

# Situated Modeling: A Shape-Stamping Interface with Tangible Primitives

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## ABSTRACT

Existing 3D sketching methods typically allow the user to draw in empty space which is imprecise and lacks tactile feedback. We introduce a shape-stamping interface where users can model with tangible 3D primitive shapes. Each of these shapes represents a copy or a fragment of the construction material. Instead of modeling in empty space, these shapes allow us to use the real-world environment and other existing objects as a tangible guide during 3D modeling. We call this approach *Situated Modeling*: users can create new real-sized 3D objects directly in 3D space while using the nearby existing objects as the ultimate reference. We also describe a two-handed shape-stamping technique for stamping with tactile feedback. We show a variety of do-it-yourself furniture and household products designed with our system, and perform a user study to compare our method with a related AR-based modeling system.

## Author Keywords

3D modeling, sketching interfaces, augmented reality, personal fabrication

## ACM Classification Keywords

H.5.2 Information Interfaces and Presentation: User Interfaces—*Input devices and strategies*

## INTRODUCTION

The idea of “design tools for everyone” [9, 13] is to help non-professionals to design and construct physical objects in the real world. However, traditional modeling methods usually lack references to the real world, making it difficult to design a model that fits well with the target environment. This paper presents a tool for users to create real-sized 3D models directly in 3D space to address this problem. In particular, we take a modeling-in-context approach where existing objects are used as a guide for modeling new objects. While a single photo [15] can provide a 2D background reference

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to model-in-context, modeling directly in real 3D space provides the ultimate reference. The 1:1 size ratio of the new object [3] relative to the existing ones allows the user to better perceive, model and visualize the result.

In this paper, we present a *Situated Modeling* approach where *existing* 3D objects are used as a guide to draw *new* 3D objects that fit with the existing ones. We advocate for the idea that an augmented reality (AR) framework works well with this situated modeling approach: *new virtual* objects can be designed and displayed alongside *existing physical* ones. For example, one may want to create a new table that fits with the available space, or a new dish holder for some existing dishes (Figure 1 top row). While one can measure the sizes of the existing objects and/or space, make a new object separately with respect to these sizes, and then place the new object with the existing ones to visualize them together, our approach can perform all these steps at the same time.

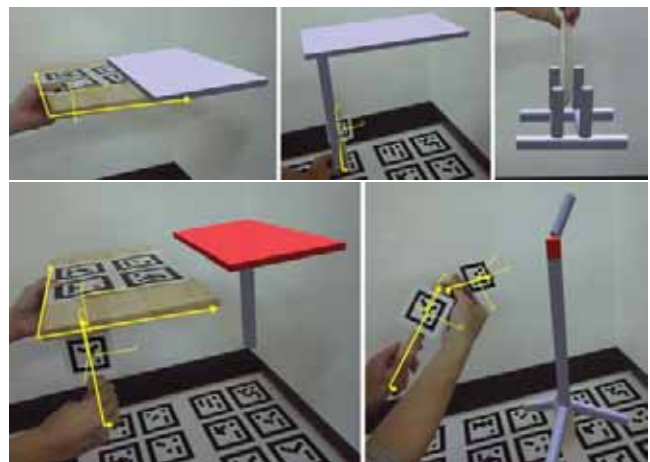


Figure 1. Situated Modeling examples (top row): We can place the primitive shapes to be in physical contact with the surrounding environment to provide a tangible guide. Two-handed stamping examples (bottom row): We stamp a physical shape (held by the dominant hand) with respect to another physical shape (held by the non-dominant hand). The latter shape provides the coordinate frame and the physical contact between the shapes provides tactile feedback.

We introduce shape-stamping methods where a user models with tangible primitive 3D shapes such as a cube or cylinder. We can *stamp* a virtual shape in 3D space that corresponds to the physical shape. We can further stamp a shape multiple times in one smooth sweeping action to extend the basic shape. These primitives represent smaller parts of larger ma-

materials such as wooden bars or plates available at local stores. They naturally support the creation of do-it-yourself household products by everyday users. In our implementation, the user wears a head-mounted display (HMD) and identifies the shapes with a set of markers.

Another significant aspect of the tangible shapes is that they naturally allow for *Situated Modeling*. The shapes can directly touch and interact with the real-world environment and existing objects. Hence we can use the real-world as a direct reference and to provide physical feedback when modeling in empty 3D space. For example, as we create a new table that follows the shape of the wall, we can use the real wall and ground as references. The new virtual table is life-sized and can be displayed immediately in the space where it will be used as the modeling process takes place.

Furthermore, as the new virtual model is being created, it is often necessary to add additional parts or shapes to the overall model. However, this is difficult as this involves stamping a physical shape in empty 3D space. We leverage previous research in two-handed manipulation that finds that the non-dominant hand is used as the frame of reference [12, 20]. We introduce a two-handed stamping technique for providing tactile feedback during stamping (Figure 1 bottom row).

We demonstrate our approach by creating a variety of do-it-yourself furniture and household products. *Situated Modeling* is demonstrated by the resulting virtual models: they already have the correct dimensions for fitting in the real-world, and can be immediately visualized together with the actual objects and environments that they may be used in. We performed a user study to compare our approach with a previous AR-based modeling system, and explored the advantages and disadvantages of having tangible interaction and physical feedback in our system.

Our contributions are: (i) Stamping interaction techniques with tangible 3D primitive shapes; (ii) Situated modeling approach where tangible shapes use real-world environment and other existing objects as a physical guide; and (iii) Two-handed stamping of shapes to provide tactile feedback.

## RELATED WORK

**Modeling-in-Context.** Instead of modeling in empty space, previous systems use pencil-and-paper sketches [26], a single photo [15], or multiple ortho-images [25] as a reference. While these systems do not allow for modeling directly in 3D space, Yee et al.'s system [29] can be used to sketch new objects in 3D space. However, it does not allow for physical interactions between the modeling tool and the existing physical objects and environment, except that it uses the real-world as a general background reference.

**AR-based 3D Modeling.** Previous systems combining AR and 3D modeling have demonstrated the design of freeform curves and surfaces [7], and the use of a physical cube for creating virtual shapes [19]. Recent work has demonstrated AR-based systems for 3D modeling [24] and painting [18]. These systems introduce hardware tools that provide haptic

feedback for operations such as moving and cutting virtual 3D models, and painting virtually on real objects. However, the above systems do not suggest using the real-world as a reference and it does not create real-sized models that fit with the existing environment. On the other hand, we suggest that the physical contacts between the tangible shapes, the existing real-world objects, and the environment are useful for providing guidance to model in empty 3D space.

**3D Sketching.** Many systems exist for directly sketching and modeling in 3D space. “3-Draw” [21] allows the user to design freeform shapes with two 6-DoF sensors. “3DM” [5] can be used to sketch organic shapes such as rocks and trees with a head mounted display and a handheld pointing device. Rough 3D shapes can be drawn with a wand in the HoloSketch system [6], or with the user’s hand in the Surface Drawing system [23]. 3D curves can be drawn with the digital tape drawing technique [10], or a physical tape input device [11]. Some systems can create usable objects [8, 28]. These existing systems ask the user to draw in 3D space without direct references to any real-world objects, and this can be imprecise. The typical drawing tool is a pen or the user’s hand. Our stamping interface is different and is suitable for the design of more precise and production-friendly models consisting of regular primitives.

**Tangible Modeling.** Previous building-block systems allow the user to arrange tangible 3D blocks [2, 4] or interlocking components [27] into a physical model, which is then recognized digitally to create a virtual model. They assume a one-to-one correspondence between each physical component and corresponding part of the resulting model, thereby requiring a large number of input tools (i.e. all physical components). Our stamping technique uses a small set of primitives and does not require this correspondence.

**Two-Handed Interaction.** We take advantage of previous research [12, 20] that finds that the non-dominant hand is used as a frame of reference. We apply this result to our framework and allow the user to stamp a shape (held by the dominant hand) with respect to another shape (held by the non-dominant hand) to provide physical feedback. A recent system [16] uses two physical cubes (one in each hand) to guide how two virtual shapes should connect. However, the physical cubes are not aligned with the corresponding virtual shapes and are used only as placeholders.

**Design Tools for Everyone.** There are tools with 2D interfaces for sketching your own plush toys [17] and chairs [22]. Tools with 3D interfaces also exist for sketching your own tables or chairs [8] and lampshades [28]. The problem of converting from virtual meshes to fabricatable parts and connectors was introduced and solved by [14]. Our work adds to this growing area, and we strived to build a tool that everyone can understand and use immediately.

## TANGIBLE PRIMITIVE SHAPES

The basic tools of our interface are a set of 3D primitive shapes (Figure 2). Each shape is a copy or a fragment of wooden materials available at local home improvement stores.

We categorize the shapes into three groups: (i) cylinder, and square-prism; (ii) rectangular-board; and (iii) small cube, sphere, and frustum. We choose these shapes as they are immediately easy to understand for most people. Having tangible shapes allows the user to manipulate and perceive them in 3D space, which helps with imagining and designing new objects.



Figure 2. Primitive shapes with markers. The transparent sheet is a symmetry tool. As a reference, the largest cylinder has length 20cm.

An important aspect of primitives is that they support the building of do-it-yourself products by everyday users. The primitives that we provide are simpler and smaller fractions of larger shapes needed to create actual models. Our shape-stamping interface supports the creation of such larger models through intuitive manipulations of the primitives in 3D space. Users of our system can buy the materials (i.e. larger wood pieces) themselves and build real objects on their own.

## USER INTERFACE

### Interactions with Primitive Shapes

**Single Stamping.** This operation allows the user to directly translate and rotate a physical primitive shape in 3D space, and *stamp* a virtual copy of it at the desired position and orientation (Figure 3). The user can toggle on and off a snapping function. If snapping is turned on, we snap the virtual shape with respect to the global virtual axes. For example, for rectangular-board shapes, if the physical shape’s plane is approximately aligned to one of the three axis-aligned virtual planes, we snap the virtual shape to the corresponding axis-aligned plane. For cylinders, if the physical shape’s axis is approximately aligned to one of the three virtual axes, we snap the virtual shape to the corresponding axis.



Figure 3. The user can translate and rotate the physical shapes in 3D space (left) and *stamp* virtual shapes (right) when desired.

**Sweep Stamping.** Instead of stamping just one virtual copy of a shape, it is often desirable to create a series of copies in one smooth sweeping action to extend the basic

shape. The small cube, sphere, and frustum are intended for stamping one-by-one and not for this interaction. For the other primitives, our interface allows for  $2 \times 2 \times 2 = 8$  types of sweep stamping. The user chooses from one of two possibilities in each category:

- Discrete or Continuous: multiple shapes are either discretized or connected continuously to form a larger shape
- Linear (constrained) or Curved (free): refers to how the primitive is moved in 3D space
- Parallel-to-axis or Perpendicular-to-axis: refers to the direction of user action with respect to the primitive shape (the axis refers to the cylinder’s axis, the square-prism’s axis, or the rectangular-board’s normal)

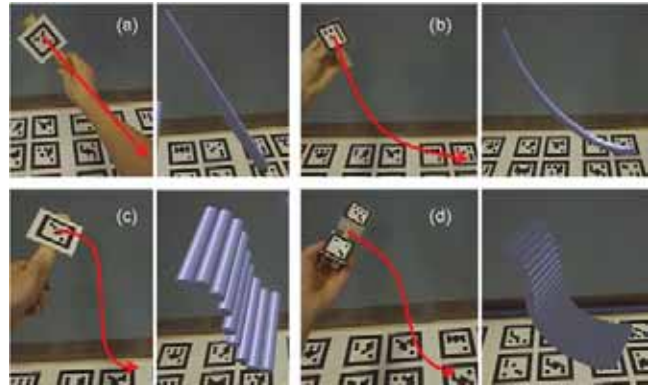


Figure 4. Sweep Stamping: (a) Continuous, Linear, Parallel-to-axis; (b) Continuous, Curved, Parallel-to-axis; (c) Discrete, Curved, Perpendicular-to-axis; (d) Continuous, Curved, Perpendicular-to-axis.

We describe the details of some of these interactions with the cylinder primitive as an example (Figure 4). Figure 4(a) shows the case for “Continuous, Linear, Parallel-to-axis”. If we sweep the cylinder primitive along its axis in approximately a straight line, the system creates multiple virtual cylinders whose axes are on the same line as the axis of the first virtual cylinder. Figure 4(b) shows the case for “Continuous, Curved, Parallel-to-axis”. If we sweep the cylinder along its axis in a 3D trajectory, the system creates a virtual curved tube-like shape. We take discretized points along the trajectory of the physical cylinder’s center and smooth these points. Each point becomes the center of a 3D circle with normal depending on the positions of neighboring points, and with the same radius of the physical cylinder. Each 3D circle is represented by evenly-spaced discretized points on the circle, and we connect the corresponding points along adjacent circles to form a virtual tube-like shape.

Figure 4(c) shows the “Discrete, Curved, Perpendicular-to-axis” case. If we sweep the cylinder in any direction that is approximately perpendicular to its axis and in a curve, the system creates a discrete series of virtual cylinders whose axes are parallel to the axis of the first virtual cylinder. Figure 4(d) shows the “Continuous, Curved, Perpendicular-to-axis” case. The interaction is the same as in case (c), but for this case, the system creates multiple virtual cylinders whose union is a connected shape. There are four other cases for



the cylinder primitive not shown in the figure, as they are less common.

### Visualization Cube

This is an additional tool for more easily visualizing the result. If the resulting model is large, or some parts of the model faces the table, floor, or wall, it is difficult to visualize it. The visualization cube allows a smaller scaled copy (proxy) of the entire model to be displayed with the cube itself as the coordinate frame [20]. We can then rotate the cube in any direction and observe the model from any viewpoint (Figure 5).



Figure 5. We rotate the visualization cube to view a smaller copy of this model from the side (left) or from the bottom (right).

### Situated Modeling

Previous work on sketching and modeling in 3D space typically asks the user to model in empty 3D space. However, it is difficult to build virtual models in empty space, as the user has to manipulate some physical drawing tools and their hands/arms in mid-air. The resulting models tend to be rough and imprecise. While this may be good for artistic or exploration purposes, the aim of our work is to create more precise shapes that can eventually be fabricated into actual usable products. The idea of *Situated Modeling* is to allow and encourage the user to directly use the real-world for physical guidance. The user can manipulate the primitive shapes in 3D space, and directly place them in contact with any existing real-world objects, the surrounding environment, and other primitive shapes. These types of physical contacts provide a tangible guide for the user during the modeling process.

Figure 1 (top row, from left) shows some examples: We slide a rectangular-board primitive shape physically along the wall to create a tabletop that fits with the wall’s shape. To create the table’s legs, we drag a physical cylinder shape until it touches the ground. We create a new dish holder by using a real dish to estimate its size. In addition, having the real-world as a context provides us with size references. The new virtual object can be modeled, edited, and visualized in the real-world environment that it will be used in.

### Two-Handed Stamping

The motivation for this interaction technique is also that it is difficult and imprecise to model in empty 3D space. When adding to the current virtual object being created, we often want to stamp a shape that is connected to the object. However, although the user can see the object virtually, there are no physical references in reality to guide the user on

where to stamp the connected shape. The idea of two-handed stamping is to provide tactile feedback to the user so that the stamping does not have to occur in completely empty 3D space. Feedback is provided by having a reference proxy primitive in the non-dominant hand and target primitive in the dominant hand [20]. The user can then have more precise control over the location of the stamped shape.

Figure 1 (bottom row) shows two examples, where a table’s leg is stamped with the tabletop as the coordinate frame, and a top branch of a clothes hanger is stamped with the vertical pole as the coordinate frame. We describe the clothes hanger example (Figure 1 bottom right) in detail to illustrate this interaction. After the vertical pole is drawn with the physical larger-cylinder shape, we would like to stamp the smaller branches at the top with the physical smaller-cylinder shape. We first “choose” the highest drawn cylinder (top part is colored red and it overlaps with blue cylinders directly below) as the new coordinate frame. This is performed by switching to two-handed mode and “choosing” the highest drawn cylinder by placing the larger-cylinder shape near it. Stamping a shape now creates a virtual shape with respect to this new coordinate frame instead of the global one. We assume the dominant hand is the right hand. We hold the larger-cylinder with the left hand to represent this new coordinate frame. The right hand then holds the smaller-cylinder, physically touches it to the larger-cylinder on the left hand, and we stamp to create a connected smaller branch. The significance here is that the smaller virtual branch can be well aligned to the rest of the virtual shape.

### IMPLEMENTATION

We use a commercial HMD (Canon VH-2007 Video see-through, Figure 6) to demonstrate our approach. The display has two cameras for capturing and tracking. It produces a stereoscopic image displayed on two small screens (one for each eye). The display resolution is 1280 x 960, and both the input and output image frequency are 60 Hz. The display system tracks a set of base markers (Figure 6), and calibrates the system’s position and orientation interactively. Each tangible primitive shape has a known geometry, and we place one or multiple markers on each of them for identification. One marker is enough to uniquely identify the shape, but having multiple markers improves the robustness of the tracking. Multiple markers can even be placed separately on the shape. For example, one of the cylinder shapes has one marker at either end of the cylinder (Figure 4d), as this setup is convenient for both user manipulation (user holds cylinder at the middle) and system tracking. Our modeling interface is independent of the hardware implementation (HMD + AR markers). Other recognition methods such as motion capture or computer vision can also be used. Motion capture is accurate and fast, but requires expensive equipment. Using computer vision techniques for recognizing primitive shapes automatically is convenient because no markers are needed, and is an attractive future extension to our system.

Yee et al. [29] discuss issues with hardware in their augmented reality system. They describe issues such as tracking and calibration performance, rendering latency, and user



Figure 6. From top left: A small set (for placing on table) and a large set (for placing on floor) of base markers for identifying the global reference frame, the HMD, foot pedals for user input, and a small mouse attached to a cylinder primitive for easier user input.

fatigue. Our tracking and calibration are more accurate in comparison, and we do not have any rendering latency. The state-of-the-art HMD technology resolves some of these issues and allows us to focus on the modeling interface.

Our prototype system uses a keyboard and foot pedals (Figure 6) to control the different modeling operations. Having a keyboard is sufficient for most operations, but a foot pedal is more convenient in some cases as the user is already holding physical tools. A foot pedal is necessary for the two-handed stamping interaction (as both hands are preoccupied). Other design alternatives are possible for user input. For example, we have tried to attach a small mouse to the primitive shapes (Figure 6). Clicking a mouse button on the shape provides an intuitive method for virtually stamping it. Other possibilities include a voice-based or gesture-based input.

## RESULTS

We demonstrate our approach by creating a variety of do-it-yourself furniture and household products (Figures 7 and 8). We show that a small set of physical primitive shapes can be used to model many types of objects. The examples in Figure 7 demonstrate the idea of Situated Modeling: the created objects fit well with their surrounding environments or original physical objects used during the modeling process. We also fabricated the real objects for these examples. These fabricated objects have simple shapes and are shown as a proof-of-concept. More complex virtual models can be converted into real objects with more sophisticated methods [14].

Figure 8 shows a variety of virtual shapes we created. The two-handed stamping was useful, for example, for connecting the rod-shapes of the clothes hangers. We used an existing chair (orange chair in figure) as a size reference when creating the lamp, chair, and bench, and we used a real photo as a reference when creating the photo frame. It was useful to visualize the relative dimensions of the virtual and real-world objects interactively when drawing and modeling the virtual ones. The table with an irregular shape was made to fit the shape of the wall. This example demonstrates the idea of Situated Modeling well, as the table is made to fit perfectly into this specific space. The cabinet was made to fit tightly under the desk and beside the chair, and the desktop

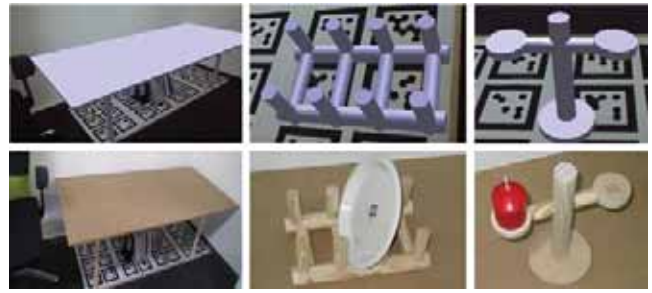


Figure 7. Virtual models created by our system and corresponding real objects built from wood pieces. From left: table (fits into environment), dish holder (fits with original dish), and candle holder (fits with original candle).

shelf was created to fit on the desk with the laptop and books. The chair with the curved surface is different from the bench in that its surface consists of a continuous/connected set of cylinders (while the bench has a discrete set). The chair in the top right of the figure demonstrates the use of the square-prism and the small cube primitive (the small cube patterns are for decoration). The shelf in the bottom right of the figure fits tightly into the available space, and its wheels are created from the small sphere primitive.

The symmetry tool (in Figure 2) can be used to create a copy of all virtual shapes with the tool (i.e. planar sheet) as the symmetric plane. This tool makes it more convenient to create some symmetric parts, and is useful for producing well-aligned and buildable shapes more easily. This tool was used, for example, when creating the horizontal clothes hanger and the bench.

## USER STUDY

We performed a user study to compare our Shape-stamping interface with the Daichi-tools interface [24]. The Daichi-tools system is a closely related previous work that uses an augmented reality approach for 3D modeling. The key differences in our approach are the ideas of stamping with tangible primitive shapes, and the physical feedback they provide during the modeling process. Hence the goal of the study is to gain insights into the advantages and disadvantages of having such an interface. As previous work has already demonstrated the effectiveness of two-handed interactions [12, 20], we do not perform further evaluation of our two-handed stamping technique.

We first ran a pilot test with three users, and made some improvements to our system based on comments from these users. Since the HMD tracking system was sometimes not robust, we added another set of large base markers to the wall of our environment. This allowed the cameras to detect the markers more clearly, and improved the tracking ability. The users mentioned that the original physical rectangular-board shape was large and not easy to handle. Hence we made a new shape of half the original size.

**Participants.** We recruited ten participants (six male and four female) from a local university for our study. Their ar-



Figure 8. Do-it-yourself furniture and household products created by our system. From top left: clothes hangers, lamp, photo frame, chairs, cabinet, table, chair, bench, and shelves. Please see the video for some of the modeling processes.

eas of study include: engineering, computer science, environmental science, economics, health, medicine, art, and design. Three of them have some experience in 3D modeling, and one of them has some experience in augmented reality. All of them were using our system for the first time.

**Method.** The participants were first given brief instructions of how to use both interfaces, and about two minutes to practice using the interfaces. We then gave them an image of a virtual bookcase in an existing environment and asked them to create it with both methods (Figure 9). For Shape-stamping, the main interaction for this study was stamping with a rectangular-board primitive. The participants were only allowed to stamp each virtual shape one-by-one, as this more closely resembles Daichi-tools. For Daichi-tools, we implemented tools to simulate the moving and cutting of virtual shapes [24]. Our implementation did not include audio feedback as this was not our focus. The main interaction for this study was moving (and creating copies) of a virtual rectangular-board. We decided that this interaction corresponds more to our stamping interaction, whereas the cutting tool corresponds more to “negative”-stamping. Half of the users started with Shape-stamping, and the other half started with Daichi-tools.



Figure 9. Image shown to users (left). Setup of Shape-stamping (middle) and Daichi-tools (right). For Daichi-tools, we needed a physical tool to represent the moving tool, and we used a cylinder primitive. Our implementation allows for moving a set of existing virtual shapes. For this study, we only used the virtual rectangular-board shape.

**Results.** We analyze the accuracy of the interfaces by recording five measurements (height, width, and depth of entire shape, and distances between floor and two middle horizontal pieces of bookcase) of the created models for each user and each interface. We compare these measurements to the ground truth bookcase in the image shown to the users. We compute the sum of absolute differences between the

ground truth and each interface for the five measurements (Figure 10 top). A paired t-test ( $p=0.00324$ ) shows a significant difference between the two interfaces. Shape-stamping has a better accuracy than Daichi-tools. Computing the sum of squared differences gives similar results. The height, width, and depth measurements for Daichi-tools tend to be larger than those for Shape-stamping. The virtual shapes created by the users tend to exceed into the space occupied by real objects. On the other hand, the distances between the floor and the two middle horizontal pieces for Daichi-tools tend to be smaller than those for Shape-stamping. Given the ground truth (the real bookcases) as a reference, the horizontal pieces created with Daichi-tools tend to be lower than the real reference pieces.

We recorded the task execution time for each user and each interface (Figure 10 bottom). A paired t-test ( $p=0.00245$ ) shows a significant difference between the two interfaces. The time to create the same virtual bookcase is faster for Shape-stamping than for Daichi-tools.

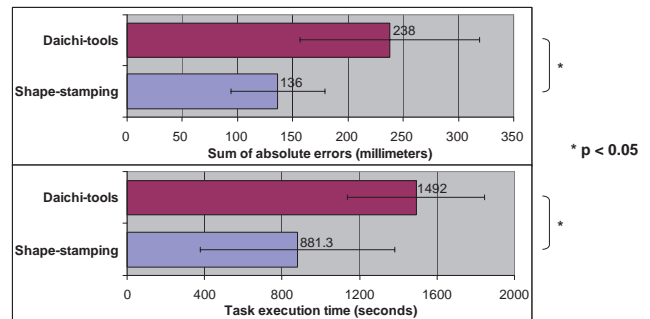


Figure 10. Plots showing task accuracy (top) and execution time (bottom). These are averages of the ten participants. The error bars show the standard deviation.

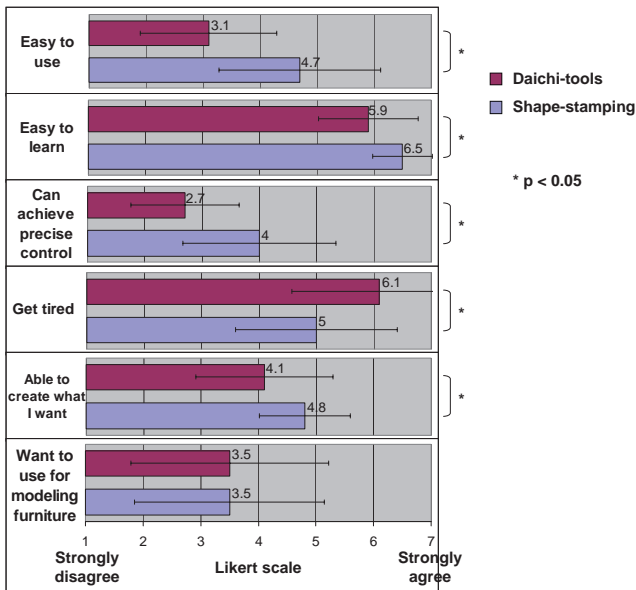
Figure 11 shows images of the virtual bookcases created by one user. The one created with Shape-stamping matches well with the two real bookcases beside it, while the one created with Daichi-tools partially intersects with the real bookcases and the floor. In general, Shape-stamping produces neater 3D shapes. These images support the result above that Shape-stamping has a better accuracy.





**Figure 11.** Virtual bookcases created by one user with Shape-stamping (left) and Daichi-tools (right). The small virtual board in front of the bookcase (right) is part of the interface, and used with the Daichi move tool.

Each user completed a questionnaire after creating the bookcases. Figure 12 shows the results. We performed six paired t-tests. The first five show significant differences ( $p < 0.05$ ) between the interfaces, showing the advantages of Shape-stamping. The last one “Want to use for modeling furniture” shows no significant difference ( $p > 0.05$ ).



**Figure 12.** Results of the user questionnaire. These plots show the average and standard deviation of the ten participants.

We then asked the users about the strengths and weaknesses of both interfaces. One common strength of Shape-stamping is that “imagining the placement of objects is easy because the size of the virtual shape is the same as the physical shape”, and one common weakness of Shape-stamping is that it sometimes cannot recognize the base markers as the primitive shape is relatively large. One common strength of Daichi-tools is that the users liked the cutting tool, and one common weakness of Daichi-tools is that it is difficult to create objects touching the floor or wall because there is a gap between real objects and the move tool that the users have to hold. Finally, we asked the users if there were other objects they would like to model with these systems, and the objects they mentioned include: TV stand, packaging box, chair, table, and book stand.

## DISCUSSION, LIMITATIONS, AND FUTURE WORK

We intend to expand the number of primitive shapes and tools in our current system, which should lead to an even larger variety of possible products. We currently only have the ability to add virtual shapes. It would be useful to remove or subtract existing virtual shapes, with a tool that performs “negative”-stamping. In addition, we can have tools for adding colors and textures. We can also interactively show the dimensions of the virtual shapes, although the exact dimensions are less important since we can “measure” the shapes with the environment (i.e. the exact length of a table is not important as long as it fits the environment).

One potential issue is how to create virtual shapes of different sizes (for the same primitive shape). We choose to not allow the operation of scaling a virtual shape with respect to the physical one before stamping it. The reason is that the scaled virtual shape would have a different size and hence cannot directly interact with the existing environment. Our current solution is to have one physical tool for each size and shape. However, if the user wants to have a large number of sizes of the same shape, a better solution is needed.

Our system is designed to produce 3D models that are well-defined as the models are created with primitive shapes. While our current interaction techniques can produce objects with some curved shapes, extending them to more general cases is a possibility for future work.

Our two-handed stamping interaction is currently not implemented for the curved tube-like shape (in Figure 4b for example) and other similar curved cases as the interaction can be ambiguous. However, it is possible to “match” sections of the virtual shape with the physical one. For the curved tube-like shape for example, each tube section of the virtual shape can be matched with the physical cylinder. As the radius of the virtual and physical cylinders are the same, we can still “match” these shapes and have a special case of two-handed stamping for these kinds of curved cases.

We cannot currently add details to the virtual models. Our system is good for rapid prototyping, testing, and visualizing of different designs of products in the actual environment that they will be used in. However, it can be useful to move to more traditional CAD software afterwards to create more detailed designs.

Some of our virtual models cannot easily be built with primitive shapes. For example, the set of discrete cylinders forming the bench needs to be connected in some way if it were to be built. Another example is the curved tube-like shape which cannot be built with wooden primitive shapes, as the curved shape is not comprised of regular primitives. More generally, our interface allows for the intersection of primitives. While we simply take the union of these shapes in the virtual world, special carving of real pieces may be needed to build the object in the real world. It is our future goal to resolve all these issues and to support the creation of such real objects. We may do so by automatically indicating to the user what individual pieces are needed, how they need

to be cut or carved, and how they can be connected together. We can even incorporate such instructions into a set of assembly instructions [1] for the end-user.

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