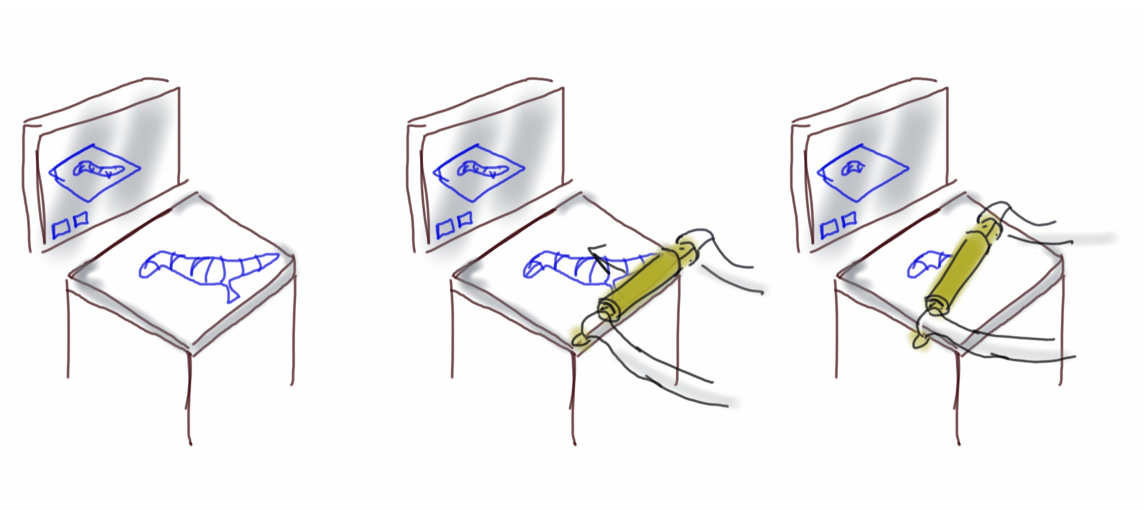
6.0.1 Scenario



(a) The KidCAD system with an empty canvas.

(b) Find a dinosaur toy.

(c) Stamp the dinosaur into KidCAD to copy it.



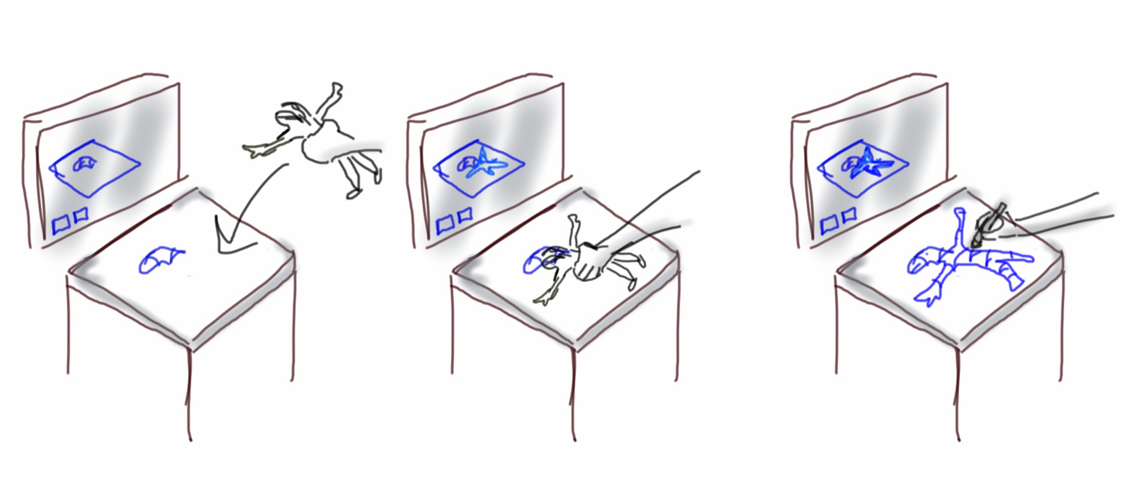
(d) The dinosaur appears where the child stamped it.

(e) The eraser tool.

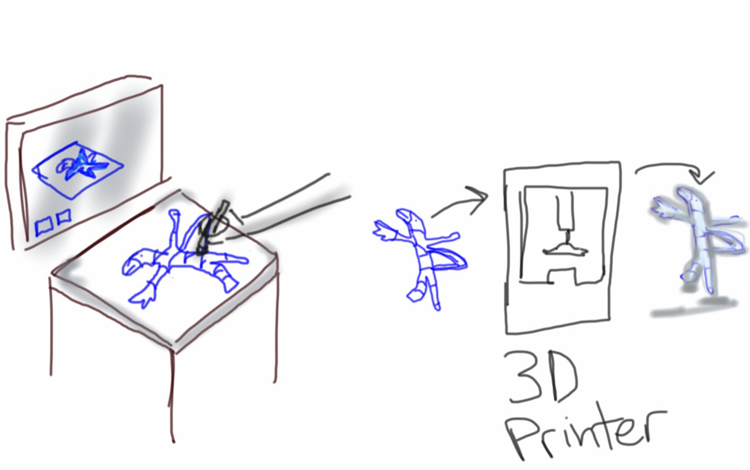
(f) Erase the body of the dinosaur.

Figure 6-1: KidCAD scenario sketches 1

KidCAD was designed to allow children to remix toys. For example a child could take a dinosaur toy, and stamp it into KidCAD's deformable surface. The dinosaur's 2.5D shape will be copied along with its 2D greyscale texture. The shape will be displayed on the gel surface in an isometric view directly where the dinosaur was stamped down, in addition to a 3D perspective on a secondary context screen. The child then could take the rolling pin tool, which functions as an eraser and roll it over the dinosaur's body and legs, only leaving the head remaining. Next the child could take a Barbie doll and stamp its body into the gel surface bellow the dinosaur head. The child will see the body combined with the dinosaur head. Next they can use the pen tool to draw in wings. Finally they can 3D print their new toy and play.



(a) Find a new Barbie doll toy. (b) Stamp the body of the Barbie doll into KidCAD (c) Pick up the drawing pen tool.

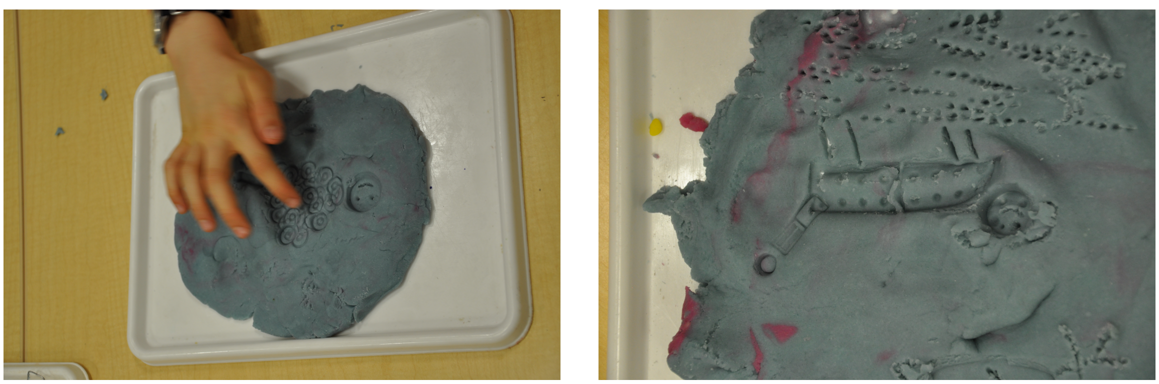


(d) Draw wings on the new toy. (e) 3D print the final design, to have a new physical toy.

Figure 6-2: Kid CAD

6.1 Background Research: Remixing Toys

Figure 6-3: A child's design in Play Dough made by stamping objects and toys.



(a) A child using his hand to smooth out an error.

(b) Small details are filled in with a fine pencil on top of stamped designs.

Figure 6-4: More designs in Play Dough.

We conducted an initial exploration to investigate if children would be interested in remixing toys and what kind of designs would emerge. As an analog for the interface we would end up designing we used Play Dough. Play Dough is a very malleable sculpting material that young children can easily play with.

(a) The children used a variety of objects to sculpt with.

(b) Repeated shapes form textures.

Figure 6-5: More designs in Play Dough.

We selected children aged 7 to 10 years old as our target audience, and as such found a class of second graders ages 7 and 8 to participate. Two groups of 6 children each participated in the study, with a total of 6 girls and 6 boys. Children were split up into two tables, each given approximately one pound of Play Dough to work with. All Play Dough was colored blue, as we only wanted to explore shape and form in this study. During the session the children's task was to create animals by stamping objects into rolled out Play Dough 1 inch thick. The rolled out Play Dough was intended to be an analog for our remixing interface. A number of toys, blocks, knives, pencils and other objects were laid out for children to use with the clay.

We observed some interesting trends that seemed to be exhibited in a number of children's designs. The most prevalent was the use of stamping to create a patterned texture.

There was often a combination of many different objects in addition to drawing into the clay. Many of the children used over 5 different tools or toys to create their animal. Children seemed quite resourceful in using existing toys or objects to create new designs.

However, almost all designs utilized drawing. Children tended to use existing objects to layout the general shape, and then use drawing to fill in more details. This speaks to the need to support a wide variety of input in future design tools.

Hands tended to be used to clean up mistakes, and erase areas, but were not used as often to create geometry. Although a number of times children used their entire hand as geometry, but there was not as much sculpting with fingers as we had expected to see.

6.2 KidCAD System

In designing KidCAD we wanted to create a system that could mirror the flexibility of clay or Play Dough, but with the added value of digital interactions. From our initial background research we found a number of important issues to consider that influenced our design.

From this background research we proposed the following design principles for KidCAD.

- *Direct Interaction* - We wanted the ease of working directly with clay and having no other distractions. Thus, it was important to have co-located projected feedback at the center of interactions. We also did not want to have any modes, but instead rely on implicit mode changes through tangible tools.
- *1:1 Scale* - Keeping the scale at 1:1, between input and display, would help facilitate the direct interaction, and allow children to very easily create a cognitive model mapping input to output. This helps achieve the goal of creating an interaction similar to clay.
- *Flexible Input* - From the observations in the background research we found that it was important to support many different kinds of input: from drawing and stamping to sculpting and hands-on manipulation of the canvas. The system needed to be fast enough to allow users to stamp shapes quickly when creating texture.

6.2.1 Interactions

KidCAD supports 2.5D interaction on a gel surface, with co-located projection. Interaction into the gel surface adds or modifies 3D geometry, where as 2D touch interaction on the surface modifies their 2D positions and orientations. Tracked tangible tools can be used to draw and erase geometry.

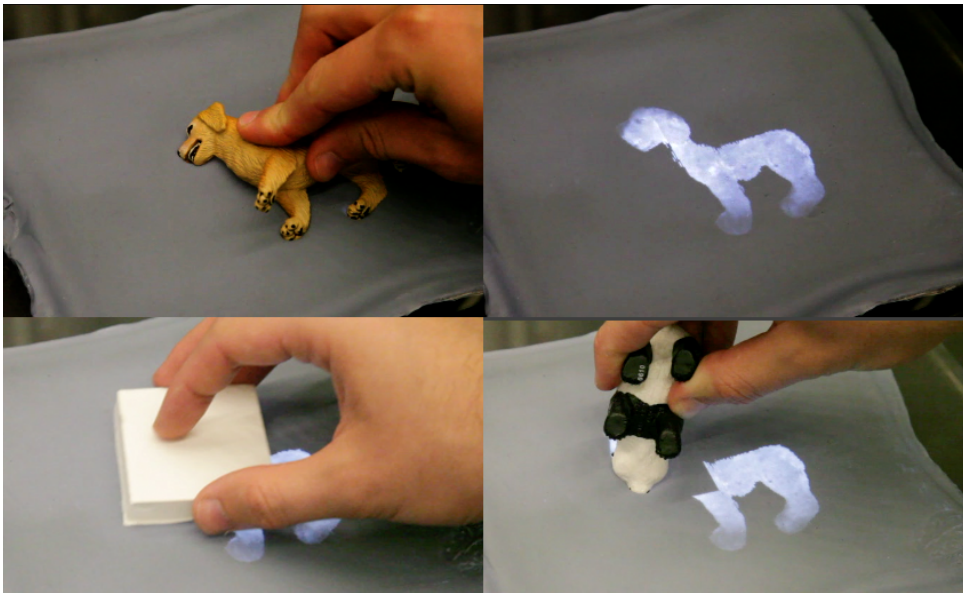


Figure 6-6: Remixing Toys with KidCAD.

Copy and Deform

To copy a physical object's 2.5D geometry, such as a toy, a user presses it into the interaction surface where they want it to appear in the digital model or canvas. The deeper the object is pressed the thicker the 3D model will be. The adding of geometry is inverted such that when a user presses into the gel, the shape is added in the positive direction of the digital model.

Objects or hands can be used to add geometry to the system. As new geometry is added it builds on top of what other geometry was under it, so that objects can be designed to be much thicker than the 1 inch depth of the gel surface. Each object that is added is segmented and can be independently modified.

Draw

In addition there is a drawing pen that allows users to draw 2.5D geometry. The height and diameter of drawn geometry is based on the depth of the pen tool in the gel, which is relational to the force applied to the pen. The pen is comprised of a roller ball with a 1 inch radius and shaft to grip.

Erase

There are two tools available to erase geometry, a rolling pin and a drawing tool. To erase users roll these tools over the areas they wish to erase. This erases both the 2.5D geometry and the 2D greyscale texture. A rolling pin tool allows users to flatten specific areas the geometry, essentially erasing the area directly under the tool. The amount of flattening is also based on the depth of the rolling pin.

Scale, Rotate, Translate

Users can select an object that was copied, or a drawn strokes, by touching them with one finger on the interaction surface. Once an object is selected users can translate the object by dragging their finger. To rotate the object users can use two fingers and rotate the fingers. To scale the object users can use a two finger pinching gesture.

Undo

Users can undo added geometry, drawings, erase gestures, and translations by selecting the undo button on the secondary screen. There is an infinite undo stack, so users can easily go back to earlier designs.

6.2.2 Output

Once users have designed a new toy, the geometry can be exported and it can be sent to a 3D printer. Currently the system requires users to load the geometry file into the 3D printer software manually, although in the future we hope to create a turn key system. We use ZCorp 3D printers to print KidCAD models as they can print in full color. Once printed children can play with their newly made toy.

Chapter 7

deForm: A Malleable High-resolution Input Device

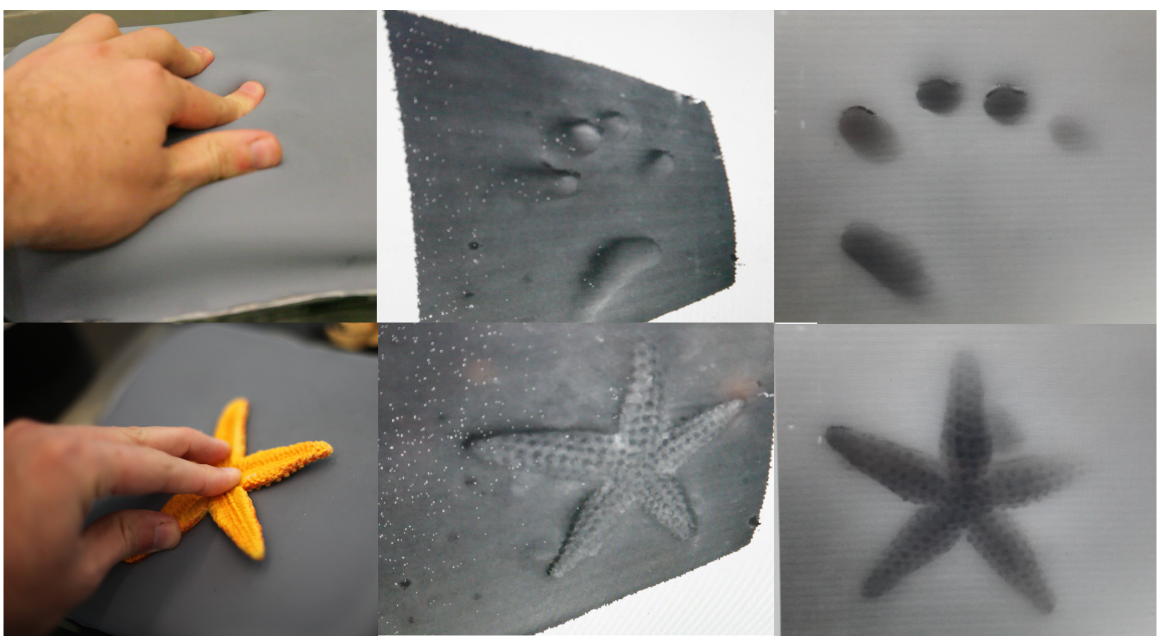


Figure 7-1: deForm.

In order to make KidCAD a reality, we first had to create a malleable interface that could support high resolution 3D scanning.

When interacting with highly malleable and deformable physical surfaces and forms in the real world, such as clay, there are diverse possibilities for input. Sculptors use their entire hands to shape and deform, not just their fingertips, providing nuanced control. Sculptors also use a variety of tools with complex shapes to displace clay or to add texture, see Figure 7-3. These tools afford higher precision and more variety than hands alone. But in addition to sculpting tools, any arbitrary object can be used to deform clay.

When sculptors deform clay, they also feel the feedback of the clay pressing back. This enables sculptors to accurately gauge how much material they are removing or the manner in which they are shaping the medium. By combining these various inputs, sculptors transform blocks of clay into expressive and meaningful forms.

What if we could combine the expressivity of clay with the benefits of digital interaction to allow for input from hands, tools and arbitrary objects with co-located visual feedback? Users could use their fingers and hands to pinch and de-press the form. They could use a physical sculpting tool to add fine detail, find a physical object to imprint a complex texture into the form. Users could also feel the deformations while producing them, because of the immediate feedback from an elastic input surface.

To capture complex interactions of hands, tools and arbitrary objects, we propose using high resolution real-time 3D scanning. Dense real-time 2.5D/3D input has only recently become available and affordable, bringing the flexibility to use arbitrary objects as input. Some camera-based solutions often focus on mid-air interaction, and lack the physical feedback of real-world malleable surfaces. Other researchers have shown that passive haptic feedback can enhance precise, expressive input [83, 129, 146].

Our solution combines a passive deformable surface with real-time 2.5D capture to support a wide variety of input. Instead of directly tracking tools, objects, or hands, our system indirectly senses them through deformations of a highly pliable surface. This approach provides passive hap-tic feedback, and makes clear to the user where the surface of interaction begins and when objects are being scanned. Any object can be used as input, and its shape and 2D grayscale texture, or albedo, are captured as it deforms the surface of the device. A high-resolution 2.5D capture system allows for increased complexity, overcom-

Figure 7-2: Hands, Tools and Objects.

Figure 7-3: Traditional Sculpting Tools.

ing the limitations of low-resolution generic deformations in order to achieve the desired clay-like sculpting.

We introduce deForm, a real-time 2.5d surface interface that uses infrared (IR) structured light scanning and projected visual feedback. We also detail our solution for tracking arbitrary and tagged tangible tools (phicons), touch and hand gestures. We then describe our method for discerning human touch from contact with tangible tools. A discussion of limitations follows.

7.1 Related Work

In this section we summarize 3D input, and its limitations. We then describe how related work has sought to bring 3D input to 2D surface input.

7.1.1 3D Input

Advances in Stereo Vision and structured light scanning have made 2.5D real-time video capture a possibility. Most recently the Microsoft Kinect, made by Primesense, uses structured lighting to capture real-time, 30hz, 2.5D geometry at a 640x480 resolution, but is tuned for room scale interactions with a wide angle lens. Custom structured lighting systems have been shown to capture realistic geometry at very high frame rates, by projecting fixed or time sequenced patterns onto objects [159].

One disadvantage of using 3D capture of points or video for input is that it does not provide physical feedback. In addition, these systems provide no physical mechanism to highlight to the user which information is being captured; there is only, in some cases, on-screen feedback. The work of haptic interfaces such as The Phantom, have explored adding mechanical actuators to 3D input to provide tactile feedback [123]. But these systems only allow for single point interactions and contain many moving parts.

One successful approach has been to combine materials that can provide unactuated, passive haptic feedback with 3D sensing. Illuminating Clay used a laser scanner to scan the front of a clay surface at 1 Hz and projected feedback directly onto the clay [110]. However, the users hands interfered with scanning, as a result of the cameras location above the surface. Passive foam blocks tracked with a vicon system and tracked fingers and tools have been used to enable 3D sculpting [127]. However, this system required augmenting hands and tools with markers, and only provided a simulation of deformations, as opposed to capturing true deformations in the surface. We hope to expand on this work by adding real-time 2.5D scanning to a passive malleable surface to capture real deformations with any object.

7.1.2 Extending Surface Input to 2.5D

There has been a wealth of research on 2D surface interaction [5]. Recently many researchers have explored adding more dimensionality to surface input through both above the surface interactions and into the surface interactions.

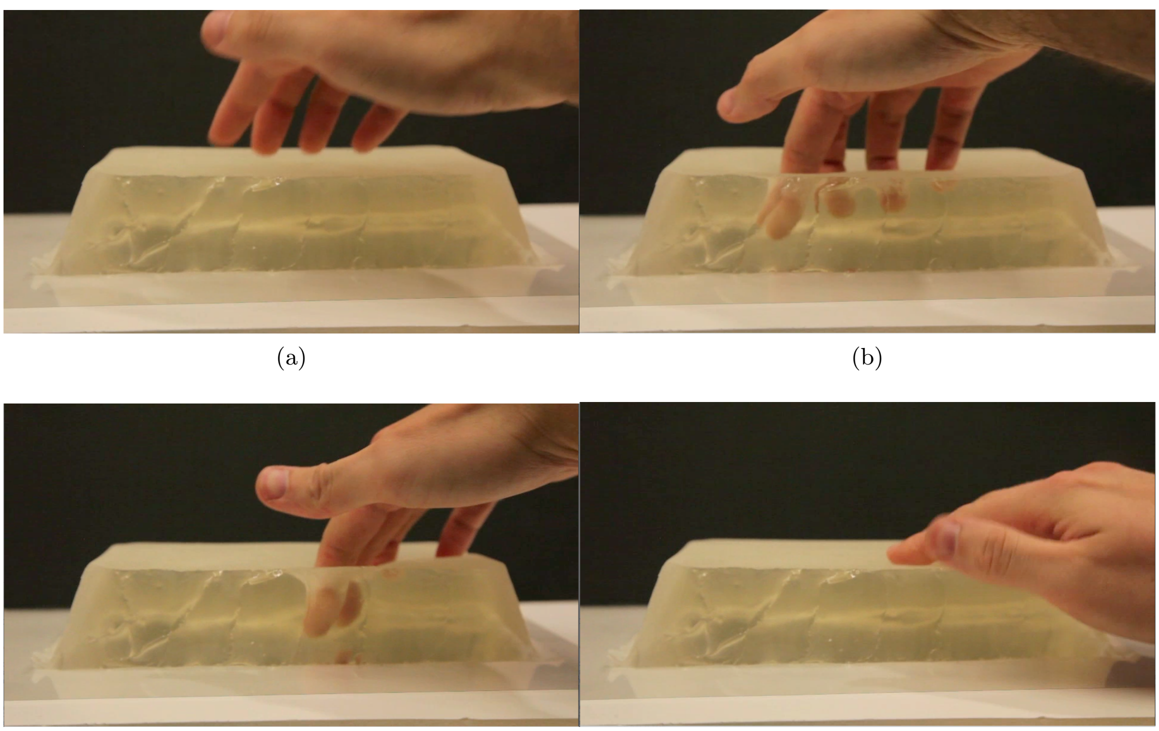
Visual Touchpad used stereovision to enable above the surface 2.5D interaction [18]. More recent work has harnessed depth-sensing cameras to facilitate above the surface interaction [55, 69]. Although these systems allow for much larger areas of interaction, they lose some of the advantages of tabletop surface systems, such as passive haptic feedback, and co-located input and output. More closely related to our work, into the surface 2.5D interaction allows users to press hands and objects against or into the surface to capture more dimensionality. Some of these systems measure pressure through force sensitive resistors [119], or mechanical deformations [106]. Other systems employ magnetic sensors and deformable magnetic material [61, 70].

Another approach is to allow the surface to be deformable and to measure its deformation with a camera. Our system takes this approach, and as such we closely review other systems in this domain. One approach uses a deformable projection screen made of lycra fabric or latex rubber, which stretches when force is applied to it, either tracked by reflected pixel intensity [23] or by tracking dots on the surface.

A number of these 2.5D surfaces have used a deformable liquid bag or gel as their basis. These systems can more clearly resolve concave shapes. This occurs because the gel or liquid applies a stronger force back on the surface to fill in concavities.

One category of gel/liquid based 2.5D systems provide pressure-sensitive input through pixel intensity from a camera mounted below the surface. Pigment dispersed in a liquid contained in a bag reflects more light the deeper an object is pressed [130]. The liquid-based approach does not provide for high-resolution 3D scans, cannot allow 2D texture information to be captured, and has physical stability issues due to fluid movement [56].

Gel-based input systems provide a stable deformable surface to interact with. Photoelastic Touch, utilizes polarizers to measure the photoelastic effect of deformations into gel surfaces [124]. This provides a fairly low resolution spatial pressure map, limited to finger scale detail. Furthermore, spatial resolution decreases dramatically with increased input force. Smith et al. showed that a deformable gel on top of an FTIR multitouch system can provide pressure information [132].



(a) (b) (c) (d)

Figure 7-4: Thermoplastic Elastomer deforms when force is applied but returns to normal state quickly.

A more sophisticated marker-based system, Gelforce uses two grids of visible markers vertically offset in the gel and a single camera to derive true 3D force vectors applied to the gel [147]. This system has many benefits, but its resolution is limited by the size of the dots. These optical dots also obscure the surface and preclude 2D texture reconstruction.

GelSight uses a gel with a painted surface and a photometric stereo system to capture 2.5D surface normals [72]. This system is limited to only accurately reconstructing shallow surfaces because photometric stereo does not capture precise depth disparities [101]. In addition Gelsight is highly dependent on surface color, requiring a thick layer of paint. Furthermore it cannot capture independent 2D texture of an object. Our system uses structured lighting to triangulate surface geometry and is less sensitive to depth discontinuities.

Our system provides many benefits beyond existing work in into the surface 2.5D input. It allows for high-resolution dense surface reconstruction, 2D texture capture in the IR spectrum, to allow for simultaneous 2D visible light feed-back at interactive rates. This chapter also introduces depth-based fiducials, and a method for discerning touch from passive tools.

7.2 System Description

Our system for 2.5D input consists of two parts: a passive, deformable gel surface coated with a thin layer of paint, and a camera projector system for real-time 3D scanning of the paint surface from below.

We use a 1 inch thick gel surface, which is cut into a square measuring 8 by 8 inches. The gel is deformable, but very elastic, and returns to its normal state after the object is removed. The gel is optically transparent and the surface is painted with a gray paint to capture only the geometry of the surface of the gel as opposed to objects above the gel. The painted surface can also be used as a projection screen. The gel sits on a piece of clear glass through which the pattern is projected onto the gel, see Figure 7-5.

deForm uses a structured light system to capture deformations in the surface of the gel in 3D. Our system implements the Three-Phase structured light scanning techniques described by

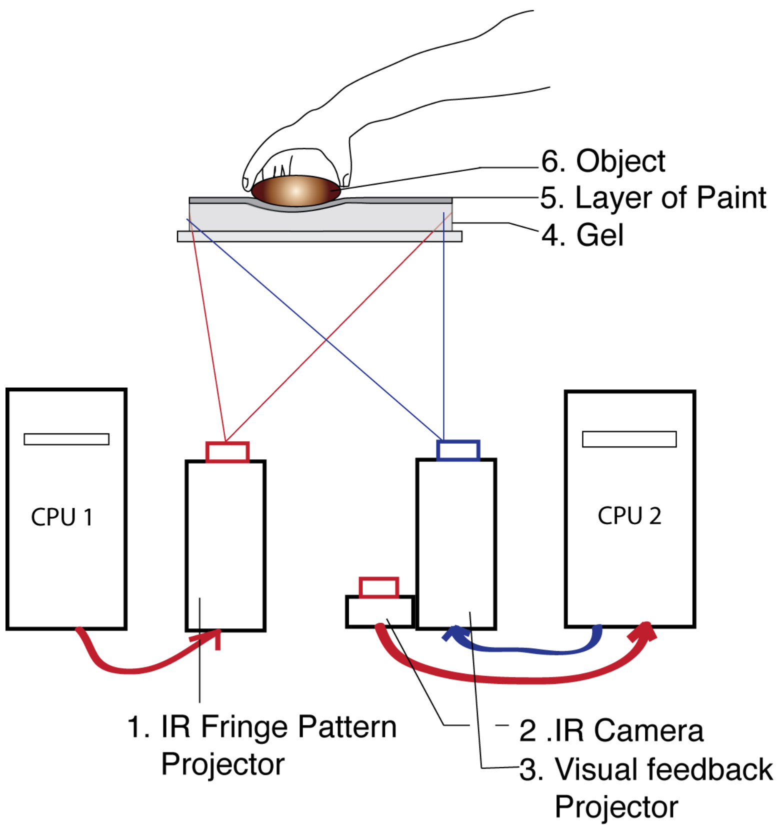


Figure 7-5: System Diagram

Zhang [159]. Three sinusoidal fringe patterns are projected on to the gel surface in sequence and captured by a high-speed point grey camera. The patterns are time sequenced, which means our system requires three projected and captured frames for one 2.5D reconstruction.

With this system we are able to achieve a high-resolution, 640 by 480, depth map at interactive rates of 20 Hz. Figure 7-6 shows a single reconstruction captured in three frames at 60fps. Three-phase structured light scanning can also reconstruct a greyscale texture image of the surface of the gel from the three phase images without requiring an additional camera or a reduction in frame rate [159]. The thin paint used lets through much of the surface color and texture, allowing us to simultaneously map the surface image of the object to its 3D scan.

Instead of projecting patterns in the visible light spectrum, the IR light spectrum is used to invisibly capture geometry. This allows for simultaneous 2.5D input in IR and projection of visible light interfaces on the gel surface for the user to interact with.

We initially attempted to use a Microsoft Kinect camera for our 3D input, but found that it was not appropriate be-cause it was designed for room scale interactions. The 70 degree field of view, combined with an active sensing area starting 30in from the device, results in a minimum sensing area of roughly 42X31 inches. At its 640 by 480 resolution the maximum spatial resolution is roughly 15PPI, far lower than our systems 80PPI. The Kinect also has a very limited z-depth resolution, at close to 0.5cm accuracy.

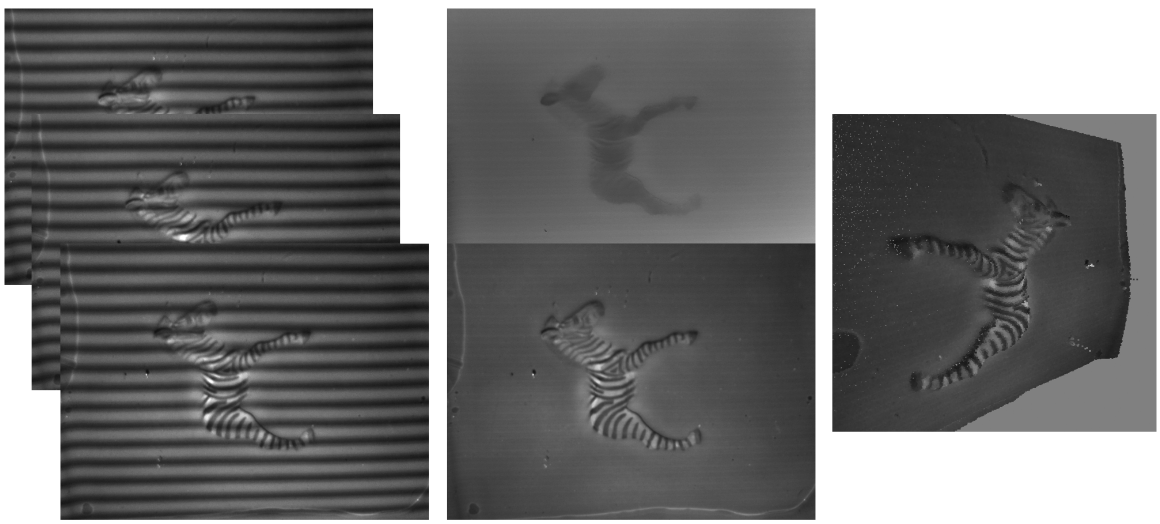


Figure 7-6: 2.5D structured light reconstruction. Left, 3 phase shifted sinusoidal fringe patterns projected in IR on gel surface. Middle Top, 2.5D depth map of Zebra toy. Middle Bottom, greyscale 2D texture reconstructed from fringe patterns. Right, 3D view with 2D texture applied.

7.2.1 Accuracy

Our system is currently able to capture surface geometry with features as small as 0.8mm with spacing between features as small as 1.6mm. We evaluated out system using a number of lasercut depth targets, see Figure 7-7. We are able to capture the overall geometry of a Lego gear, a fairly complex 2.5D object. There is some reduced accuracy due to the gel surface, but this is minimal. Deep concavities are not accurately reconstructed.

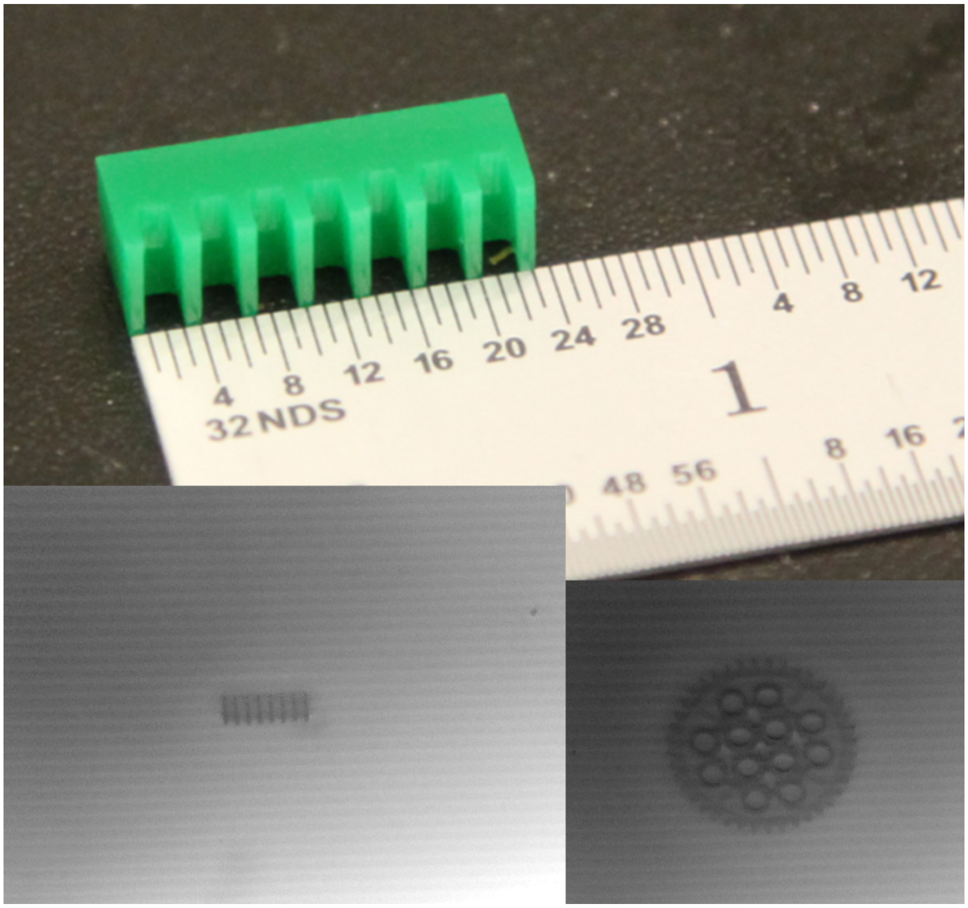


Figure 7-7: Top, Target used to measure accuracy. 0.8mm pins with 1.6mm spacing. Below, left target clearly resolved. Right Lego gear clearly resolved

7.2.2 Tracking

Using a background subtraction algorithm on the reconstructed depth map, our system is able to easily detect objects, fingers and tangible tools pressed into the surface. After segmentation and labeling, we are able to track these objects and classify their average and maximum depth if necessary. We can also estimate the relative rotation and orientation of the object, providing 6 Degree of Freedom input. We estimate the pitch and roll, by averaging the normal vectors over the object. The rotation or yaw can be estimated by finding the major axes, but this approach only works with non-rotationally symmetric objects.

The system can also estimate the force applied by the object, based on both its depth in

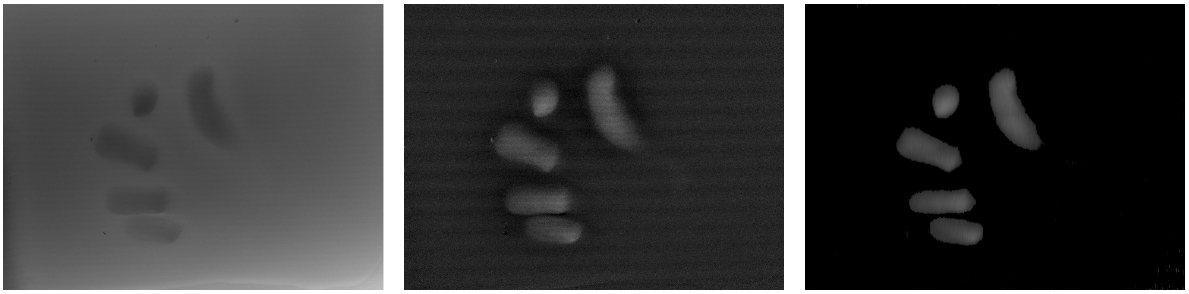


Figure 7-8: Left to right. Raw depth map of fingers pressed into gel. Background subtraction. Thresholded 2.5D image.

the gel and the surface area of the object in contact with the gel. The gel has a uniform durometer and so requires a relatively uniform force to de-form it. By integrating the area bounded by the object in the depth map, we can estimate the relative force in the Z direction. This could be useful for determining the pressure applied to a stylus as opposed to a flat hand.

7.2.3 Tangible Tools

Our system can support input from both arbitrary objects and tagged objects such as tangible phicons (physical icons) [68]. Deformations from arbitrary objects can be mapped directly to input, while using special tagged tangible controllers to pre-form specific operations.

Arbitrary objects/tools

deForm can capture, in 2.5D, arbitrary objects pressed into the gel surface. We can use these 2.5D geometries to de-form virtual meshes or to control 3D scenes. A wide variety of objects can be used to deform the surface, allowing for a diverse set of input means, beyond a single stylus. Multiple shapes can be captured at the same time.

For example, traditional wooden sculpting tools could be used to deform digital models. Many projects have sought to use traditional paintbrushes with digital interfaces [105, 145], to capture particular properties and styles.

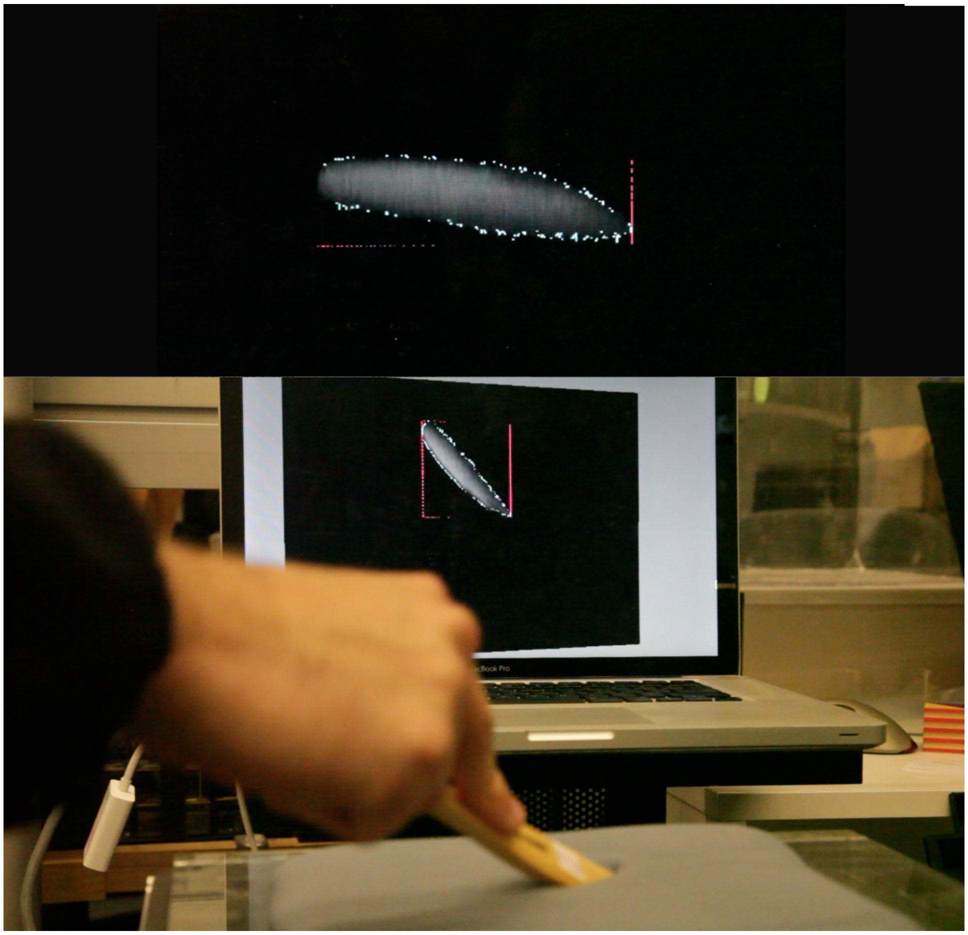


Figure 7-9: Tangible tools can be tracked as well from the depth map. Here a sculpting tool is background subtracted and labeled.

Since deForm can capture both 2.5D geometry and 2D grayscale texture information, the system can function as a fast 3D scanner. Optical multitouch systems have used scans of 2D graphics, such as real photographs and documents [155], to create an easy, direct way to input information. Our system adds another dimension to that intuitive approach. For example, a child could copy her toy by pressing it into the gel. The toy could then be modified in the digital world or uploaded to represent a digital avatar in a game. We discuss the concept of remixing toys in the application section below.

7.2.4 Tangible Controls

IIn some applications, developers may require specific tangible tools to perform predefined operations. Many systems for tangible interaction choose optical markers to track tangible tools quickly and easily [74].

Our system is able to use 2D optical markers by detecting objects 2D greyscale textures. We have used Reactivision markers with our system and tracked them when pressed into the gel surface and on the surface. In addition, our system can estimate the pitch and roll of the markers through the techniques described above.

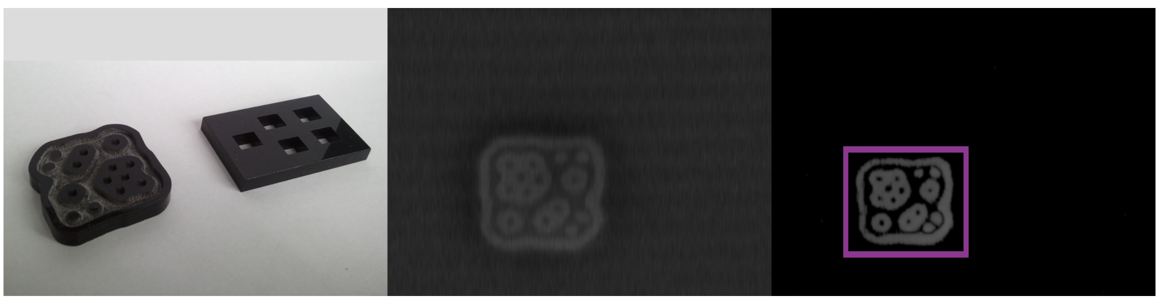


Figure 7-10: Depth encoded markers. Left two laser cut reactivision markers modified to encode pattern in height. Middle, depth map of depressed marker. Right, tracked and labled depth marker.

deForm also encodes marker information in physical depth rather than visible light, which can be tracked in a depth map. This approach allows for other information to be en-coded beyond a 2D pattern. In addition, the physical shape of a marker is easily changed, allowing for dynamic tags. This technique could also be applied to other depth-based input devices that do not capture 2D texture.

We encoded Reactivison information into depth markers by laser etching acrylic plastic, mapping black and white to height values. Using depth-encoded Reactivision markers, we are able to easily track these tags using just the depth map image, see Figure 7-10. As a result of to the gel surface some error remains due to poor reconstruction of small, interior details . A modified Reactivision tag, with larger holes and fewer interior graphics, shown in Figure 7-10, allows for a recognition accuracy of 95% when directly pressed into the material. The adjustment limits the address space but greatly improves tracking performance.

Mechanical components, such as buttons and sliders, could be added to these tangible controllers, as implemented for Slap Widgets [150]. We could encode different information into the depth of a single mechanical pin. For example, instead of a single on/off button we can have pressure sensitive buttons. Alternatively, rotation could be encoded in a pin by using a cam type system.

7.2.5 Touch Interactions

Our system supports traditional multitouch input, but due to its depth, it can capture more complex hand interaction.

Into the Surface Touch interactions

Iconic Gestures

Using the 2.5D depth map deForm is able to support a number of different pressure-sensitive touch gestures, such as pinching and rotating, by tracking finger positions in 3D. We can extract finger locations from the threshold depth map through thresholding and blob detection.

Beyond simply detecting gestures by finger tracking, we are able to detect certain gestures from the displacement of the gel. When an object or finger is pressed into the gel, the gel deforms around the object, increasing in height surrounding the perimeter of the object. When pinching, the gel is displaced between the fingers greatly. This provides an easy way to detect pinching, by looking for areas in the depth map that have increased in height. This is just one example that highlights the differences between our system which captures the geometry of deformation, and a system which merely senses pressure.

The friction that occurs when users articulate their fingers while pressed deeply into the gel, necessitates a vocabulary of gestures based on mostly isometric relative change, rather than absolute positions. This approach would also benefit from the passive haptic feedback that the gel provides.

Beyond iconic gestures

Because our system can detect more complex hand poses than simple touch points, there is a large opportunity to support touch interactions beyond iconic gestures. We can use the 2.5D geometry of the hands to directly manipulate a mesh, much as one would manipulate clay. This type of interaction is explored in later discussion.

Touch Interactions on top the surface

We can use the reconstructed 2D texture image of the gel surface to do basic diffuse IR multitouch sensing. In the texture image we can clearly see finger-tips finely resolved even before they greatly deform the surface, as shown in Figure 7-11. We can use simple background subtraction and thresholding to find the finger or hand points in contact with the surface. This 2D image can then be compared to the background subtracted depth image to find touch points that are not pressing into the surface. This allows for touch interactions both on the surface and into the surface. For example, touch on the surface could be used as a hover mode, and pressing into the screen could select. Alternatively, touch gestures on the surface could change global application parameters, but touch gestures into the surface could change local parameters.

7.2.6 Discerning touch from tools

Many optical systems that support multitouch interaction discern touch points from other objects by looking for the size of the blobs [45]. This method is fairly robust, but is not foolproof. Un-tagged tangible tools, such as a sculpting tool, may appear similar to a finger. To resolve this ambiguity, we propose the use of capacitive sensing in addition to optical sensing. Capacitive sensing relies on the change in capacitance between an electrode and the environment. Unlike human hands, non-conductive objects do not change the capacitance greatly. This allows deForm to distinguish between touch and tools.

Because our system relies on a very deformable and flexible surface, embedding traditional capacitive sensors on the surface is not ideal. Rather, we use conductive paint on the

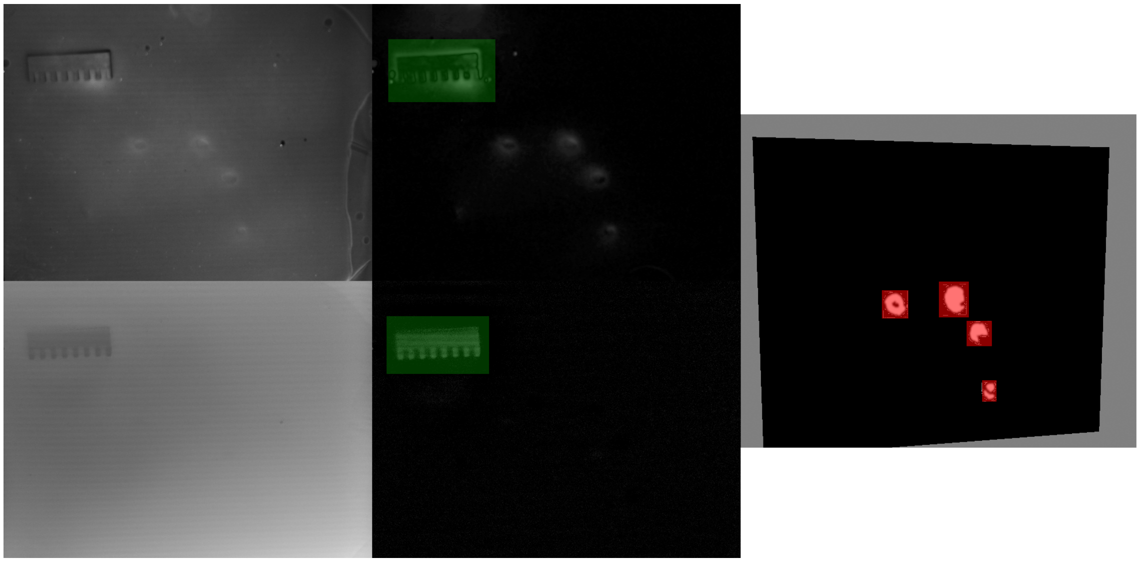


Figure 7-11: Using the reconstructed 2D grey scale texture to provide on the surface multitouch. Top Images are 2D greyscale and background subtracted greyscale image. Bellow Depth information is subtracted from greyscale image to find only touches on the surface, as shown in the right picture.

surface. A thin layer of silver-based conductive paint is applied to surface of the gel. With this set-up the system distinguishes between the presence of a hand and a non-conductive tool.

7.3 Technical Implementation

The gel structure is a soft, shor 00 durometer, thermo plastic elastomer called Ultraflex sold by Douglas and Sturges, which is heated and cast. We have explored different durometer gels and found a narrow range acceptable; if the gel is too stiff, it will be more difficult to use, too loose and the gel surface will deform too easily and not retain its shape. Once painted, talc powder or cornstarch is applied to lessen the gels stickiness.

In order to capture each projected fringe pattern frame we synchronized the camera with the vsync line of the VGA input of a projector. We used a DLP projector because the mirror arrays can update within the frame interval, unlike many LCD projectors. Using a DLP projector, we were able to achieve rates of reconstruction at 20 Hz, by project-

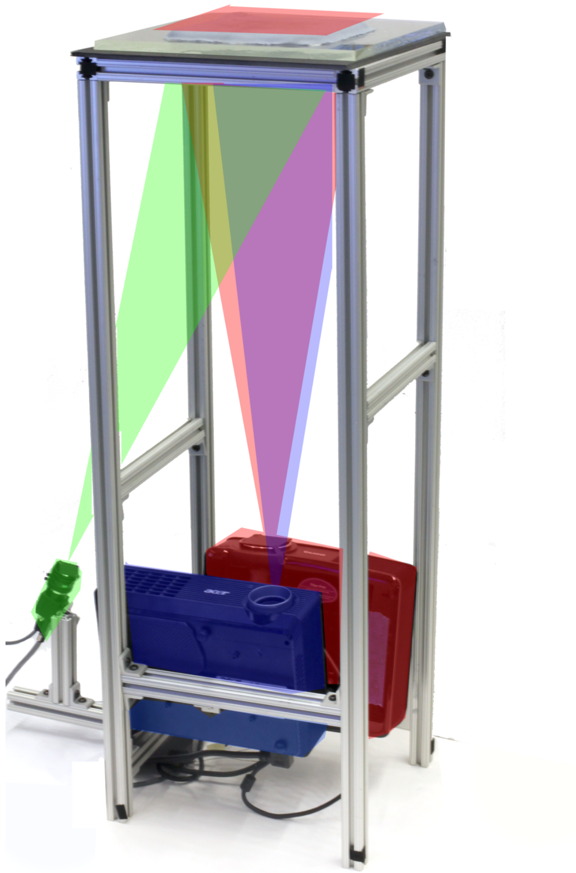


Figure 7-12: deForm setup. IR (highlighted in red) and Visible Light (blue) projectors mounted in 80/20 box projecting upwards through glass to gel surface. An IR camera (green) off to the side captures deformations in the gel.

ing and capturing at 60 Hz. This technique should scale to much higher frame rates, as described in [159]. We calibrated the projector and cameras to correct for lens distortion using standard techniques [80].

To correct for gamma differences between projector and camera and phase errors, we implemented Zhangs calibration for phase error correction, which uses a look up table to match the recorded phase with the ideal phase [160].

To project IR patterns, we modified our DLP by removing the IR cut filter in front of the bulb and replacing it with a cold mirror that reflects visible light and allows IR to pass [24].

We attached a IR pass filter to our Point Grey grayscale camera so as to capture only IR light.

We mounted the two projectors, IR and visible light, on the inside of a box shown in Figure 7-12. We mounted the camera off to the side to observe deformations in the pattern projected on the gel surface. We placed the painted gel surface on top of the box on a piece of glass. One computer generates the patterns and another captures the geometry and displays interface elements. We created the software using C++, using Open Frameworks and openCV. We built our system on top of the open frame-works structured lighting library, ofxStructuredLighting.

7.4 System Limitations

The resolution of our reconstruction is dependent on both the camera and projector, which makes this system limited or unsuitable for reconstructing large surfaces. The trade-off between size of the reconstructed area and the PPI is quite clear, so a table size system would have a less appeal. However, the system could be combined with a digital SLR to capture single higher resolution scans, especially when combined with projector defocusing, which removes the constraint of projector resolution [87].

Currently we are using a time-multiplexed approach to capture the three required patterns to reconstruct the geometry. As a result of the time delay between each frame, large amounts of motion causes errors in reconstruction. This makes the current system ill-suited for applications such as gaming. However, smaller errors are corrected by replacing erroneous data points with information from the previous frame. Increasing frame rates could improve this problem. In addition, other phase-based structured lighting techniques have been developed to solve this problem. The 2 plus 1 phase approach is less sensitive to motion [159]. An-other approach is to separate the patterns by color (often Red, Green and Blue channels) as opposed to time.

The current system requires a large total height due to the use of a camera and projector system, which can rarely be as thin as other approaches such as capacitive or FSR based input devices. It may be possible to reduce the height required by using wider field of view cameras and short throw projectors, or by introducing some sort of wave guide, such as [81].

Currently the system requires paint on the surface of the gel both to aid in reconstruction and as a projection surface. Heavy use degrades the paint over time, causing problems such as light leaks and lower quality reconstruction. Im-proving the robustness of the paint would lead to a more durable solution, and might also limit friction. Sliding and dragging are more difficult due to the friction caused by the gel and paint. Currently, we apply a lubricant, but this is an insufficient solution outside of the lab setting.

Chapter 8

KidCAD Software Implementation

The KidCad software is built on top of the deForm sensing platform described in chapter 7. Input from deForm is filtered and translated into an object model, which is later displayed and modified.

8.1 Filtering deForm Input

The raw depth information from the deForm sensor is filtered. First, background subtraction is used to only detect relative deformation of the gel surface. Next, the system calculates the overall deformation by summing all of the pixels in the depth map. If the sum is greater than a threshold, the system interprets sensed deformation as user input. We then break up the interaction into sections where an object or multiple objects are deforming the surface. During the time that any object is deforming the surface, we find the maximum depth per pixel over that time, and store it as a greyscale value in a 2D depthmap. Once the object is removed, we add that maximum depth per pixel to the model and preview this to the user as they are deforming it.

8.2 Object Model

Each object in the system represents a input from the user while they deform the surface. When a user removes an object and stops deforming the surface, a new object is created.

The object is represented by two 8bit greyscale images, a depth map and a greyscale texture image. The depth map stores the object geometry as a 2.5D surface. Each pixel value represents the height or the corresponding surface point, ranging from 0 to 2.0 inches.

8.2.1 Object Transformation

In order to translate, scale or rotate objects our system uses 2D affine image transformations on the the 8bit depth map and the greyscale texture image. As this is a lossy process, the original images are stored without transformations applied. All combined transformations are saved in a matrix, which is multiplied with the original images each time a transformation occurs.

8.3 Graphics Rendering

To display the 3D model from the object model, the system combines all of the objects together. Each objects 8bit depth map is summed to form a new 32bit depth map. This new depth map is used as a displacement map to deform a triangle strip with 640 by 480 vertices. The displacement is rendered on the graphics card through a OpenGL SL shader.

The 2D greyscale texture is mapped to the 2.5D mesh. The 2D greyscale texture is a combination of all object's 2D textures, however only one texture per pixel is visible based on the order they were added. The newest object's 2D greyscale texture will occlude older textures.

8.4 Interaction Through Touch

Touch points on the surface are passed to the touch controller code, which will modify the model of each object that is being touched. 2D affine image transformations are calculated and then applied to objects' models by warping the images as described in section 8.2.1.

8.5 Output

Once the user has chosen to 3D print the new design, a .ply file is made. The .ply file contains a vertex mesh, as well as color values for each vertex. The mesh is generated from the sum of all objects, and is similar to the one used in the display functionality.

This .Ply file is then sent to a Zcorp 3D printer. The ZCorp printer can print 3D objects in full color.

8.6 Implementation

The kidCad software is written in C++ with OpenFrameworks libraries. The software runs on a Apple Mac Book pro from 2009, with a 2.8GHz Core 2 Duo, at 20 frames per second.

Chapter 9

Evaluating KidCAD

We conducted a number of preliminary in-lab user studies in order to evaluate KidCAD and better understand how children use our system. Particularly we were interested in understanding what children would create with our system, what patterns of use would emerge, and what areas to improve upon in further versions. Beyond this we also want to evaluate the system across the dimensions often used to measure success in Creativity Support Tools described in chapter 5: Exploration, Expressiveness, and Supporting Many Paths.

Five children aged seven to ten years old participated in our preliminary study, in single child sessions with their parent (P1 seven year old male, P2 eight year old male, P3 nine year old male, P4 ten year old female, P5 ten year old female). Participants were selected through an email message sent to a MIT mailing list.

Sessions lasted about 30 to 50 minutes. The study set up included the KidCAD system, a second screen featuring a 3D perspective view of the model, and an assortment of toys and objects children could use with the system, shown in Figure 9-1. Each study session began with an introduction to the KidCAD system, and an explanation of its features. Next the participant had a warm-up task to get used to the system, and was free to play around for five to ten minutes. In the second task the participant was asked to create two animals, an elephant and a rhinoceros, using the KidCAD system and the assorted toys and objects, see Figure 9-2 for a collection of elephants. The final task was for the participant to create a story with a character and design a toy of that character using the system, and then to tell the story to his or her parent. After the session, participants were asked a number of interview questions, pertaining to their experiences with the system. The sessions were video-tapped and later transcribed and analyzed.

Figure 9-1: Provided objects used with KidCAD during the study.

9.1 Exploration

We observed participants combining many different objects during the creation of a single model. For example, to design an elephant participants used an average of five different objects, often using these objects multiple times. Participants would often search for the object that fit their needs, and then try a few different locations with it above the gel surface before they pressed it in to copy it. This seemed to highlight the importance of having co-located projected feedback.

When they found that a part they had imprinted did not work as well as they had hoped, participants primarily used the erase tool to delete that part. If there was not that much progress on the model they would often instead just clear the entire canvas. Two participants

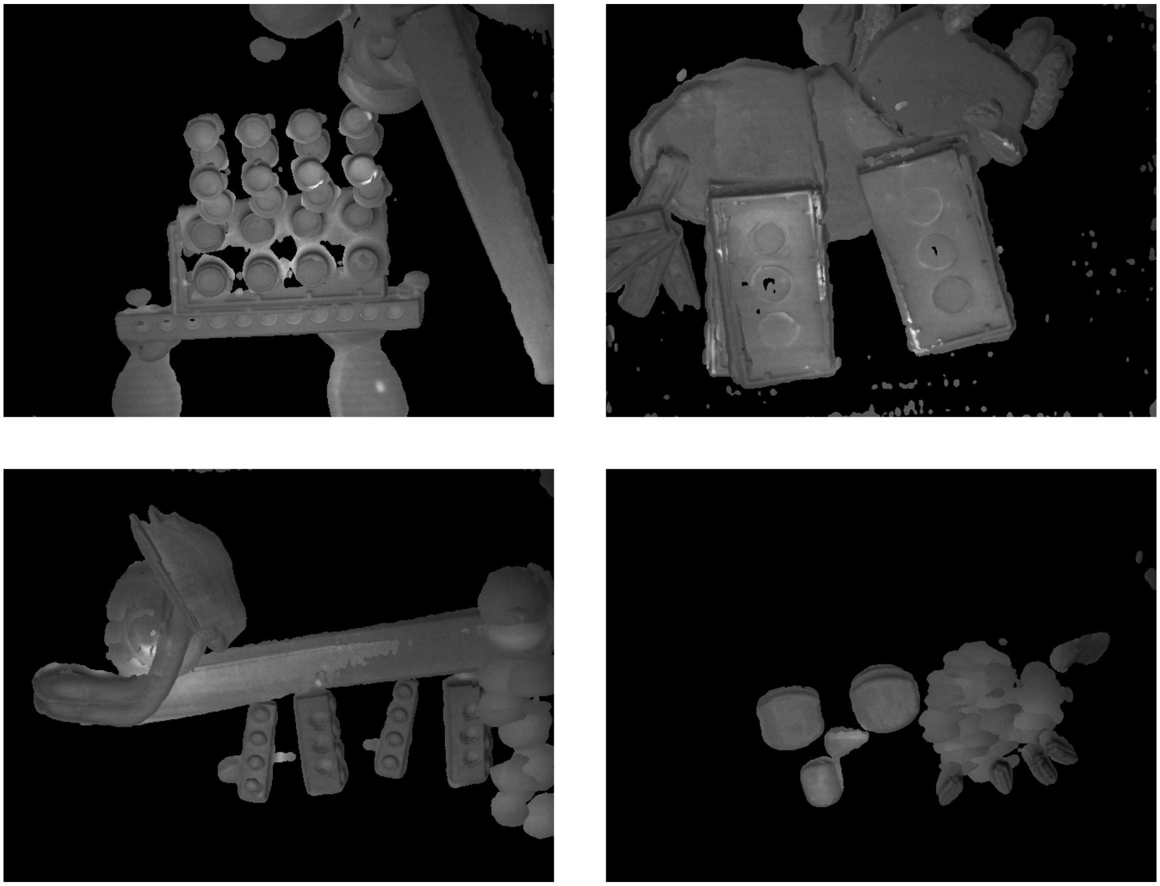


Figure 9-2: Elephants Designed Using KidCAD.

in working towards a single design cleared their designs more than five times, suggesting that further backtracking techniques could be useful. However because they could copy objects and create geometry so quickly users did not seem to have a problem starting over from scratch.

Other users found the clearing function to be liberating, and cited that as a large advantage over clay. One parent discussed with his son P3, that the ability to clear things very easily, combined with the speed of copying objects enabled him to create many different scenes quickly.

9.2 Expressiveness

As documented in the objects created, users were able to create identifiable objects, and be satisfied with the results. All of the participants in the post-test interview answered that they would want to keep a 3D printed copy of at least one of the objects they created.

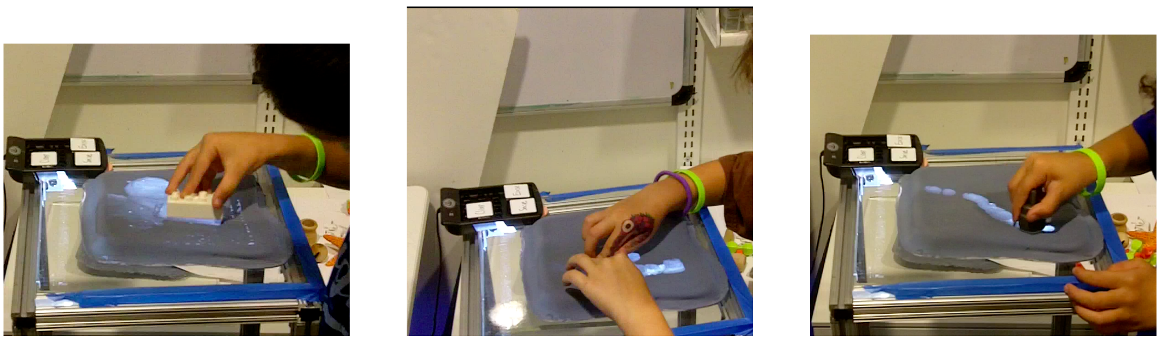
Many of the users felt that the system was very expressive. When asked what she enjoyed about the system, one female participant, P5, remarked, "it was like sculpting with clay... I like how accurate it is, when I imprint the shape it is so accurate." She said she would use it at home to sculpt things instead of using clay.

However, other participants found the system somewhat lacking in accuracy. One participant felt that it was better suited for roughing out shapes and then it would need to use something else later to get more detail. P3 added, "probably I could use the things I already have to make imprints of maybe a rough draft, of sort of the basic idea of what it would look like, but not all of the details." To get the details he suggested that he would "probably print a copy out and draw on that copy to show all the details. So you have the basic structure [with KidCAD], and then [later] move around all the details." To him the pen tool did not provide enough accuracy to add the detail he wanted. In addition he wanted the system to be more reliable and copy parts of objects "only where you put the pressure down." The system was too responsive for him in some regards. P1 felt that it was difficult to always use KidCAD to "get exactly what you want" but that KidCAD was still useful because it allowed you to take more time and easily change things.

Participants seemed to be much more expressive in 2D than in 2.5D, and much less concerned with the 2.5D shape than the 2D projected feedback on the gel. Many participants only rarely looked at the other screen, and participants rarely seemed to focus on creating more intricate 2.5D shapes with varied depths.

However, when participants did try to create 2.5D or even 3D structures they found the tools lacking. One participant, P2, tried for around six minutes to create a DNA double helix with overlapping strands. The participant was unsatisfied with the fact that he could not create empty space between two of the strands when they overlapped. This seemed to highlight the limitations of 2.5D geometry vs true 3D geometry.

9.3 Supporting Many Paths



(a) Stampers (b) Sculptors (c) Sketchers

Figure 9-3: Different ways of interacting with KidCAD

We observed many different styles of use during the KidCAD trials, however for the most part they fell into three categories: “stampers”, “sculptors” and “sketchers”.

“Stampers” used KidCAD along the lines that we had created the system. These participants mostly used existing object, and copied them by stamping them down into KidCAD. They also used the drawing tool and erasing tool, as well as using their hands, but for the most part they were remixing existing objects.

“Sculptors” instead focused on using their hands or other tools to sculpt a 3D form. Even if they used objects, for the most part they were not copying the shape, but instead using it to deform the 2.5D geometry. These children treated the gel surface very closely to how one would sculpt with clay, often repeating the same basic path with their fingers or other tools to create more depth. One participant, P5, explained that the gel had a very similar feel to it to clay and that she liked the deformability. These users also seemed more concerned with the 3D form than many of the others, and looked at the 3D perspective view more.

The third group, “Sketchers,” primarily used the drawing tool. They did not concern themselves with the 2.5D view and treated the canvas very pictographically. They created much of the content themselves and were less focused on remixing objects. P3 for example explained that he would use it for "exactly what I was doing, to make drawings for a story... like if I was telling a story to someone I would use this to make illustrations of what it would look like."

Although we did not design KidCAD for all of these different patterns they seemed to be well liked by those who used them, regardless of which pattern they primarily used. All of these different paradigms are afforded to the user because of the wide variety of input supported by KidCAD. In addition there is no need for mode changes, instead users simply pick up different tools. It is easy for children to change styles quickly from one design to the next. This highlights the flexibility of KidCAD which in many ways mirrors that of clay; there are endless opportunities to modify clay, no one style is correct.

9.3.1 Story Telling with KidCAD

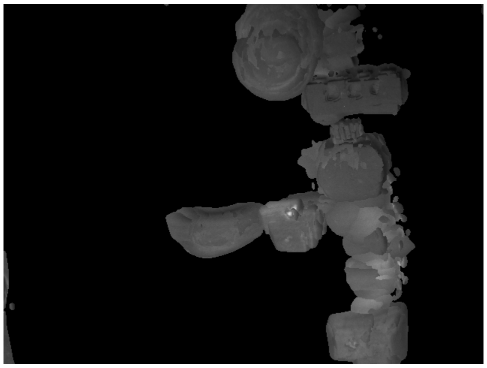
Another trend that we observed was the use of KidCAD for story telling. The last task of the study encouraged participants to create a story and then design a toy of the main character of the story. Most of the participants came up with stories around their characters, but only designed the single main character. Participant P3 created his character first using KidCAD, but then illustrated the entire story using KidCAD to depict each scene. P3 created four different characters for the story, and had many different locations. He used the flat work area of KidCAD as a 2D canvas to have characters interact on. See figure 9-4 on page 128 for the transcript of the story and the scenes illustrated with KidCAD.

One interesting trend that we observed was that by including whole existing toys in the story as characters, children could easily create many different scenes very quickly, by simply stamping them down where they wanted the character to appear in that scene. That coupled with the ease of clearing the entire canvas, allowed P3 to create his story quite quickly.

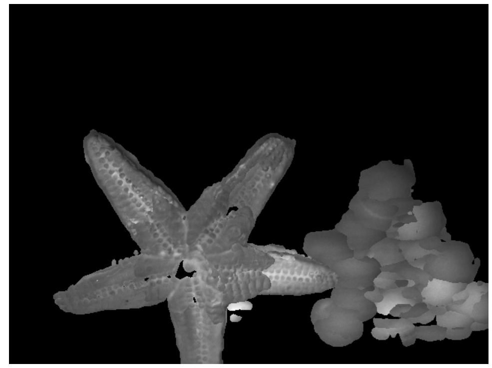
9.4 Conclusions

KidCAD provides an easy way for children to create 2.5D models. Because it is so easy to copy geometry, users can explore many alternative designs, and quickly sculpt a number of different designs. Participants used many objects along with drawing and hand sculpting to create their designs. Many patterns of use emerged, primarily "Stamping," "Sculpting," and "Drawing." On the whole, children found the system to be expressive, but some users wanted more control, especially with the drawing tool.

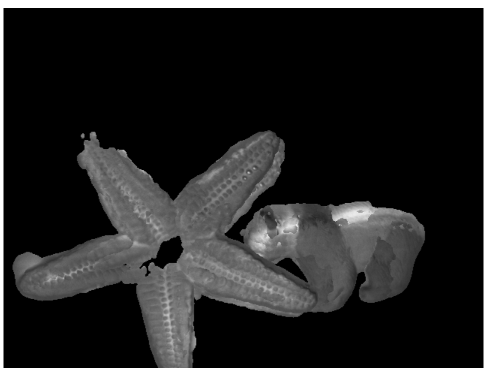
The pictorial nature of the 2.5D canvas supports both sculpting and drawing illustrations of scenes for stories. The 2D feedback on the gel surface itself seems to accentuate the 2D illustration style, as many participants rarely used the secondary 3D view. More work is required to support full 3D and to reconcile the 3D view with the 2D projected feedback.



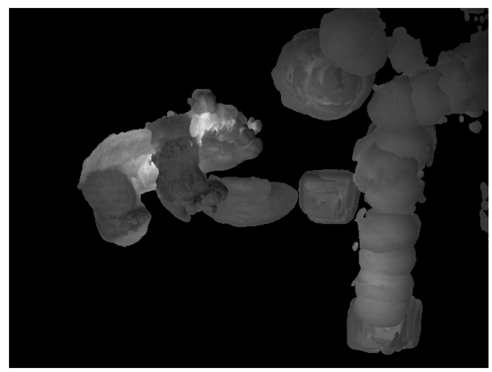
(a) Once there was a little man named Mr. Big Head. And he Had a big head.



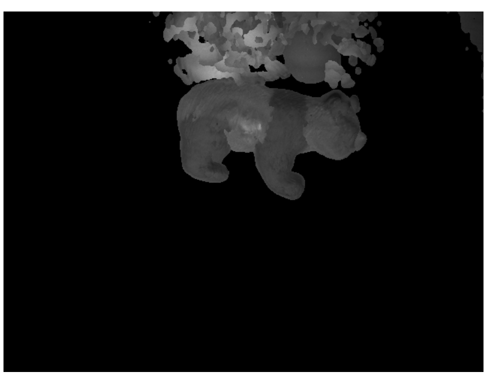
(b) One day Mr. Big Head met a star fish. The starfish was in his way and he bumped into him.



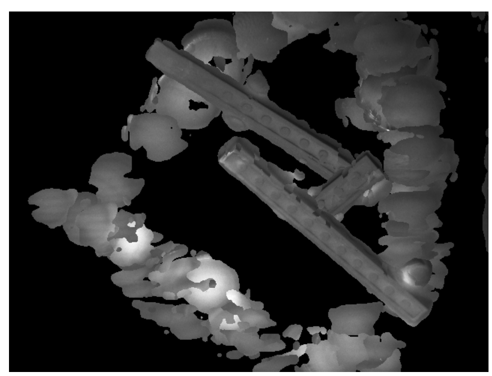
(c) So then Mr. Starfish, called up his friend Mr. Giant Panda.



(d) And told him to eat Mr. Big Head.

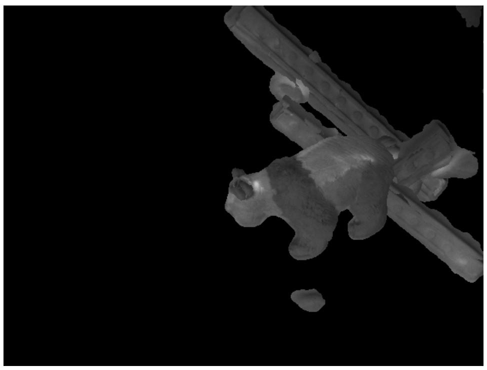


(e) But then, the panda jumped so high that he hit a cloud.

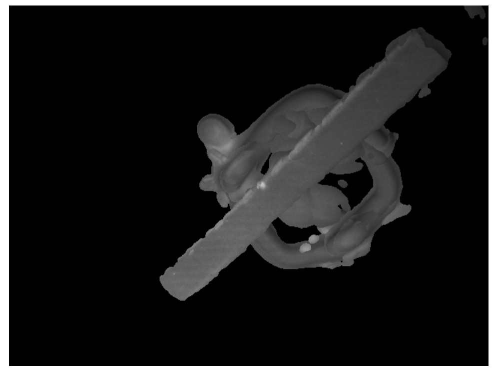


(f) The cloud was about to get read for a Thunder and Lightning storm.

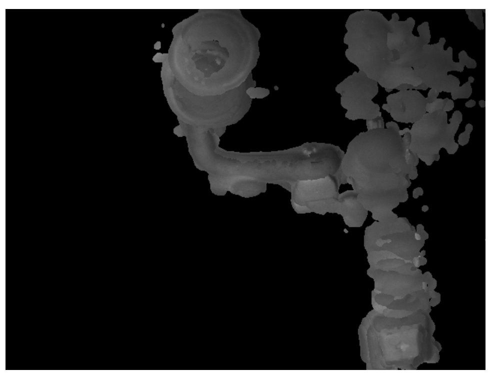
Figure 9-4: Story Illustrated with KidCAD 1



(a) And the panda hit it.



(b) Therefore it didn't rain.



(c) And Mr. Big Head Kept on walking. The End.

Figure 9-5: Story Illustrated with KidCAD 2

Chapter 10

Discussion: Copying Becomes Creation

CopyCAD and KidCAD highlight a new type of design, focused on remixing, that blurs the line between the physical world and the digital world.

10.1 Supporting Improvisational Design

In many ways CopyCAD and KidCAD point towards a type of improvisational design, that is much easier in the physical world. In the physical world, objects can be used for any purpose: they can be glued together, taken apart and or sawed in half. The beauty of atoms is the ease with which they can be rearranged with tools and processes that the human have developed over millennia. However, the negative side to modifying objects in the physical world is the entropy created through this rearranging. It is often impossible or time-consuming to go backwards. In addition, in the physical world designers and fabricators are limited to the same number of atoms that the objects were originally comprised of; you can't suddenly change the object's scale or rapidly add more material. The digital world allows for these types of interactions quite easily, but they have continued to lack the flexibility of the real world, the flexibility that allows for improvisation.

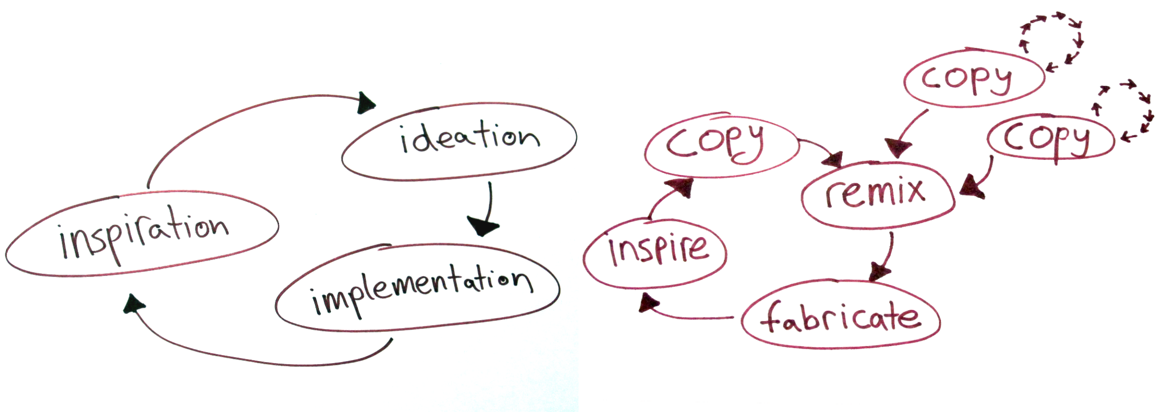
CopyCAD and KidCAD allow for this quick and dirty improvisation because they draw so much from input from the real world. By focusing on easily copying geometry from existing objects, CopyCAD and KidCAD limit the amount of time designers need to spend on modeling, one of the most time-consuming aspects of digital fabrication. This fact coupled with the tangible and augmented nature of CopyCAD and KidCAD provide a hybrid between the physical and digital world, that allows for rapid improvisational design.

10.1.1 Milliseconds Matter

CopyCAD and KidCAD support copying from objects more quickly than many other systems because they situate the tools for scanning directly into the design tools. The speed at which one can preform a function, in this case 2D or 3D scanning of objects, will change user behavior. If it takes 10 to 20 seconds (for current 2D scanning) or even 10 to 20 minutes (for current 3D scanning), users will not copy very often. CopyCAD and KidCAD can scan objects almost instantly, which changes the notion of "scanning." In addition the act of scanning in CopyCAD and KidCAD is also linked with placement, and is situates directly in the design. In fact users may not even need to scan an object to explore different alternative placements with CopyCAD and KidCAD. Instead they may just move the physical part around, to see how it would fit in to the model, because of the 1:1 scale and projected graphics. Users can explore many more designs in a shorter amount of time with CopyCAD and KidCAD, but more importantly it changes the notion of copying from a time-consuming activity to a tool no different from a paint brush. Copying can become more expressive.

In addition CopyCAD and KidCAD seek to create a quicker loop between design and fabrication. Firstly by creating an augmented space, directly on the material at a 1:1 scale, we hope to limit the need for as many physical prototypes. By embracing design at scale, we give up potential for added precision but embrace clarity. Secondly, because these two tools are so closely tied with digital fabrication, there is less time required to machine or fabricate these parts, although we are still limited by the speed of CNC machines. And finally, by embracing input from the real world we hope to speed the entire process of design, limiting the total number of parts that must be designed from scratch.

This new process of Remixing Objects is not unlike the iterative design process. Tom Brown of IDEO describes their design as an iterative cycle through inspiration, ideation and implementation [18]. Here I view the Remix design process as inspire, copy, remix, fabricate; the designer is inspired by an object, copies it and maybe a number of other objects, remixes them by modifying and adding his or her own content, and finally fabricates the new remixed object, which can then inspire new designs. See figure 10-1 for a diagram of these two cycles. However, we hope that CopyCAD and KidCAD can allow novice designers to move through this loop more quickly, and explore many alternatives.



(a) IDEO's Design Process (b) Remix Design Process

Figure 10-1: Iterative Design

10.1.2 Everything is a Tool

CopyCAD and KidCAD both seek to expand the opportunities for input into CAD interfaces. When it is easy to copy the shape of an object, that object becomes a tool for creative expression. In the physical world nearly any object can be used to deform materials like clay or foam. Naturally some objects will work better as tools for one material over another, but there is a limitless supply of objects that can be tested and used as tools for deformation.

In most computer systems we are often limited by the predefined set of tools that software engineers ordained.

This work seeks to expand that set of tools to include any object in the physical world. In the case of CopyCAD there are many opportunities for finding shapes and forms in the physical world, and using them in the digital. But CopyCAD also encourages using other materials that the user can shape and deform. For example, clay can be used to quickly sculpt a form that can easily be captured by CopyCAD; this could in many cases be much easier than drawing or sketching the form in a software program. KidCAD makes the distinction between object and tool even more blurred; a user can take any object and use it to deform the surface of KidCAD. Much like Kimiko Ryiokia's "World as Pallet" metaphor for her I/O Brush work [122], here, we embrace any and every physical object as a tool.

What makes this possible is the use of cameras as sensors. The flexibility of input afforded by camera-based systems can almost mirror the flexibility of the real world. The rise of real-time 3D scanning, changes the notion of 3D scanning from capturing a single snapshot to providing 3D input for an interactive system. Traditionally, 3D scanners have been a tool for copying objects into the digital world. Now the scanning is so fast that it becomes invisible, and instead the physical object being scanned is the tool, and a more expressive tool than 3D scanners ever were. This builds on the notion of sensing for Organic User Interfaces as outlined by Jun Rekimoto [115]. He describes the added flexibility inherent in the move from sensing single points of input to more dense reconstruction.

However, CopyCAD and KidCAD differ in their notion of physical object as tool. By using the object, operator, operand metaphor as a lens we can see how these tools differ. Using the CopyCAD system the physical object being copied is the operand, and the operator is the "copy" command. This is a very traditional use model. However, KidCAD instead uses the physical object as the operator; the act of using this physical object as a tool to deform implicitly copies the 3D shape. KidCAD approaches the flexibility and usability of clay in the physical world by making the commands for copying implicit in action, and fundamentally moves much closer to the true nature of tangible interfaces, which can blur the line between the physical and digital world.

10.2 Materiality

In addition this work seeks to bring human hands back into the design process. Original craft and production tied hands to the final form; human hands would carve the wood, sand the finish, apply the lacquer. However today hands are divorced from production, the closest they come is through the same keyboard and mouse I use to write this document. Digital Fabrication removes hands from the design process, but provides great flexibility and skill. CopyCAD situated interaction closer to the material, closer to production. Although KidCAD is divorced from the final means of production, the hands and materiality are central to its design. These systems represent a new type of digital craft, that in many ways has much stronger ties to traditional craft production than existing CAD software.

So much of the power of CopyCAD and KidCAD comes from their embrace of the materiality of design. Digital CAD systems have revolutionized design but often at the cost of an understanding and an appreciation for physical material. The reason this work resonates so well with users is because our systems have an appreciation for the material interaction.

CopyCAD embraces the material from which the design will be machined by allowing direct interaction on that material. In the traditional CAD world, textures such as wood or steel can be applied to digital models to give users the impression of what they will look like when they are finally machined. CopyCAD instead projects the model directly onto the material; the user can see how the actual grain in the wood will work with projected lines to be cut. A user can draw lines directly on the material, and instants later see those lines machined, as if they were cutting directly with their pen. CopyCAD also embraces the physicality and materiality of existing objects, allowing users to manipulate them with their hands and interact with the projected feedback. It is the physical material that is real, not the digital model; why should we need to simulate the physical material as well? In traditional CAD design the model being designed is trapped inside the monitor, CopyCAD seeks to free the model and place it in the context of the physical world.

The importance of physical, material interaction is central to KidCAD. The passive, deformable gel surface provides physical feedback to the user, that helps them feel how much material they are deforming in the digital model. This feedback, coupled with the co-located projection, gives the user a very natural sculpting experience that is radically different from mouse-based graphical user interfaces. KidCAD allows the user to directly use their hands and other tools to inform the design, and the 1:1 scale allows users to spend little mental energy on the interface and instead focus on sculpting and creating 2.5D forms. By embracing materiality we create a more natural experience.

10.3 Authorship

Although CopyCAD and KidCAD focus on remixing existing objects, it seems clear that people using these tools feel that they have "made" their final objects. Copying and remixing in their minds are no different from creation. In part, this is because selection and composition are as much a creative experience as other forms of expression. Collage is so compelling because it allows designers to take existing media and re-contextualize it. Remixing allows anyone to have a voice and to tell their own story through existing media. But remixing is not only copying; users of KidCAD and CopyCAD combine existing objects, modify them, and add new content to create their own objects. Remixing is creation.

An additional factor in the question of perceived authorship is Michael Norton's "Ikea Effect" [96]. Norton demonstrated that the process of assembly is enough to increase the value one holds on a given object. In these systems, the very fact of spending time to design something, even if just to copy and combine a number of parts, seems to impart a higher value on the objects than simply purchasing one. It seems that if the argument that Remixing objects is not creating is raised, that remixing objects is certainly perceived creation to the user. This effect may be even stronger with our systems because they are using their hands to directly interact with the digital models, instead of indirectly using a mouse; they feel closer to the design, and closer to the craft.

This greater emotional connection with objects designed with CopyCAD and KidCAD also seem to point towards increasing the self efficacy of design in users. These tools could be gateways for users into further digital craft work.

10.3.1 Licensing Issues

Even if users feel they are are creating while remixing, content owners may not view remixing objects in a similar vein. This work stirs up a number of legal concerns that, for the most part, have not been very active yet due to the high cost associated with 3D scanning and 3D printing. However, these tools are now becoming more accessible to end users, and we may start to see larger companies taking notice, and more legal precedents being set [149]. Designers and companies producing physical objects should learn from the mistakes of the Recording and Film industries [90] and instead embrace this new form of creation, by observing that user-led design creates economic value for them [148], and allow users to remix copyrighted and patented objects. By embracing open standards like Open Source Hardware, companies can ensure now that their products can be remixed and modified by users in the future when tools become more available.

Chapter 11

Future Work

11.1 An API for Objects

Both CopyCAD and KidCAD take a brute-force approach to "copying" objects. The systems have no previous knowledge of the objects and instead use computer vision to approximate the object's shape in either 2D or 2.5D respectively. However, a large number of objects that exist in the world were previously designed, and someone, somewhere probably has a much better idea of what its dimensions are, especially objects made in the past decade. What if these systems could tap into that knowledge to get higher resolution information?

If we look at the world of online mashups as an analog, we see a similar trend. The first web mashups used a similar brute-force approach to look at the DOM and "screen scrape" information; basically, these systems took what was meant to be human readable information and created programs to enable machines interpret them. But, with the Web 2.0 movement a great number of websites realized the large potential in providing web services, and began to create "Application Programming Interfaces" or APIs. These APIs provided other web services with the ability to gain much lower-level information, and an easy to use framework to access it; APIs made screen scraping irrelevant and allowed designers to create even more exciting and powerful mashups.

In the future objects could provide APIs to end users. This type of concept has been hinted at before, such as Bruce Sterling's idea of an internet of things and "spimes" in his book Shaping Things, where objects have a history of where they were built, what goes into them and who used them [135]. However, we suggest a much broader API for objects, that could allow users to obtain things like color schemes, or ratios of height to width, in addition to complex high-resolution geometry. So much effort goes into describing and designing objects, how can we let end users make use of that data? Built in RFID tags, or optical shape recognition could link physical objects to this data easily and directly.

An API also can be used to help address licensing issues. For example, a designer could select which properties they wish to grant access to and which they wish to retain ownership of, and other users would only have access to copy properties to which they have been granted access.

11.2 Higher-Level Copying

In addition to APIs for objects, we would like to be able to copy higher-level information from objects. Currently CopyCAD and KidCAD just copy the raw outline, or shape of an object. Instead our system could allow users to more intelligently copy what they want, for example this objects corner radius and fillets or that objects patterned texture. More sophisticated computer vision techniques could be used to segment objects smartly, or even to identify common parts between two objects and allow designers to easily swap them.

Design tools could support applying a subset of one object's attributes to another, allowing novice users to try many different "themes" easily. This type of CAD by Example could open possibilities for extended creativity and quick prototyping.

11.3 Sharing

Beyond remixing with the physical objects that users have available to them in their close proximity, many users may want to have access to a wide variety of digital models available online. For example, the website Thingiverse.com has many tens of thousands of digital models. How can we design interfaces for remixing that allow both physical objects, as well as a larger set of digital objects, as input? Problems such as browsing and connections between parts become larger issues. In addition how can we encourage users to share their design's with others easily?

11.4 Integration with Existing Tools

Although we designed CopyCAD and KidCAD for makers and crafters, we believe that integrating scanning tools into design tools would benefit professional designers as well. For example CAD designers using Solid Works could use their traditional GUI interface, but then drag their mouse cursor off into the physical world and select geometry to copy and paste from an object on their table. In a way this would make every object in the physical world a CAD file, from which geometry could be copied. Of course users would have to have a camera mounted above their workspace, but it is possible to imagine a time when CAD users see no difference in copying a gear assembly from a file on their computer or from a physical object on their desk. We believe the key is to make this interaction seamlessly integrated into the tool and no different than copying geometry from inside the program.

11.5 Different Scales

In CopyCAD we explored copying 2D shapes and machining 2D objects and in KidCAD we explored copying 2.5D shapes. What changes are needed to accommodate full 3D objects and how do interactions change?

In addition both of these systems are limited to small, almost hand held objects. How can we explore allowing users to remix much larger objects but in a direct way?

11.6 Reprogrammable Matter and Radical Atoms

CopyCAD and KidCAD represent a hybrid world, or an augmented design tool, where they exist partly in the physical world and partly in the digital, through the power of projection. Although they allow for tangible input with physical objects, they are limited to only displaying realtime 2D graphics and provide no active haptic feedback. Instead they can only very slowly output physical shapes through CNC machines, which are essentially very slow physical displays. What if these physical displays could be made much faster, approaching the 24, 30, or 60 frames per second that we often view interactive graphics at? Surely one could not find a milling machine or 3D printer that could move that fast today, but what if we are willing to sacrifice resolution or the permanence of that object. How can we create physical 3D interactive displays that allow for direct 3D interaction with digital models?

Researchers are exploring shape displays today, which can change physical form almost as fast as todays 2D displays. Shape displays render physical shapes often through the use of a matrix of linear actuators. Liethinger's Relief interface combines a 12X12 array of motorized linear actuators with a soft skin, onto which projected imagery can provide added fidelity [88]. This device allows for both the computer and the user to change the shape of the display, allowing for interactive modeling.

Shape displays may provide an exciting new platform for research into direct interaction in CAD interfaces, allowing users to change physical properties directly, both seeing and feeling the results in real time. Our concepts of remixing physical objects gain even more meaning when objects can be copied and deformed or modified in a tangible 3D actuated interface.

Daniel Liethenger, Leonardo Bonanai, and I prototyped an interactive system Contour,

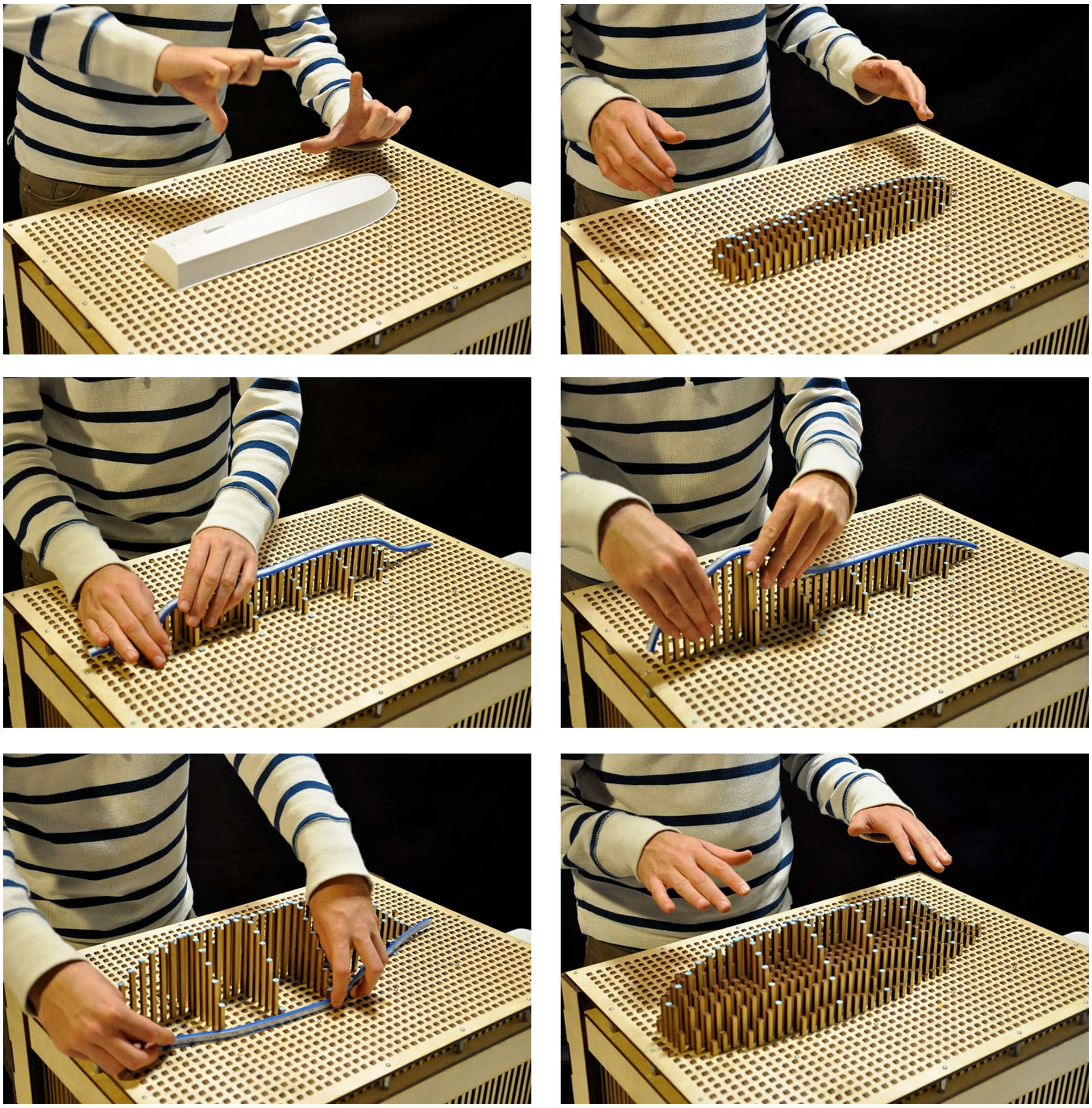


Figure 11-1: The Contour system video prototype. Users can copy physical objects, which are transformed into physical 3D geometry. Next users can directly modify that physical form, to modify it to their needs.

for remixing physical objects through tangible actuated displays. This system has only been prototyped through stop motion animation, however it points towards exciting new directions direct manipulation and tangible 3D interaction.

In Figure 11-1 a designer copies a physical boat model through an iconic gesture, and after it is removed, a physical shape of that size and placement is rendered through a shape display with a two pixel per inch resolution. Next the designer can select which curves he wishes to modify, and use a flexible curve tool to modify its shape. The user can move between wireframe and a dense model through an additional gesture.

This again highlights the power of integrating scanning tools into the design interface is highlighted. In addition, as is the case with KidCAD, any physical object can be used to deform the geometry. However, Contour points towards a system where direct physical sculpting can be combined with parametric design, allowing certain features to drive other features.

Although Relief and the proposed Contour system are limited to 2.5D shapes and tied to static surface, it is possible that further out in the future these constraints will be gone. The concept of Programmable Matter or “Radical Atoms” is currently being explored by physicists and engineers to give physical particles the flexibility of digital bits [108, 121]. When imagining a world with programable matter, remixing objects takes on new meaning and applicability. Physical objects could be combined easily without glue or any other means, and then cleanly return to their prior two forms.

Chapter 12

Conclusion

This thesis presents the design and implementation of two systems for tangible remixing of physical objects. By integrating 2D and 3D scanning into augmented tangible design tools we show that existing physical objects can directly serve as tools to create geometry for new digital objects. These new tools enable novice designers and children to quickly and easily design objects for rapid digital fabrication. We build upon a growing body of work in tangible interfaces that seeks to make design a more physical experience.

Our CopyCAD system introduces tangible and augmented interaction to 2D CAD design. By projecting digital models directly onto physical material at a 1:1 scale, users can better understand how their final designs will look in the physical world. Users can quickly copy the shape of physical objects into their digital models directly where they are placed, modify them and then machine resulting parts. This system allows crafters and makers to quickly move their design process between the physical and digital worlds, and easily remix objects.

We also introduced KidCAD, a system that enables a natural 3D sculpting interaction through the use of the deForm 2.5D, realtime, deformable input device. Children can copy 2.5D geometry of existing toys into their digital designs by imprinting the toys into the gel interface of deForm. Children can use any physical object as a tool to deform a 3D digital designThe 2D surface touch interaction provides tools to draw, erase and to modify existing geometry. Through this interaction they remix toys, which can then be 3D printed.

Through background research and preliminary evaluations we show the opportunities and advantages of remixing physical objects through tangible tools. With the use of CopyCAD and KidCAD, users can design new objects such as jewelry or toys. Our tools provide an easy entry point into the world of digital fabrication.

We hope that this work will influence future researchers to look more broadly for input from the physical world, embrace remixing as a valid form of design, and make Computer Aided Design increasingly tangible.

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