"Like This, But Better": Supporting Novices' Design and Fabrication of 3D Models Using Existing Objects

Patrick A. Carrington, University of Maryland Baltimore County
Shannon Hosmer, University of Maryland Baltimore County
Tom Yeh, University of Colorado Boulder
Amy Hurst, University of Maryland Baltimore County
Shaun K. Kane, University of Colorado Boulder

Abstract
Despite the prevalence of affordable "maker" tools such as 3D printers and laser cutters, actually creating digital models remains out of the reach of most everyday users. Even when users are able to design or fabricate items, some everyday users may be more interested in modifying or replacing objects that they already own rather than inventing new items. Addressing the needs of these users requires taking a different approach than that taken by most computer-aided design tools. To address this need, we introduce the notion of *design from imperfect examples*, in which existing objects are scanned and modified to create new objects. We present examples of this design approach and describe the development and formative evaluation of the Easy Make Oven, a prototyping tool that enables novice users to create simple 3D designs based on their existing possessions.

Keywords: Creativity; Rapid Prototyping; 3D Modeling; Making
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Research Data: In case you want to publish research data please contact the editor.
Contact: carpat1@umbc.edu, hosmer1@umbc.edu, tom.yeh@colorado.edu, amyhurst@umbc.edu, shaun.kane@colorado.edu

1 Introduction

The rise of the Do-It-Yourself (DIY) movement has generated intense excitement among technology researchers and the popular press. Rapid prototyping tools such as 3D printers, once found only in high-end technology laboratories, are now available to consumers at costs comparable to personal computers and other consumer electronics. With access to these technologies, everyday users now have the capability to design and fabricate physical objects in their own home, creating new opportunities for individuals to exercise their creative expression and to create new, custom physical objects (Gershenfeld 2007; Lipson 2010; Mota 2011).

While at-home fabrication technologies have great potential to change the way that individuals create and use physical objects, the current reality of creating and fabricating 3D objects presents several challenges. First, most 3D design and fabrication tools remain expensive and difficult for novices to use. Computer Aided Design (CAD) tools such as AutoCAD[i], SolidWorks[ii], Rhino[iii], and Blender[iv] are relatively difficult to use, are expensive, and have a steep learning curve. In recent years, software developers have created new 3D modeling tools that provide more novice-friendly user interfaces. These tools, which include SketchUp[v], 3D Tin[vi], and Tinkercad[vii], can enable novices to begin experimenting with 3D design, but still require some training to learn, and may be difficult to use for some individuals. Other tools, such as MakerBot Customizer[viii] and Shapeways Creator Apps[ix], enable users to customize existing 3D models, such as by resizing an object or adding embossed text, without requiring users to manipulate 3D models. However, users of these tools are limited to the models and customization options supported by the application developers.

Second, even when user-friendly 3D modeling tools are available, these tools do not necessarily support the needs of non-expert users. Most existing 3D modeling tools, even those that target novices, expect users to design new 3D models from scratch. However, everyday users may be less interested in creating new creative works, and may instead be interested in more mundane tasks such as replacing lost items or repairing broken items (Shewbridge et al. 2014). Just as traditional paper printers are used to print everything from airline boarding passes to drafts of an in-progress novel, 3D printers in the home will likely be used for both creative and mundane tasks. Thus, providing end users with access to at-home

3D design and manufacturing tools requires designing tools that match the needs and perspectives of everyday users, and may require the exploration of new perspectives on what it means to design and fabricate 3D objects.

In this paper, we present our work to date on exploring new perspectives and design tools to support everyday users in designing and fabricating physical objects. In particular, we introduce a design approach that we refer to as *designing from imperfect examples,* in which end users start with existing objects, specify how those objects could be modified, and create new and improved versions of their original possessions. We have explored this approach over several months through interactions with a prototype device, the Easy Make Oven, which supports scanning, modifying, and fabricating 3D objects on an interactive surface. We describe our conceptual approach to *designing from imperfect examples,* introduce the Easy Make Oven prototype, document our experiences using this prototype, and identify opportunities for further exploration of this design approach.

2 Related Work

2.1 **The DIY Movement and At-Home Fabrication Technology**

Recently there has been a renewed interest in do-it-yourself activities for repair, customization, and creation (Kuznetsov and Paulos 2010; Torrone 2011), and in at-home fabrication (Gershenfeld 2007; Lipson 2010; Mota 2011). Consumer-grade fabrication tools such as 3D printers, laser cutters, CNC mills and routers have become an accessible alternative to industrial manufacturing tools that have traditionally been prohibitively expensive, and have typically required extensive expertise to operate. Open source 3D printer initiatives such as the RepRap[x] and companies such as MakerBot[xi] have helped make 3D printers available in homes, hacker spaces, schools, and libraries. As the price of these technologies continues to drop and their performance continues to increase, at-home fabrication will likely continue to increase in popularity.

2.2 **Software Tools to Support At-Home Fabrication**

Rapid prototyping and small-scale manufacturing technologies provide new opportunities for self-expression, customization, and education for end users. In addition to supporting the general population, these technologies also provide opportunities to support people with disabilities through the creation of custom assistive technologies (Hurst and Tobias 2011), and to engage young children (especially girls) in STEM activities through the creation of compelling computer-driven creativity (Buechley et al. 2008).

While fabrication technologies have begun to move from industrial environments into the home, software tools to support the creation of 3D objects by everyday users have mostly lagged behind. Many of the commercial tools that enable everyday users to create 3D models follow the design of professional CAD tools, and thus provide a steep learning curve for novices. However, researchers have explored alternative strategies for enabling end users to design and fabricate physical objects, including 3D scanning, 3D sketching, designing with existing 3D objects, and designing with tangible user interfaces. These approaches are briefly summarized here.

2.2.1 3D Scanning

Inferring an object's shape from a 3D scan is an extensively researched computer vision problem. Traditionally, 3D scanning has required a fixed scanner device that uses either a laser or a calibrated camera to capture the shape of a 3D object (Chen et al. 2008). However, this traditional approach requires a dedicated 3D scanning setup, which most end users do not have access to. Recent approaches to 3D scanning have explored the use of consumer hardware such as 2D cameras and consumer-grade depth-sensing cameras. Systems such as AutoDesk's 123D Catch[xii], KinectFision (Izadi et al. 2011), and work by Jota and Benko (2011) enable users to create 3D models by capturing a series of images with a mobile device or portable depth-sensing camera. However, these techniques require users to capture dozens of images of the object, which may be time consuming. Furthermore, this approach produces an approximate 3D model based on the image data, but this model may contain errors that the user would need to correct using a 3D modeling program.

2.2.2 3D Sketching

An alternative to scanning physical 3D objects is to capture 2D sketches and convert them into 3D objects. For example, a 2D perspective drawing can be converted into a 3D object (Lipson and Shpitalni 2007). However, this approach requires the user to be able to accurately create perspective drawings, which many everyday users are not able to do. The Designosaur, Furniture Factory, and ModelCraft systems (Oh et al. 2006; Song et al. 2006) translate users' simple sketches into 3D-printable models, but are limited to creating a specific subset of objects. Other tools, such as constructable (Mueller et al. 2012) and LaserOrigami (Mueller et al. 2013), enable users to create 3D objects by assembling laser-cut 2D components, which are themselves sketched via an interactive drafting table. These systems enable the creation of a subset of 3D objects, but do not allow users to design from existing physical objects.

2.2.3 Designing with Existing 3D Objects

Instead of relying on users to create new designs, novices can reuse or remix pre-existing designs from a saved object library. Funkhouser et al. (2004) created a tool that allowed users to create objects by combining parts selected from a database of 3D models. This approach prevents users from having to create 3D objects from scratch. However, using such a library may decrease creativity by encouraging users to rely on the database rather than their own ideas, and may limit the types of objects that can be created.

2.2.4 Designing with Tangible User Interfaces

Yet another approach to end-user 3D model creation is to provide a custom, tangible interface that enables users to manipulate 3D objects or representations of these objects. For example, Easigami (Huang and Eisenberg 2012) allows users to manipulate 3D models by folding physical polyhedral pieces. The uCube (Leduc-Mills and Eisenberg 2011) takes an alternative approach, providing users with a set of tangible "towers" covered with buttons that can be pushed to specify the shape of a 3D object. Using these prototypes, users can create low-resolution primitives relatively quickly, but are constrained in the types of objects that can be created.

KidCAD and CopyCAD (Follmer et al. 2012; Follmer et al. 2010) are tangible interfaces for capturing and remixing physical objects. KidCAD consists of an interactive surface coated with a pliable layer of modeling clay, which can be used to capture impressions of objects. CopyCAD consists of an augmented 3-axis milling machine that allows users to remix physical objects by copying, deleting, and drawing components of scanned objects in order to create new objects. MixFab (Weichel et al. 2014) enables users to scan existing 3D objects and combine them with 3D primitives in an augmented 3D workspace, enabling users to model accessories such as boxes and cases for their objects in the augmented space.

KidCAD, CopyCAD, and MixFab are the closest matches to our approach of *designing from imperfect examples* in that they enable existing physical objects to be combined and remixed to create new digital objects. Our prototype, the Easy Make Oven, follows a similar approach to these systems, but supports different input and interaction methods, such as combining physical objects with sketches. While our prototype shares some similarities with these prior systems, we believe it presents a unique approach to designing and developing 3D objects.

2.3 Everyday Making

Most fabrication technologies are designed to facilitate the creation of new objects. These objects may be intended for a variety of purposes, including artistic expression, engineering, or professional design (e.g., Oh et al. 2006; Lipson and Shpitalni 2007). Other technologies, such as KidCAD (Follmer et al. 2012) and the uCube (Leduc-Mills and Eisenberg 2011), are oriented toward creative expression and fun. However, these tools are relatively unconstrained, and offer flexibility at the cost of providing relatively little guidance.

However, everyday users, especially novice users, may be reluctant to engage in such unstructured design, or may not be interested in creating original objects. Blikstein (2013) coined the term "keychain syndrome" to describe his observation that novice users of 3D printers were more interested in customizing simple objects, such as keychains, rather than creating new objects from scratch.

The term "everyday making" has been used to describe the types of making and fabrication activities that non-expert users may wish to perform. Our previous study of everyday making practices in the home, using an experience prototype of a 3D printer, found that non-expert users were sometimes interested in creating new items, but were often more interested in modifying or replacing their existing objects (Shewbridge et al. 2014). Our approach in this research is to support these activities of everyday making by providing support for creating 3D designs that improve upon users' existing possessions.

3 Design from Imperfect Examples

As shown in the previous section, there are many possible approaches to creating and fabricating 3D objects. In this section, we describe our approach to supporting everyday making by providing tools that enable users to capture 3D representations of objects that they possess, modify those objects, and fabricate new, improved versions of those objects. We refer to this approach as *design from imperfect examples.*

We have developed this approach following several years of working with novice designers, including students, in a university-based maker lab. This approach is also informed by prior research in the everyday making needs of novice users, as described in the previous section. Finally, our approach has been informed by the design, deployment, and extended use of a prototype design system for novice users, the Easy Make Oven, which is described in the next section.

Designing from imperfect examples supports novice users in two ways. First, because novice users are unlikely to have extensive 3D modeling skills, this approach emphasizes methods for creating 3D objects that require minimal 3D design skill or experience. Specifically, this approach leverages users' existing possessions to enable the creation of new, improved objects. Second, prior research shows that novice users may wish to create 3D objects both for creative expression and for more mundane tasks, such as repairing broken objects (Shewbridge et al. 2014). Our approach thus supports the needs of novice users by providing a solid foundation for scanning, replicating, and modifying existing objects.

3.1 "Like This, But Better"

Our approach to designing from imperfect examples takes inspiration from the phrase *"like this, but better."* In our interactions with students and other novice designers, we noticed that novice users often wish to create something related to something that they already possess. We adopted this phrase to describe users' desire to design a better version of something that already exists. We found that the expression "like X, but Y" described a wide range of possible design activities. Table 1 offers several examples of how this perspective may be applied to common design activities.

"Like this, but…"	How to support in design tools
bigger, smaller, longer	Enable objects to be scanned and resized.
the same size as X	Enable objects to be resized to match the user's other objects.
personalized	Enable users to personalize objects with writing or design.
accessorized	Enable users to create accessories (e.g., cases) for objects.
more of it	Enable users to clone objects.
not broken	Enable users to repair broken objects.

Table 1. "Like this, but better" serves as a motivating anthem for designing from imperfect examples, and suggests a variety of possible design workflows.

3.2 Tools Supporting Design from Imperfect Examples

In the previous section, we presented *design from imperfect examples* as an approach to conceptualizing and performing 3D object design and fabrication in a way that is accessible to everyday users. Core to this concept is the ability for the user to start with an existing object, articulate how the object can be improved, apply these improvements to a representation of that object, and fabricate the improved object. We envision this type of activity being supported by a variety of tools, and indeed some existing tools such as KidCAD (Follmer et al. 2012) and MixFab (Weichel et al. 2014) support some aspects of this design approach. In the following section, we introduce the Easy Make Oven, a prototype that we developed and deployed in order to explore the opportunities of designing from imperfect examples. The Easy Make Oven presents one approach to designing from imperfect examples, but it does not represent the only approach to conducting such a design process. We introduce the system below and describe its capabilities, limitations, and future potential.

4 Case Study: The Easy Make Oven

The Easy Make Oven is a novel hardware-software prototype that we developed to explore the potential of designing from imperfect examples. The Easy Make Oven is a large touch screen-based tabletop computer that can be used to scan, manipulate, and export 3D objects. A primary innovation of the Easy Make Oven is that 3D objects can be scanned using the tabletop's internal imaging sensors, and can be directly manipulated through touch and gestures on the table surface. We constructed the Easy Make Oven's hardware and software ourselves, and have deployed it in our research lab for several months.

The current Easy Make Oven prototype consists of an optical multi-touch table that uses sensing technology similar to existing optical tabletops such as Microsoft PixelSense[xiii]. The current Easy Make Oven prototype is based on a custom-built a direct imaging (DI) table with backlit projection, internal infrared lighting, and an infrared webcam. The tabletop hardware is roughly the size of a standing table at

24x33x35” (Figure 1). The Easy Make Oven uses custom computer vision software, written using the OpenCV library[xiv], to track touches as well as to capture objects and sketches placed on the table. While the current prototype runs on a custom-built interactive surface, the Easy Make Oven software does not rely upon any custom hardware or sensors, and should be compatible with other DI-based surfaces such as the Microsoft PixelSense[xiii].

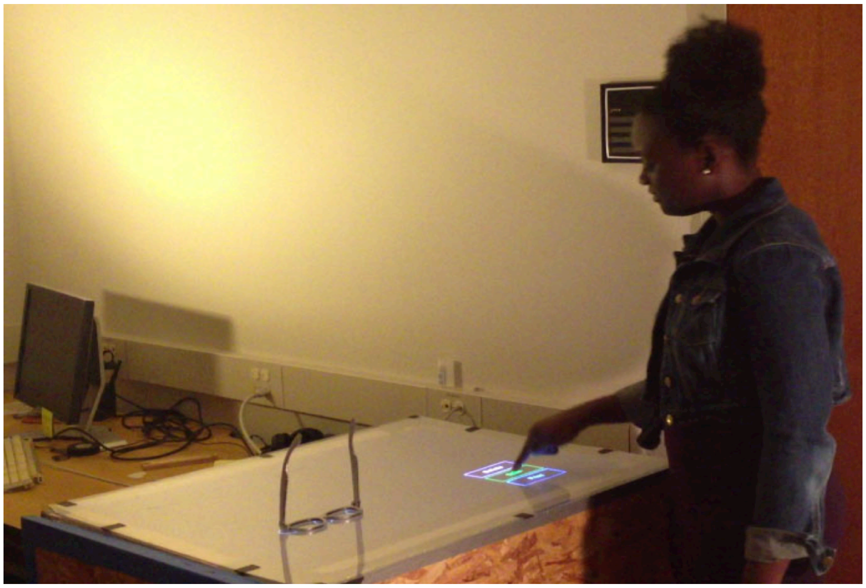

Figure 1. The Easy Make Oven prototype consists of an optical-based interactive tabletop that can track touches and scan physical objects. The Easy Make Oven may be used to create 3D models by manipulating and combining scanned physical objects and sketches. A video demonstration of the Easy Make Oven may be found at http://youtu.bew/4wm3nu07bjl

4.1 Using the Easy Make Oven

The Easy Make Oven allows non-expert users to scan, edit, and fabricate 3D objects. Rather than requiring users to manipulate 3D models using a traditional graphical user interface, the Easy Make Oven enables users to create 3D objects by scanning existing objects, combining scanned objects, and modifying scanned objects using touch gestures.

4.2 Capturing Objects

Because objects are placed on a surface and captured using a 2D camera, the Easy Make Oven does not provide a full 3D object scan, but instead captures a high-resolution “slice” of an object or sketch. These scans may be extruded into three dimensions and may be combined to create physical objects. Currently, the Easy Make Oven enables users to capture or create objects using the following methods:

- **Scanning objects.** A user may place an object on the table and press the *Scan* button to capture it. The Easy Make Oven captures an image of the object’s outline using computer vision techniques described in the following section.

- **Scanning sketches.** The user may sketch an object on a piece of paper and press the *Scan* button to capture it.

- **Direct touch input.** The user may draw shapes directly on the surface using a fingertip or a stylus.

- **Combining scanned objects.** Objects created using each of these techniques may be combined. For example, a user might scan in a physical pendant, resize it, and combine it with a drawing to produce a version of the pendant with a new inscription based on the drawing (Figure 2).

A.  B. 

Figure 2. Scanned objects and output created by the Easy Make Oven. (A) Silver glasses were cloned using the Easy Make oven: the frames were printed on a 3D printer and the arms were laser-cut; (B) A pendant of a bird on a heart was created by mashing up a pre-existing heart-shaped pendant with a hand-drawn sketch of a bird.

4.2.1 Image Processing

The Easy Make Oven uses a webcam to capture images of the surface at a resolution of 1280 by 960 pixels. Because images captured from the table surface may feature artifacts such as camera noise, haze, and reflections, we developed a custom image processing pipeline , for capturing and cleaning up object scans using OpenCV[xiv]. First, background subtraction is used to reduce the effects of uneven lighting and reflections (Stauffer and Grimson 1990). Second, the noise in the image is reduced through frame averaging (Lim 1990). Third, a binary threshold is used to separate the contour of the object, which appears bright in the image, from the image halo and other background noise. Fourth, the Canny edge detection algorithm (Canny 1986) is used to identify contours in the thresholded image, including internal contours (i.e., grooves, ridges or holes). Finally, the Douglas-Puecker algorithm (Douglas and Puecker 1973) is used to smooth the detected edges and simplify the scanned contours. Objects are scanned at their original scale so that they may be manipulated directly on the tabletop.

4.2.2 Manipulating Captured Objects

The Easy Make Oven stores scanned objects and sketches as contours that can be directly manipulated on the interactive surface using standard multi-touch gestures (Wu and Balakrishnan 2003). Our current prototype supports the following manipulations:

- **Scale.** An object can be scaled using a multi-touch pinch-to-zoom gesture. Objects are displayed at actual size, and can be scaled to match other physical objects placed on the table, such as scaling a scanned wrench to match a physical nut (Figure 3).

- **Move and combine.** The user can reposition objects by dragging them with a finger, and may combine multiple objects into a single object by dragging one object on top of another.

- **Set thickness.** Objects in the Easy Make Oven are composed of multiple, stacked, two-dimensional “slices”. Once an object is scanned, its thickness can be set using a menu of pre-set thicknesses presented on the left edge of the screen. Currently, the user can set the thickness of each individual contour in increments between 0mm and 18mm. Setting a contour’s thickness to zero allows the user to mark a hollow area inside a scanned object.

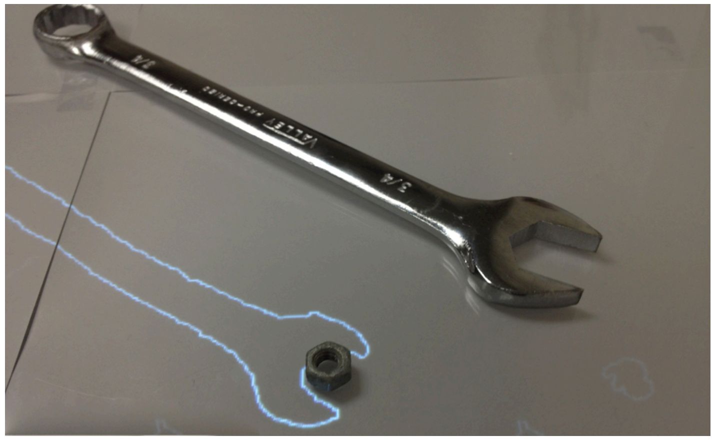

Figure 3. The Easy Make Oven allows users to scan physical objects on a large interactive surface and modify scanned objects using gestures. In this example, the user scans a wrench, and then uses a multi-touch pinch gesture to scale the scanned wrench model to match a physical nut.

4.2.3 Fabricating Objects

Once the user is satisfied with their creation, they can export their prototype as a 3D model or 2D vector object. The Easy Make Oven converts scanned objects into 3D-printable shapes by rendering the contours in OpenSCAD[xv], a programmatic 3D modeling tool, and extruding them to the user specified thickness levels. The rendered shapes are then exported as 3D models in stereolithography (.stl) format. This file format may be imported by a variety of open source and commercial software packages, or may be printed via a 3D printer. Because some users may wish to fabricate objects using a laser cutter, the Easy Make Oven can also export objects as 2D vector drawings in Drawing Interchange Format (.dxf).

If the user wishes to manipulate the scanned object further, he or she may edit the exported files using vector editing software (for 2D objects) or 3D modeling software (for 3D objects). However, models produced by the Easy Make Oven are designed to be printable without any additional manipulation or tools needed. In addition, more complex objects can be created via included scripts that can transform the scanned output into *.stl* files. An example of this interaction is creating a 3D-printed box for a scanned object by adjusting the size parameters of an existing box model.

4.3 What Can You Make with the Easy Make Oven?

The Easy Make Oven enables the creation of 3D objects by combining scans and drawings of 2D objects. In practice, the Easy Make Oven works best with objects that have a flat side that can be placed on the scanning surface, such as tools or jewelry. Objects that are rounded, such as bottles or bowls, cannot easily be scanned using the Easy Make Oven, although it is possible to capture their approximate shape and size. The Easy Make Oven's editing interface is similar to SketchUp, in that users manipulate 2D outlines, and may stretch or combine them to produce 3D shapes. Currently, the Easy Make Oven does not provide robust tools for manipulating objects in 3D, which reduces its flexibility in creating objects, but also reduces the complexity of its user interface.

In the simplest case, the Easy Make Oven can produce flat, two-dimensional objects of arbitrary thickness. The Easy Make Oven can scan, copy, and create remixed versions of objects such as tools, flatware, toys, and jewelry. Given that we have targeted the Easy Make Oven for everyday use by non-designers, we have been especially excited to see the Easy Make Oven used to create, remix, and repair a variety of everyday objects, including children's toys, model railroad parts, wrenches, guitar picks, hair combs, earrings, and pendants. However, the Easy Make Oven is not limited to simply creating flat objects. These 2D slices can be combined to create larger 3D objects. For example, a user can scan a physical pendant, erase the inscription on the pendant, and replace it with a new inscription from a paper sketch (as shown in Figure 2B). Finally, we have used the Easy Make Oven to scan and create "flat pack" objects made up of multiple planar sections and assembled by the user after fabrication. An example of such an object is the eyeglass frame shown in Figure 2A. To create a copy of an existing pair of eyeglasses, we scanned the front and side of the existing glasses, fabricated each piece separately, and glued the fabricated pieces together. This process of scanning, printing, and assembling objects opens many new avenues for creating objects with the Easy Make Oven.

4.4 Evaluating the Easy Make Oven

The main features of the Easy Make Oven have been developed and tested through an extended deployment in our research lab. Students and faculty in our lab have used the Easy Make Oven, alone and in small groups, to scan and create a wide variety of objects. However, the primary purpose of the Easy Make Oven is to enable non-experts to collaboratively create 3D objects. To evaluate the potential of the Easy Make Oven for supporting 3D design by novices, we conducted a formative user study in which a group of users with minimal 3D design experience collaboratively scanned and created 3D objects using the Easy Make Oven.

4.4.1 Participants and Procedure

We evaluated the Easy Make Oven prototype via a group design activity with 8 university students (5 female), recruited from a class on 3D design. These students were only recently introduced to 3D design tools, and had previously used TinkerCAD and the MakerBot Replicator to create 3D objects as part of a class activity. Participant ages ranged from 19 to 23 (M=21.1, SD = 1.55).

At the start of the activity, participants were given a brief introduction to the Easy Make Oven hardware. Participants were given a set of diverse art supplies, objects, tools, and 3D printed objects as source materials, but were not given specific tasks or instructions about what to create. The group od participants spent approximately one hour using the Easy Make Oven to create 3D models (Figure 4), and then viewed their creations using a 3D model viewer.

A. B. C.

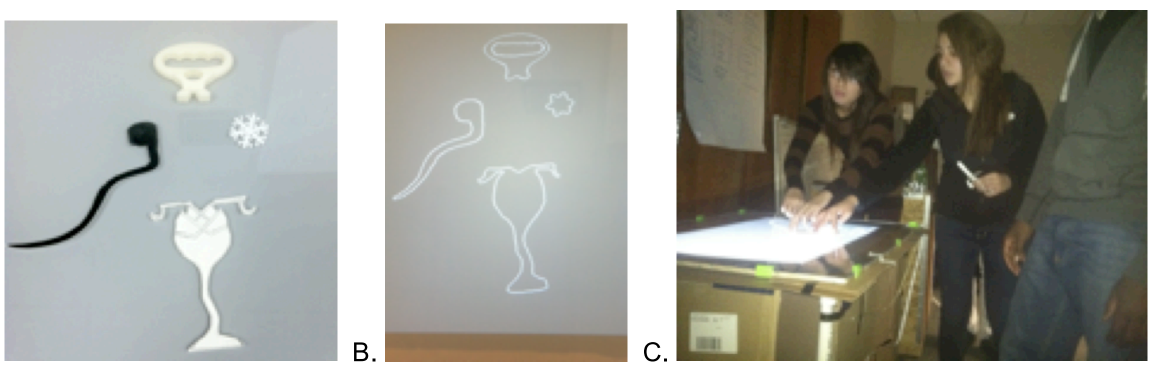

Figure 4. Scanning objects using the Easy Make Oven. (A) Participants chose physical objects and drawings to scan; (B) The Easy Make Oven captured the scanned objects; (C) Participants collaboratively edited scanned objects.

4.4.2 Use of the Easy Make Oven

Participants created several designs using the Easy Make Oven. Most of the participants in our activity favored using paper sketches as input, but combined both sketches and physical objects in their designs. Participants were not explicitly instructed to work together, and began the session designing independently. However, participants did share the Easy Make Oven hardware, and worked more closely together as the activity progressed. Participants used the large surface to scan multiple objects simultaneously, as well as to divide work work: one participant would position an object to scan, while another would use the on-screen touch controls to scan and manipulate the object. When some participants encountered problems in scanning objects due to limitations of the Easy Make Oven hardware, they worked together to create more accurate scans by moving or adjusting the scanned object. By the end of the design activity, several participants were working together to create new objects to scan.

Although we did not explicitly require participants to work together during the design activity, we found that participants collaborated of their own accord. The Easy Make Oven's large interactive surface provided sufficient space for simultaneous use by multiple users.

4.4.3 User Feedback

Following the design activity, we asked participants to talk about the objects that they designed and about their experience using the prototype. Participants compared their experience with the Easy Make Oven to their prior experience using TinkerCAD, and noted that the Easy Make Oven provided them with new and different ways of creating 3D objects. Seven of the eight participants said that they were able to create objects using the Easy Make Oven that they wouldn't have been able to create in TinkerCAD. As one participant stated:

> "*With TinkerCAD it is hard to visualize what your object is going to look like because you create it using the small shapes like squares and circles. The tabletop scanner allows you to create objects and see the whole shape as you create the final object. You may not be able to make the exact shape but you can at least start with a shape that is close."* (19 year old, female, psychology major)

Overall, the students who used the Easy Make Oven indicated that they were satisfied with the quality of the generated models, and most of the participants felt that creating an object by scanning and modifying an existing object provided them with the capability to create 3D models that were beyond their ability to create in TinkerCAD.

5 Discussion

Our development and testing of the Easy Make Oven prototype supports the notion that *designing from imperfect examples* is a useful approach to designing 3D objects, even for users with minimal design training. Furthermore, this approach can support everyday users' desire to copy, repair, and modify their existing objects (Shewbridge et al. 2014).

The Easy Make Oven prototype has been useful as a proof-of-concept, and we have found that it presents a compelling and enjoyable experience for novice designers. However, the current Easy Make Oven prototype is limited by several design decisions. Perhaps the most notable limitation of the Easy Make Oven is that it currently does not support direct 3D scanning of physical objects. While we have considered adding 3D scanning and manipulation features to our prototype, to date we have deliberately avoided this approach for several reasons. First, it can be difficult to scan 3D objects with high precision, and most current 3D scanning techniques require the user to clean up scanned models using a 3D modeling tool. Second, since users interact with the Easy Make Oven via a two-dimensional surface, incorporating more complex 3D shapes would fundamentally alter the nature of interaction with the system. Currently, users place objects or drawings that they wish to scan on the surface, capture a 1:1 scale representation of that object, and directly manipulate this representation. Incorporating more complex 3D models would mean that users would be required to manipulate a representation of a 3D object on a 2D screen, which would increase the complexity of interacting with the system. As we have shown, the Easy Make Oven's "2.5D" object model enables a wide range of creative expression. While the constraints of the Easy Make Oven may limit the types of objects that may be produced, our testing of this prototype has shown that these constraints can also inspire creative use of the system.

A second limitation of the Easy Make Oven prototype is that its scanning system cannot easily scan objects with major convex and concave structures, such as cups or other containers. This limitation may be addressed in the future by incorporating additional sensing methods, such as an external camera, or by combining multiple scans of a single object to create a composite image.

One advantage of the Easy Make Oven versus related systems is that it uses the existing imaging system found within a touch table to capture objects, which enables the Easy Make Oven software to be used on existing touch tables. However, the Easy Make Oven's use of an infrared camera limits its ability to scan some objects, such as those that are reflective, metallic, or transparent. Furthermore, due to the lighting configuration used by the direct-imaging-based surface, dark-colored objects are not easily scanned because they do not reflect enough light. These limitations may be worked around in various ways, such as by coating a reflective or transparent object with a matte material, or placing a light-colored sheet of paper on top of a dark object to scan it. Augmenting the Easy Make Oven with additional cameras could improve the robustness of object scanning. We have experimented with combining the Easy Make Oven's infrared camera with a visible light camera, and have found that this enables us to scan objects that are difficult to capture using infrared alone, while also allowing the system to capture colors and patterns of the scanned object, which could be used in the future to more accurately duplicate objects.

6 Future Work

In addition to improving Easy Make Oven's scanning capabilities, there exist many opportunities for extending our prototype with new design capabilities. One scenario we have recently begun to explore is the scanning, fabrication, and assembly of multi-part objects, such as the eyeglass frames shown in Figure 2A. Currently, a user may scan each part separately and assemble the printed parts using glue or tape. Future versions of the Easy Make Oven could enable users to scan multiple parts and add custom connectors for combining these parts. We have also begun to explore using the scanning surface to capture measurements of the users themselves. For example, the Easy Make Oven could resize an existing model of a ring based on the width of the user's finger.

While we have tested our prototype extensively in the lab, we intend to explore how our prototype may be used by individuals of different ages, different levels of experience, and even different physical abilities. We intend to test the Easy Make Oven with such diverse populations as children, expert designers, and individuals with disabilities.

Finally, while the size of the Easy Make Oven's surface supports collaboration between multiple users, the current prototype provides little explicit support for collaborative design work. We are interested in adding additional collaborative features, such as the ability to determine which user made a specific change, and the ability to track changes to a design made over time. We intend to explore the collaborative affordances of the Easy Make Oven through future user studies with additional novice designers, as well as with domain experts such as assistive technology specialists or jewelry makers.

7 Conclusion

While there have been many recent advancements in the availability of low-cost tools for fabricating physical objects, there currently exists a mismatch between available fabrication tools and the software for designing and modifying the objects that will be fabricated. Even simple 3D modeling programs can present significant usability challenges to novice designers. Thus, there is an opportunity to create fundamentally different types of user interfaces to enable novices to design and create 3D objects. In particular, we believe that capturing, combining, and remixing existing objects and sketches can enable non-expert users to create useful and interesting 3D objects. This approach, which we call *designing from imperfect examples,* enables users to create 3D objects based on existing objects, rather than starting from scratch. Our prototype system, the Easy Make Oven, supports this approach by enabling novice users to combine existing objects and sketches on an interactive surface. Our formative user evaluation of the Easy Make Oven shows that this approach enables novice users to create 3D objects that they would otherwise be unable to create.

References

Blikstein, P. Digital fabrication and 'making' in education: the democratization of invention. In J. Walter-Herrmann & C. Büching (Eds.), FabLabs: Of Machines, Makers and Inventors. Bielefeld: Transcript Publishers (2013).

Buechley, L., Eisenberg, M., Catchen, J., and Crockett, A. The LilyPad Arduino. Proc. CHI '08, ACM Press (2008), 423-432.

Canny, J. A computational approach to edge detection. IEEE Transactions on Pattern Analysis and Machine Intelligence, 8(6), (1986), 679-698.

Chen, C.-C., Lu, M.-C., Chuang, C.-T., and Tsai, C.-P. Vision-based distance and area measurement system. WSEAS Transactions on Signal Processing 4, 2 (2008), 36-43.

Douglas, D. H., & Peucker, T. K. Algorithms for the reduction of the number of points required to represent a digitized line or its caricature. Cartographica: The International Journal for Geographic Information and Geovisualization, 10(2), (1973), 112-122.

Follmer, S., Carr, D., Lovell, E., & Ishii, H. CopyCAD: remixing physical objects with copy and paste from the real world. Proc. UIST EA '10, ACM Press (2010), 381-382.

Follmer, S., & Ishii, H. KidCAD: digitally remixing toys through tangible tools. Proc. CHI '12, ACM Press (2012), 2401-2410.

Funkhouser, T., Kazhdan, M., Shilane, P., Min, P., Kiefer, W., Tal, A., Rusinkiewicz, S., and Dobkin, D. (2004). Modeling by example. ACM Transactions on Graphics, 23(3), 652-663.

Gershenfeld, N. Fab: The Coming Revolution on Your Desktop–from Personal Computers to Personal Fabrication. Basic Books (2007).

Huang, Y. and Eisenberg, M. Easigami: virtual creation by physical folding. Proc. TEI ’12, ACM Press (2012), 41-48.

Hurst, A. and Tobias, J. Empowering individuals with do-it-yourself assistive technology. Proc. ASSETS ’11, ACM Press (2011), 11-18.

Izadi, S., Kim, D., Hilliges, O., Molyneaux, D., Newcombe, R., Kohli, P., Shotton, J., Hodges, S., Freeman, D., Davison, A., and Fitzgibbon, A. KinectFusion: real-time 3D reconstruction and interaction using a moving depth camera. Proc. UIST '11 (2011), ACM Press, 559-568.

Jota, R. and Benko, H. Constructing virtual 3D models with physical building blocks. Proc. CHI EA ’11, ACM Press (2011), 2173 - 2178.

Kuznetsov, S. and Paulos, E. Rise of the expert amateur. Proc. NordiCHI ’10, ACM Press (2010), 295-304.

Leduc-Mills, B. and Eisenberg, M. The uCube. Proc. IDC ’11, ACM Press (2011), 72-80.

Lim, J. S. Two-Dimensional Signal and Image Processing. Prentice Hall (1990).

Lipson, H. and Shpitalni, M. Correlation-based reconstruction of a 3D object from a single freehand sketch. (2007), article 44.

Lipson, H. Factory@ Home: The Emerging Economy of Personal Fabrication. (2010).

Mota, C. The rise of personal fabrication. Proc. C&C ’11, ACM Press (2011), 279-288.

Mueller, S., Lopes, P., and Baudisch, P. 2012. Interactive construction: interactive fabrication of functional mechanical devices. Proc. UIST '12, ACM Press (2012), 599-606.

Mueller, S., Kruck, B., and Baudisch, P. LaserOrigami: laser-cutting 3D objects. Proc. CHI ’13, ACM Press (2013), 2585-2592.

Oh, Y., Johnson, G., Gross, M., Do, E. Y. The Designosaur and the Furniture Factory: simple software for fast fabrication. Proc. ICDCC ’06, Springer (2006), 123-140.

Shewbridge, R., Hurst, A., Kane, S.K. Everyday making: identifying future uses for 3D printing in the home. Proc. DIS '14, ACM Press (2014), 815-824.

Song, H., Guimbretière, F., Hu, C., & Lipson, H. (2006). ModelCraft: capturing freehand annotations and edits on physical 3d models. Proc. UIST ’06, ACM Press, 13-22.

Stauffer, C., and Grimson, W. E. L. Adaptive background mixture models for real-time tracking. Computer Vision and Pattern Recognition 2, IEEE Computer Society (1999).

Torrone, P. Public libraries, 3d printing, fablabs and hackerspaces. MAKE Magazine (2011). http://blog.makezine.com/2011/05/11/public-libraries-3d-printing-fablabs-and-hackerspaces

Weichel, C., Lau, M., Kim, D., Villar, N., and Gellersen, H.W. (2014). MixFab: a mixed-reality environment for personal fabrication. Proc. CHI '14, ACM Press (2014), 3855-3864.

Wu, M. and Balakrishnan, R. Multi-finger and whole hand gestural interaction techniques for multi-user tabletop displays. Proc. UIST ’03, ACM Press (2003), 193-202.

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[i] AutoCAD. http://usa.autodesk.com/autocad
[ii] SolidWorks. http://www.solidworks.com
[iii] Rhino. http://www.rhino3d.com
[iv] Blender. http://www.blender.org
[v] SketchUp. http://www.sketchup.com
[vi] 3D Tin. http://www.3dtin.com
[vii] TinkerCAD. http://tinkercad.com
[viii] MakerBot Customizer. http://www.thingiverse.com/apps/customizer
[ix] Shapeways Creator Apps. http://www.shapeways.com/creator
[x] RepRap. http://www.reprap.org
[xi] MakerBot. http://makerbot.com
[xii] 123D Catch. http://www.123dapp.com/catch
[xiii] Microsoft PixelSense. http://www.microsoft.com/en-us/pixelsense
[xiv] OpenCV. http://opencv.org
[xv] OpenSCAD. http://www.openscad.org