

A Motion-guided Interface for Modeling 3D Multi-functional Furniture

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Abstract

While non-expert 3D design systems are helpful for performing conceptual design, most existing works focused on modeling static objects. However, the 3D modeling interfaces can include more interactions between the user and the models that are dynamic (and can be interacted with). In this paper, we propose a 3D modeling system for the conceptual design of interactable multi-functional furniture. Our contribution is in the design and development of a motion-guided interface. The key idea is that users should create interactable furniture components as if they are interacting with them with their hands. We conducted a preliminary user study to explore users' preferred hand gestures for creating various dynamic furniture components, implemented a 3D modeling system with the preferred gestures as a basis for the motion-guided user interface, and conducted an evaluation user study to demonstrate that our user interface is user-friendly and efficient for novice designers to perform conceptual furniture designs.

CCS Concepts

- Computing methodologies → Shape modeling; • Human-centered computing → Gestural input;

1. Introduction

3D modeling plays a significant role in conceptual design. While commercial computer-aided design (CAD) software with complex user interfaces are helpful for experts to create precise models in the final phases of design, there already exists many non-expert 3D design systems [IMT99, OJGD06, SLM11, NGDA*16] which are helpful to novices for modeling their conceptual designs effectively and intuitively. Most of those works focused on modeling static objects (which remain still during user interaction) and ignored dynamic objects (which have multiple poses during user interaction). However, their 3D modeling interfaces could include more interactions between the user and the models that are dynamic. Figure 1(d) shows an example of a cabinet model that is modeled with our system and consists of multiple poses that can be interacted with. For this cabinet, note that the door at the upper-right corner can swing open, the door at the bottom-left corner can be folded down, and the door at the bottom can slide open. The interactions with these types of components and their corresponding 3D modeling operations help the user to visualize and model their expected functions (e.g. how the doors open) during the conceptual design stage [LACS08, LOMI11].

In this paper, we propose a 3D modeling system for the conceptual design of interactable multi-functional furniture. Our key contribution is in the design and development of a “motion-guided” user interface. Our interface helps novice users with little or no previous experiences in 3D modeling to create personalized 3D furni-

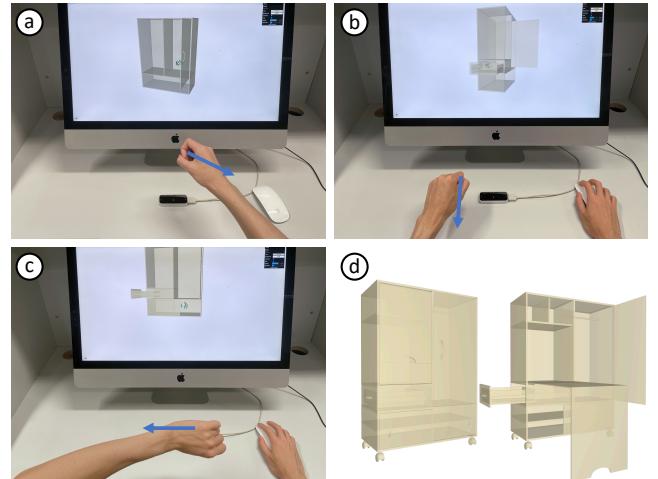


Figure 1: Modeling a cabinet with our system: (a) grab and pull along the arrow to create a right swing door, (b) pull out along the arrow to create a drawer, (c) grab and slide along the arrow to create a sliding door, (d) the completed furniture design in compressed state (left) and expanded state (right).

ture models with modeling operations that are related to the interactable components that are being modeled. The key idea of our “motion-guided” interface is that in order to create furniture with

the interactable or dynamic components, users should perform 3D modeling operations as if they are interacting with the furniture components with their hands. For example, to create a cabinet door that swings open, they use their arms and hands to perform a swinging motion (Figure 1(a)) as if they are opening a door in empty space. Our system recognizes the motion and automatically creates a virtual door fitted in front of an existing and partially completed virtual 3D model. Similarly, users can perform a “pull out” motion to create a drawer (Figure 1(b)) or a “slide open” motion to create a sliding door (Figure 1(c)).

We follow a user-oriented approach [WMW09, WLK^{*}14] to design and implement our system. First, we conducted a preliminary user study to explore the users’ preferred hand motions or gestures for creating various furniture components. We then implemented a 3D modeling system with the preferred gestures as a basis for the motion-guided user interface. Finally, we conducted an evaluation user study to demonstrate that our user interface is user-friendly and useful for novice users to perform conceptual furniture design.

Users showed high agreement in the ease, memorability and efficiency of our interface in the final evaluation user study. Our interface is easy to remember because users just perform gestures or motions as if they were interacting with dynamic components (e.g. doors, drawers, wheels, etc.), or depicting the surfaces of the static components (e.g. planks, legs, etc.). It is also efficient and it saves users from performing the complex 3D modeling operations usually needed in traditional 3D modeling interfaces. For example, in our cabinet in Figure 1(d), the user would simply perform the natural hand gestures that correspond with how they would interact with the cabinet (e.g. opening, folding, or sliding the door) to model the more complex parts of the overall cabinet shape.

2. Related Work

There exist previous works that explore the motion-guided concept in various ways and related works in the areas of hand gestural interfaces for 3D modeling, and 3D modeling systems and interfaces for novices. We review these works below.

2.1. Motion-Guided Concept

The motion-guided concept is a generic idea. Here we focus on the works involving the integration of user motions into the 3D modeling and animation process, and the works that create 3D models with dynamic parts.

Several works incorporate user motions as part of the 3D modeling user interface. BodyAvatar [ZHR^{*}13] made avatar modifications based on the user’s body motions. They used the user body as a physical proxy of the virtual avatar, but did not explore how users can naturally interact with the 3D model being created. Lee et al.’s works [LCMS16, LSBS18] are closely related to our work. They took user interactions with a desk as input to design parametric desks. However, they only explored interactions for static components such as planks or keyboard, but ignored dynamic components such as doors, drop-leaf tables or wheels. Besides modeling, widget motions [DYP03] or finger motions [LS12] have been used in creating and editing full-body animations, and hand motions have been used to specify and manipulate animations of physical phenomena [AKK^{*}19]. Different from these works which aimed to

author animations by users’ motions, our work explores users’ interactions with the components to be modeled and the animations are the result of the interactions.

Some previous works create 3D models consisting of dynamic parts (or multiple-poses). Most of them [ZXS^{*}12, XLX^{*}16] focused on creating specific types of mechanical assemblies with dynamic parts. Another previous work (ChronoFab [KGM^{*}16]) developed a 3D modeling tool to craft sculptures that aimed to visualize the physical motions of animated creatures. Our work also create dynamic objects, but we focus on the user’s motions that naturally correspond to the motions of the dynamic furniture components being modeled, and use them as the key idea to develop a natural user interface for 3D modeling.

2.2. Hand Gestural Interfaces for 3D Modeling

There are many previous works on hand gestural interfaces. We focus on reviewing those related to having hand gestures or natural user interactions as part of the user interface for 3D modeling.

The user’s hands can effectively perform modeling operations in various ways. The usual CAD mouse operations such as object manipulation and camera navigation can be replaced by hands with predefined gestures [WPP11]. Similar types of hand gestures can also be applied to manipulate and create objects in virtual environments [KAHF05], augmented reality [ATOGCM15] and mix reality [WLK^{*}14] environments. Another intuitive usage of hands in 3D modeling is for geometric deformations. Free-form deformations can be performed by hand dragging and twisting [LKG^{*}03, CS17], hand-based sculpting [SBS06] or using hand-based constraints [Ram15]. Besides the bare hand operations, ToolDevice [ATO^{*}12] used hands and physical tools that imitate real-life woodworking tools to build virtual models. Hands are often used to help people describe shapes. Previous works model the shape from palm drawing [SPS01], primitive-based drawing [LHO^{*}12], finger sketching [WLK^{*}14, HR18, JZF^{*}21], or motion tracking [HW11]. Instead of using hands to construct a shape directly, captured hand information [KB16] or hand-drawn scaffolds [KALB18] were used for 3D conceptual sketching.

Although the above previous works utilized gestures or hand motions in various ways, none of them studied how people can use hands to describe multi-pose dynamic furniture components, and none of them used the user’s motions as a natural and convenient interaction method to create the components of a 3D furniture model.

2.3. 3D Modeling Systems for Novices

There exist previous works that support novices in creating 3D shapes. For the purpose of making modeling as easy as drawing, sketches are widely used to create 3D curves or surfaces. Since 2D sketches are ambiguous in depth, existing methods use inflation [IMT99, NISA07], prior-based inference such as constraining the objects to specific classes [WBCG09, SLM11], context information [LSMI10, ZLDM16], or data-driven training [DAI^{*}18, NGDA^{*}16] to fill in the missing data. In contrast, our natural user interface is not affected by depth ambiguity as users can visualize the tracked hand skeleton on the screen. Hence users can move their real world hand position to adjust the relative 3D position between the virtual hand skeleton and the 3D model being created.

Modeling by Example [FKS^{*}04] is another way to help novice

users to create models efficiently. To combine the parts of different shapes, shape deformations [XZCOC12] or predefined parameterized primitives [SSL*14] are needed. Our work also uses the concept of modeling with parameterized primitives, where our primitives can be static or dynamic furniture components. However, we focus on developing a natural user interface where users can incorporate natural hand gestures as part of the modeling operations to create these parameterized primitives.

3. User Study: User-defined 3D Modeling Gestures

We are inspired by previous works that take an elicitation of user gestures approach [WLK*14, WMW09]. To improve the intuitiveness of our modeling interface, we conducted a preliminary user study to elicit the gestures and motions that users prefer to use when they are performing certain 3D modeling operations.

3.1. Tasks and Procedure

We conducted the user-defined gesture study with a methodology similar to MixFab [WLK*14]. Twelve participants (six were female) from various departments at our university were invited. Their ages range from 22 to 28 ($M=25.67$ years, $SD=1.72$) and most of them had little CAD experience. The whole process took about 25 minutes.

Each participant was given three parts of tasks. For the first part, they were shown videos with a simple (or unfinished) cabinet or table, and then an additional dynamic furniture component first appeared in a compressed state and then gradually moved to its expanded state (e.g. a closed door appeared at the front of the cabinet and then it opened). Participants were asked to imagine that the initial (or unfinished) cabinet or table is placed in front of them and to perform hand actions to create the dynamic component. For the second part, participants were shown videos with a simple (or unfinished) cabinet or table, and then an additional static furniture component appeared (e.g. a horizontal plank appeared inside the cabinet). Similarly, the participants were asked to perform hand actions to create the static furniture part. For the third part, participants were shown videos which displayed various CAD operations (e.g. translating or scaling an object), and then they were asked to perform hand motions to perform each operation. During these three parts, participants were told that the same gesture could be used in more than one task. All the user gestures were recorded by a camera.

After each gesture, users were asked to fill a questionnaire to rate the gestures' suitability for the corresponding task and how easy it was to perform on a rating scale from 1 (very unsuitable / very hard) to 5 (very suitable / very easy). After all the tasks were finished, participants were further asked about their prior CAD experience and how much that experience influenced the proposed gestures (rating scale, 1 no experience / no influence to 5 a lot of experience / strong influence). Since most participants had little CAD experience ($M=1.75$, $SD=0.75$), the rating of the influence of prior experience ($M=2.00$, $SD=1.13$) was low.

After we finished the user study, we manually extracted and classified the participants' motion gestures guided by the taxonomy of gestures [WMW09] with additional physical characteristics. Specifically, for each task, we first grouped the collected gestures

from "form dimension" defined by Wobbrock et al. [WMW09], and then further subdivided the gestures by hand pose, palm orientation and trajectory. Second, following "nature dimension" [WMW09], for each task, we summarized explanatory descriptions for its grouped gestures. Quantitative data collected through the questionnaires, as well as the amount of user agreement among their gestures were used to judge the quality and confidence of the users' gestures.

3.2. Results and Observations

All of the participants proposed a desired gesture or motion for each task. Here we report the gestures or motions that were proposed by two or more participants.

3.2.1. Creating Dynamic Components

Table 1 shows each task given to the users for creating dynamic components, and the corresponding users' gestures and some statistics from the preliminary user study. It shows that users tend to create these dynamic or interactable components by gestures/motions representing how they use those components.

3.2.1.1. swing door & sliding door. Participants showed relatively high agreement for creating a left/right swing door and a double swing door (Figure 2), and most of them proposed a "opening" motion. For the task of creating a sliding door, seven out of the twelve users kept performing a grabbing and pulling motion, and five users chose to use a flat palm to indicate a sliding motion to open the door.

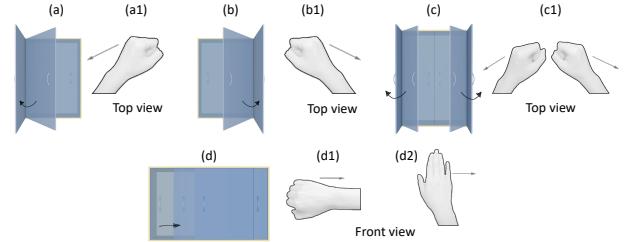


Figure 2: (a) left swing door, (b) right swing door, (c) double swing door; (d) sliding door; (a1)-(d2) the corresponding motions proposed by the participants. See Table 1 for more details.

3.2.1.2. drawer/shelf. For the drawer/shelf with a horizontal handle, eleven out of twelve participants performed a pull-out motion as if to open it to "create" it. Five of them pulled out the drawer with the palm facing downward and six of them with the palm facing upward. Higher agreement was achieved in the task of drawer/shelf with a vertical handle. Eleven participants pulled out the drawer/shelf with their palms facing sideward (Figure 3).

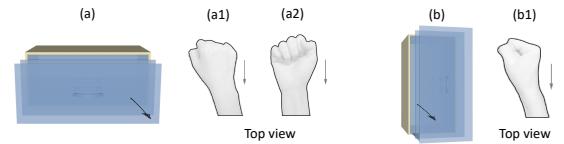


Figure 3: (a) drawer/shelf (horizontal handle), (b) drawer/shelf (vertical handle), (a1-2) & (b1) the corresponding motions proposed by the participants. See Table 1 for more details.

Table 1: List of tasks and the corresponding hand gestures/motions (proposed by two or more users) during the preliminary user study. *c* is the count of how many users suggested the gesture, *s* is the reported suitability and *e* is the reported ease. *A* is the agreement among the users as defined by Wobbrock et al. [WMW09]. Chosen gestures are written in italic.

Task / Gesture	c	s	e/A
left swing door			0.58
<i>left hand opens the door</i>	9	4.44	4.89
right swing door			0.71
<i>right hand opens the door</i>	10	4.80	5.0
double swing door			0.71
<i>2h open the door</i>	10	4.80	4.80
sliding door			0.51
<i>1h grabs & pulls aside</i>	7	4.86	4.86
<i>1h spreads & swipes</i>	5	4.60	4.60
drop-down door			0.39
<i>1h grabs & pulls down (palm ↓)</i>	7	4.43	4.27
<i>1h grabs & pulls down (palm ↑)</i>	2	4.5	5.0
fold-down desk			0.18
<i>1h grabs & pulls down (palm ↓)</i>	3	4.00	4.33
<i>1h grabs & pulls down (palm ↑)</i>	2	5.00	4.50
<i>2h grab & pull down</i>	3	3.67	4.67
shoe cabinet			0.47
<i>1h grabs & pulls down (palm ↓)</i>	8	4.38	4.50
drawer/shelf (horizontal)			0.43
<i>1h pulls out (palm ↑)</i>	6	4.50	4.83
<i>1h pulls out (palm ↓)</i>	5	4.80	5.00
drawer/shelf (vertical)			0.85
<i>1h pulls out (palm sideward)</i>	11	4.55	4.64
wheels			0.19
<i>2h hold cabinet & rotate</i>	2	4.50	5.00
<i>2h rotate wheels</i>	4	3.25	3.50
<i>1h rotates wheels</i>	2	3.50	3.50
drop-leaf			0.28
<i>1h grabs & flips up</i>	3	4.67	5.00
<i>1h spreads & lifts up</i>	8	4.38	4.50
keyboard tray			0.28
<i>1h grabs & pulls out</i>	5	4.40	5.00
<i>2h spread & slide out</i>	2	4.50	4.50
<i>2h grab & pull out</i>	3	4.33	4.67

Creating Dynamic Components

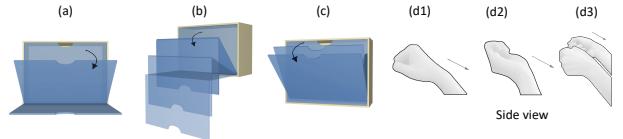


Figure 4: (a) drop-down door, (b) fold-down desk, (c) shoe cabinet, (d1)-(d3) the corresponding motions proposed by the participants. See Table 1 for more details.

3.2.1.4. wheels. The agreement among the user gestures for creating wheels is low. Four participants proposed their own unique motions. The others performed motions that can be generalized into three types (Figure 5). First, two participants performed motions to hold the cabinet with two hands and rotate it. Second, four participants performed motions to rotate the wheels with two hands. Third, two participants performed motions to rotate the wheel with one hand.

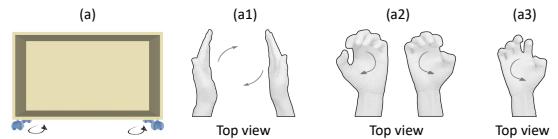


Figure 5: (a) wheels, (a1)-(a3) the corresponding motions proposed by the participants. See Table 1 for more details.

3.2.1.5. keyboard tray. Users performed three types of gestures to create a keyboard tray (Figure 6): one-handed grabbing and pulling out (five users), two-handed grabbing and pulling out (three users), and two-handed sliding out with flat palms (two users). All of these gestures were performed with the palms facing upward.

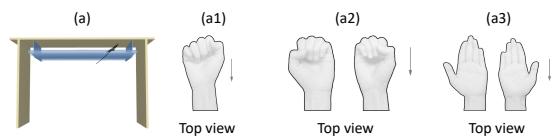


Figure 6: (a) keyboard tray, (a1)-(a3) the corresponding motions proposed by the participants. See Table 1 for more details.

3.2.1.6. drop-leaf. For the task of creating a drop-leaf plank for the table, participants mainly showed two ways of natural interaction (Figure 7). Three users proposed the motion of grabbing the plank and flipping it up along its intended flipping direction, while eight users proposed to use a flat palm to perform a motion to “lift up” the drop-leaf plank.

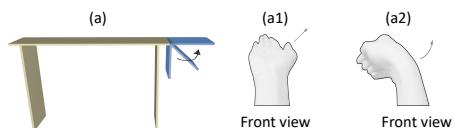


Figure 7: (a) drop-leaf, (a1)-(a2) the corresponding motions proposed by the participants. See Table 1 for more details.

3.2.2. Creating Static Components

As a complete piece of furniture can be composed of both dynamic and static components, we also explored how users created static components. Table 2 shows that users tend to create the static components by using their palms to “draw” along the imaginary surfaces of the components.

Table 2: List of tasks and the corresponding hand gestures/motions (proposed by two or more users) during the preliminary user study. Notations are the same with Table 1.

Task / Gesture	c	s	e/A
horizontal plank			0.42
2h spread & swipe horizontally	3	4.3	4.67
1h spreads & swipes horizontally	7	4.57	4.71
vertical plank			0.58
1h spreads & swipes vertically	9	4.44	4.89
two parallel vertical planks			0.71
2h spread & swipe vertically	10	4.20	4.60
clothes rail			0.50
1h grips & moves horizontally	8	4.63	4.63
2h grip & move away horizontally	2	5.00	5.00
2h pinch & move away horizontally	2	5.00	5.00
legs			0.58
2h grip & draw legs	9	4.11	4.33
ladder			0.17
1h grips & draws "z"	4	4.00	4.75
translate			0.31
1h grabs & moves	5	4.20	4.60
1h spreads & moves	3	4.00	4.67
pointing & moves	3	4.67	4.67
scale			0.48
2h spread & stretch	2	5.00	5.00
2h grab & stretch	8	4.25	4.63
delete object			0.18
1h grabs and then throws	3	5.00	5.00
1h spreads & swipes outward	3	3.67	4.67
pointing & swipes outward	2	4.00	5.00
change candidate			0.29
1h spreads & swipes vertically	4	5.00	4.75
pointing & swipes vertically	3	4.75	4.5
click with index finger	3	5.00	5.00
pan			0.21
1h spreads & moves camera	3	4.33	5.00
1h spreads & moves scene	3	3.33	4.67
1h grabs & moves camera	3	3.67	4.33
rotate			0.17
1h holds & rotates	2	5.00	5.00
2h hold & rotate	4	4.25	4.25
zoom			0.26
1h opens	5	5.00	4.80
2h spread & stretch	3	4.33	4.67

3.2.2.1. plank(s) Users generally proposed to spread their flat hand(s) and swipe along the direction of the intended plank surface to “create” the plank(s) (Figure 8). For the creation of one horizontal plank, seven out of twelve users used one hand and three users used two hands. For one vertical plank, nine users used one hand, while for two parallel vertical planks, ten users used two hands.

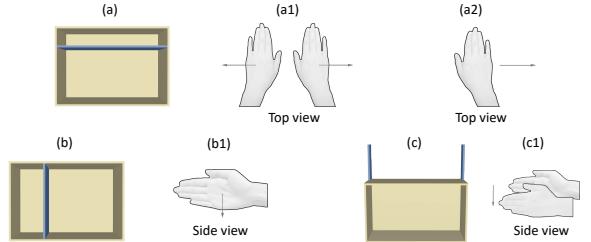


Figure 8: (a) horizontal plank, (b) vertical plank, (c) two parallel vertical planks, (a1)-(c1) the corresponding motions proposed by the participants. See Table 2 for more details.

3.2.2.2. clothes rail, legs, ladder For the task of creating clothes rail and legs, users proposed to grip the imagined object and move along its surface (Figure 9). Users proposed three gestures for creating clothes rail: one-handed gripping, two-handed gripping and two-handed pinching. In the case of legs, users used two hands as if they were gripping the legs and moved downwards to draw them.

Since the ladder is a relatively more complex shape, we have asked users to use relatively simpler gestures and motions to create it. Eight out of twelve users proposed their own unique gestures. Four users proposed a similar gesture: gripping a horizontal rung and then repeatedly moving in a “z”-like pattern.

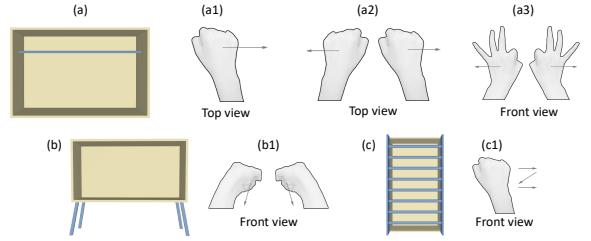


Figure 9: (a) clothes rail, (b) legs, (c) ladder, (a1)-(c1) the corresponding motions proposed by the participants. See Table 2 for more details.

3.2.3. Object Manipulations

Object manipulations are some basic operations (e.g. translate) of a 3D modeling system, and we also explored how users performed these operations. The tasks (in this category) given to the users, the corresponding gestures from the users, and some statistics from the preliminary user study are listed in the middle of Table 2.

3.2.3.1. translate Users proposed the same basic type of motions to perform a moving motion to “translate” or move the object to be moved (Figure 10). The specific gestures were a bit different, but of three main types: three users proposed to grab the object with one hand, five users proposed to spread one hand (and keep it flat), and three users made an “index finger pointing” gesture.

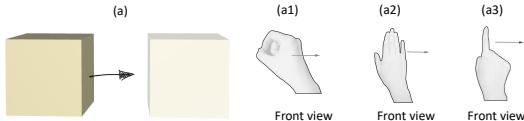


Figure 10: (a) a cube is translated along the arrow, (b1)-(b3) the corresponding motions proposed by the participants. See Table 2 for more details.

3.2.3.2. scale Users tended to use both hands for the scaling task (Figure 11). Two users spread their hands with palms facing each other and then stretched the two hands outwards/inwards to scale the shape. Eight users grabbed the object and then stretched the two hands outwards/inwards to scale the shape.

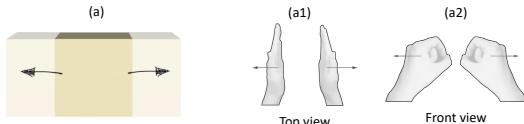


Figure 11: (a) a cube is stretched along the arrow, (b1)-(b2) the corresponding motions proposed by the participants. See Table 2 for more details.

3.2.3.3. delete object & change candidate Users proposed three main ways to delete or remove an object (Figure 12). First, three users performed a grabbing motion with one hand as if to grab the object and then made a throwing motion as if to throw it away. Second, three users spread one hand and performed a swiping outward motion as if to swipe the object away. Third, two users did a “index finger pointing” gesture with a finger and performed a swiping outward motion as if to swipe the object away.

The task of “change candidate” means that there are multiple candidates that users can choose from, and the users were asked to perform gestures/motions to change to another candidate. Three users clicked the candidate directly with the index finger and seven users swiped vertically as if they scrolled the screen. Four of the latter swiped with a spread hand and the other three made a “index finger pointing” gesture and swiped.

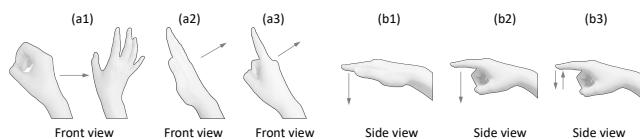


Figure 12: (a1)-(a3): gestures proposed by the participants to “delete object”; (b1)-(b3): gestures proposed by the participants to “change candidate”. See Table 2 for more details.

3.2.4. Camera Navigation

The bottom of Table 2 shows the tasks of camera navigation, the corresponding user gestures and some statistics from the preliminary user study. Users made a variety of gestures/motions to perform camera panning, rotating and zooming, and this led to relatively low agreement of the gestures among the users. In this section, we do not show the corresponding figures as in the above sections, as it should be obvious for the reader given the descriptions in the previous tables and the previous figures.

3.3. Discussion

Similar to the observed patterns in Wobbrock et al. [WMW09] and Weichel et al. [WLK*14], we observe that the suitability and ease values are reasonably high and user agreement tends to be inversely proportional to the task complexity. For example, creating a ladder and wheels are more complex tasks, and they have relatively lower agreement among users. On the other hand, creating planks and swing doors are simpler tasks, and they have relatively higher agreement among users. Although the agreement varies, similar to the previous works, we find users tend to depict the shape to create static components. Moreover, we find users tend to perform motions representing how they interact with the object to create dynamic components, which was not explored in the previous works. For example, to create wheels for a cabinet, users rotated the wheels with one or two hands, or rotated the cabinet with two hands. The specific motions are different, but they all indicate how users would interact with the wheels.

From the results of our preliminary user study, we chose an appropriate gesture for each task except for camera navigation. We do so with the count of how often a gesture was proposed as the main criteria, after excluding gestures with ease lower than 3.6. In some cases where the suggestion count is not distinctive, we also looked at the suitability and ease ratings. For wheel, although the gesture “2h rotate wheels” was proposed by 4 users, its ease is 3.5. Therefore, “2h rotate wheels” was excluded, and we chose “2h hold cabinet & rotate”. For “delete object”, because it’s hard to distinguish between “1h grabs and then throws” and “1h grabs & moves” (which was assigned to “translate”), we chose “1h spreads & swipe”. The evaluation in Section 6.2.1 shows that these choices do not affect the user experience. Our chosen gesture for each task is written in italic in the results in Tables 1 and 2. For the task of camera navigation, we discuss it in the next section.

4. User Interface

The users of our system mostly use our motion-guided 3D modeling interface by performing hand motions with their arms and hands on top of a Leap Motion Controller (LMC), while they visualize the virtual results on a PC screen (Figure 1).

Users can use our chosen gestures to create dynamic and static furniture components. For object manipulations, we allow for both gestures and mouse input, and the users can use either of them according to their preference and efficiency. For camera navigation, we decided to not use the users’ gestures but to use the mouse input for the following reasons. First, the low agreement for the “camera navigation” gestures means that we cannot find a consistent and intuitive gesture for most users. Second, the mouse input is superior to gestures in terms of precision. In addition, it was efficient for the users to use one hand to perform the gestures and the other hand to control the mouse.

4.1. Object Manipulations

To keep the feasibility of our created furniture like those in “Design by Example” [SSL*14], only reasonable translating and scaling are allowed. When the object is selected by mouse click or finger tap, its color will turn red and the opacity of the other parts will turn to 0.5, while the axes along which the object can be manipulated will be shown (Figure 13(c)). Users can translate or scale the object with

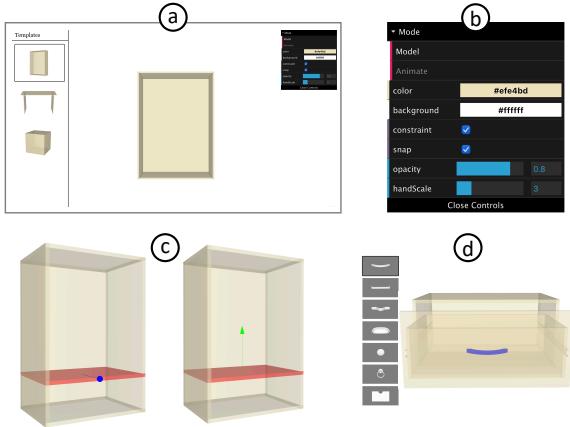


Figure 13: (a) overall user interface (with initial templates on the left); (b) right panel to control the basic settings; (c) a plank is selected to be scaled (left) or translated (right); (d) a handle is selected to be changed (the candidates are shown in the left column).

corresponding gestures or dragging the shown axes with the mouse like most CAD software. To improve efficiency, objects that can be translated will be selected automatically as soon as they are created, and be deselected after 3 seconds of inactivity or by clicking the blank area.

4.2. Left Panel

On the left side of the screen, there is a panel with shapes or components for the users to choose from. At the start of a modeling session, the left panel shows a few simple template shapes that users can choose from to start with (Figures 13(a) and 14(a)). These are intended to be simple and basic shapes from which the users can start with. Users can choose one of these shapes, change its size and delete its sub-planks for more flexible modeling. Then the left panel will be hidden. During the subsequent modeling, for the cases that a user gesture corresponds to more than one possible component (for example, in Figure 14(e), a drop-down door, fold-down desk, or shoe cabinet all correspond to a similar “pull down” gesture), the left panel will appear with the list of possible candidate components, and users can perform the “change candidate” gesture to choose one of them. To achieve some diversity, some components such as handles or legs can also have several candidates. When the component to be changed is selected by double mouse clicks or double finger taps, its color will turn blue and the opacity of the other parts will turn to 0.5. The left panel will appear to show the list of possible candidates for substitution (Figure 13(d)).

4.3. Right Panel

On the right side of the screen, there is a panel with options that the user can choose from (Figure 13(b)) with the mouse. These include: choosing an animation mode where the user can click to close/open the expanded/compressed components, choosing the 3D model’s color or the background’s color, the current component’s ability to snap/align to the existing model, the current component’s ability to be constrained by its neighbors (e.g. Figure 13(c), the middle plank cannot be moved higher than the top plank or lower than the bottom plank), the current model’s opacity value, and the relative scale of the virtual hand skeleton.

4.4. Walkthrough: Constructing a Cabinet

We demonstrate our system’s usage by illustrating the steps of constructing an example cabinet model (Figure 14).

First, we choose a basic template shape from the ones in the left panel (Figure 14(a)), and scale it to the desired size. To add a horizontal plank, we move our flat palm along the arrow (Figure 14(b)). Then the newly generated plank will be selected automatically and we can grab it to translate it along the shown axis (i.e. the green Y-axis in Figure 14(c)). Next we perform a gesture of pulling out a drawer to create a drawer at the left corner of the cabinet (Figure 14(d)). For the right corner (Figure 14(e)), we perform a gesture of one hand grabbing and pulling down. As this gesture matches with multiple possible components, the left panel then shows the possible candidates. The user then swipes up to choose the shoe cabinet from the candidates (Figure 14(e)). Then for the top part of the cabinet, we perform a grab and slide gesture to construct a sliding door (Figure 14(f)). We then use two hands to perform the gesture of opening a double-door to create it in the middle part of the cabinet (Figure 14(g)). To make it a wardrobe, we move the fist horizontally to add a clothes rail (Figure 14(h)). Finally, in order to increase the moving flexibility of the cabinet, we make the gesture of rotating with both hands to add wheels to the bottom of the cabinet (Figure 14(i)). During modeling, the dynamic components are automatically opened (to their expanded states). We can change the mode to the animation mode, click to close the expanded components, and obtain the cabinet model in a “compressed” state shown in Figure 14(j).

5. System Implementation

We built our modeling system in a desktop environment with a Leap Motion Controller. Our interface was implemented in JavaScript using the Leap Motion SDK and Three.js library.

5.1. Gesture/Motion Recognition

From the observations of our preliminary user study, we found that users tend to perform 3D modeling operations as if they are naturally interacting with the furniture objects when creating dynamic furniture components, and use flat palms or fists to describe the shapes when creating static furniture components. Additionally, rather than using various complex hand gestures, users were likely to use different motion trajectories with the same natural hand pose to create different components.

Based on these observations, we focus more on the hands’ orientations and trajectories. We classify the valid gestures of a single hand given by the participants roughly into three poses according their fingers’ extension states (similar poses are used in Magical-Hands [AKK*19] for animation):

- Pose 1: All five fingers are extended.
- Pose 2: All five fingers are not extended.
- Pose 3: The index finger is extended while the others are not

At frame i , we obtained the hands’ skeleton from the tracking sensor with the palm normal, hand velocity, finger extension states and finger velocity. With this information, we classify the state of frame i to a gesture (those in Tables 1 and 2) or invalid motion. The classification method will be described in the next paragraph. For every continuous N frames, if some state repeats over N_m times,

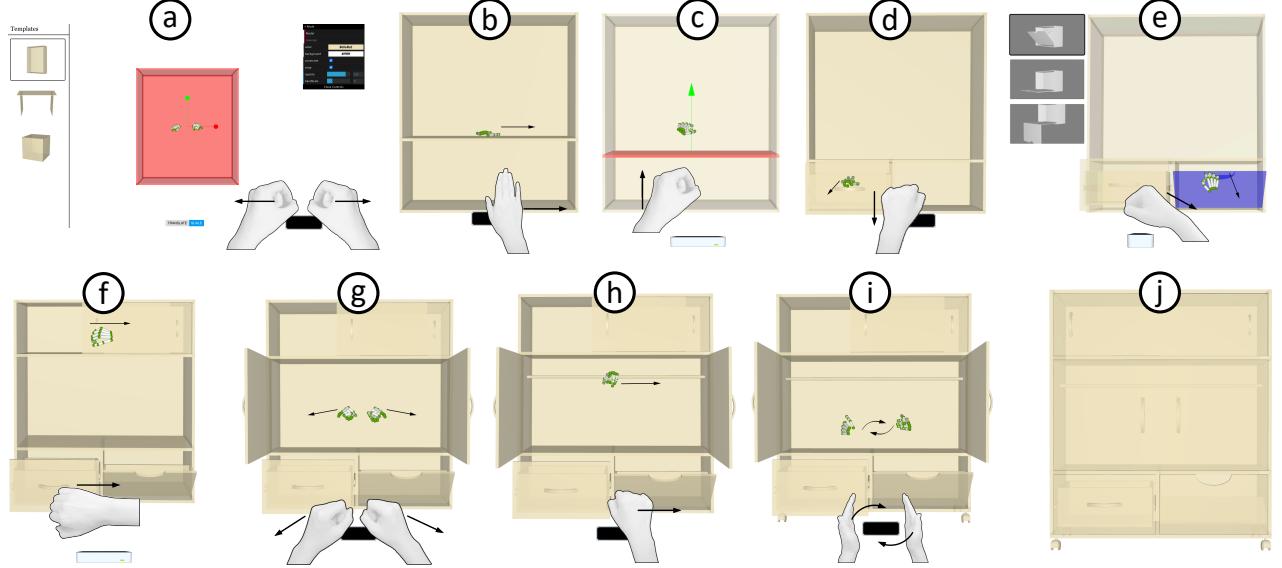


Figure 14: Walkthrough: We illustrate the steps of constructing an example 3D cabinet model with our system. The icons of the hands and Leap Motion Controller under each image correspond to the actions in the real world. See the text for the detailed descriptions of each step.

the gesture will be recognized and its corresponding task will be conducted. Taking sensitivity and accuracy into consideration, we set $N = 20$ and $N_m = 15$ after our own trials with the system. We also set a throttle time of 2 seconds to avoid redundant recognition.

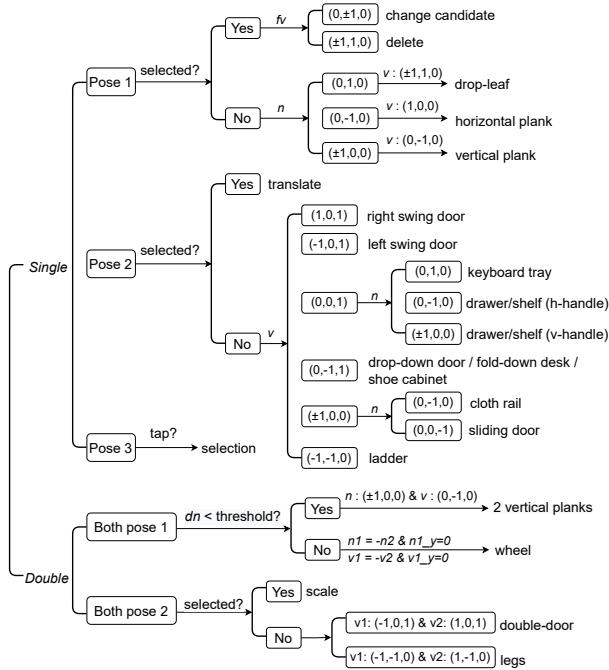


Figure 15: Enumerations of hand poses, hand velocity (v), palm normal (n), finger velocity (fv), palm normal difference (dn) between adjacent frames, and its corresponding task. Cases not included correspond to invalid gestures.

To recognize which gesture the user is performing at frame i , we first enumerate the cases according to the number of valid hands. The following discussion is based on LMC, which uses a right-handed coordinate system with +Y up. For a single valid hand, we check whether the gesture belongs to the predefined poses 1-3. If not, the motion state for this frame is invalid. If the gesture is classified into pose 3, we check for the “tap” operation, which means hand velocity $\|v\| < v_{min}$ and index finger’s velocity $\|v_f\| > v_{max}$ (we set $v_{min} = 50$ mm/s and $v_{max} = 100$ mm/s). If the gesture is classified into pose 1 or 2, we check if some model component is being selected. If so, we next check if the motion meets the requirements for object manipulation or component changing. For example, for pose 1, we check the velocity direction of the index finger. If the moving direction is close to $(0, \pm 1, 0)$, it is changing component. If it is close to $(\pm 1, 1, 0)$, it is deleting the selected object. If the gesture is classified into pose 1 or 2 but no object is being selected, then we check if it meets the requirements for creating some component. Also taking pose 1 as an example, first we check whether the hand normal is close to the direction of $(0, 1, 0)$, $(0, -1, 0)$ or $(\pm 1, 0, 0)$ and then check the velocity direction for the tasks of creating drop-leaf, horizontal plank, or vertical plank. All the enumerations (including the cases for two valid hands) and crucial requirements are listed in Figure 15. Cases which are out of the requirements correspond to an invalid gesture. To increase the flexibility of gesture recognition, we set a threshold of 20° for normal direction checking. Furthermore, to lower the probability of false recognition, we set a speed threshold of 200 mm/s to ignore small hand movements.

5.2. Furniture Components

We prepared 3D furniture components for users to create them in our system. These components were predefined with the combina-

tion of the basic geometric primitives from the Three.js library. The size of each component type depended on its parameters such as width, height and depth, and the structural arrangement for its sub-components (e.g. the relative position and orientation of the basic primitives like planks and cylinders to the whole component) are predefined. The thickness of the planks was set as a constant and it was not changed when the size of the component was changed. For multi-pose components, their parameters for “expansion” such as translation direction and distance, or rotation axis and angle are also predefined. In addition, as our system conducts auto-composition of the new component and the existing model, we only allow feasible translating and scaling. For example, the plank can only move along its normal direction. Therefore, additional parameters for the manipulation availability in the x,y and z-axes are also predefined for each component.

5.3. Auto-Composition

Our system automatically fits the new furniture component to the current 3D model according to the user’s hand position and camera direction. This automatic procedure avoids time-consuming tasks such as scaling, rotating and aligning.

We use a binary tree structure to store the spatial information of the model. The leaf nodes of this binary tree are the “spare compartments” that can be further assigned components. The user starts with the provided basic template (such as an unfinished cabinet, table and a box) and its corresponding predefined “spare compartments”. With each recognized hand gesture, we find the leaf nodes that contain the hand(s) in the 2D rendered scene. If more than one leaf nodes are found, we choose the one that contains the hand(s) in the 3D scene or the one closest to the camera if no leaf node contains the hand(s) in 3D space.

The corresponding parameterized component we defined in Section 5.2 will be rotated but kept axes-parallel according to the direction of the camera. Its parameters and position will be set from the found leaf node and hands’ position. The “spare compartment” will be divided into two leaf nodes, be deleted, be updated, or be replaced with the new “spare compartment” according to the category of the newly added component.

6. User Study: System Evaluation

To evaluate the usability, efficiency and intuition of our modeling interface, we invited twelve participants (6 females) from our university for the user study. Two of the participants had some experience with CAD systems and the other ten had a little or no CAD experience (rating scale, 1 no experience to 5 a lot of experience, $M=1.83$, $SD=1.11$). Moreover, four of the users had a lot of Leap Motion experience and the other eight had never used Leap Motion (rating scale, 1 no experience to 5 a lot of experience, $M=2.08$, $SD=1.62$). The total session time was between 55 and 70 minutes.

6.1. Tasks and Procedure

6.1.1. Teaching Stage

First, we demonstrated our idea of using hand gestures to create 3D furniture models. Then we displayed the usage of the LMC and emphasized the space range where hands can be tracked by the LMC. We then showed the hand gestures for each specific task

with the LMC and users could see the hand skeleton tracked by the LMC on the screen. During the teaching stage, to help users remember and comprehend better, we told them the design principle of hand gestures for creating dynamic components is to imagine how they would interact with the components, and the design principle of hand gestures for creating static components is to depict the shapes. Then users were asked to perform the hand gestures freely upon the LMC and made sure that their hands can be tracked well. After users were able to use the LMC, we showed them the basic usage of our system with the “cabinet construction” walkthrough (Figure 14). After that, users were given five minutes to familiarize themselves with the interface and they could ask us any questions during this time. The whole tutorial took about 20 minutes.

6.1.2. Model Reconstruction

We prepared four models for users to rebuild. The first two models (Figure 16(a-b)) were simple in structure, and they built these as a “warm-up”. The next two models (Figure 16(c-e)) had greater structural complexity and more detailed components. We used the virtual 3D models instead of real photos for reconstruction since the 3D models with animations (of the dynamic components) can display the objects better than images. The first 3 models (Figure 16 a-c) are built based on typical furniture in the real world, while the last cabinet (Figure 16 d-e) is complex and uncommon. For all four models, users could use the mouse to perform active animation of the dynamic components. For example, users could click to open the door to see if it had planks inside. Each user could interactively observe the models within two minutes and then they were asked to reconstruct them. While they were modeling, they were able to switch to see the required model at any time they wanted. After the users finished modeling the first two models, half of them were asked to build models 3 and 4, and the other half did them in the reverse order (i.e model 4 and then 3). We recorded the time it takes for each user to build each model. After users finished building the four models, they were asked to build one or two more furniture model(s) of their choice within 20 minutes.

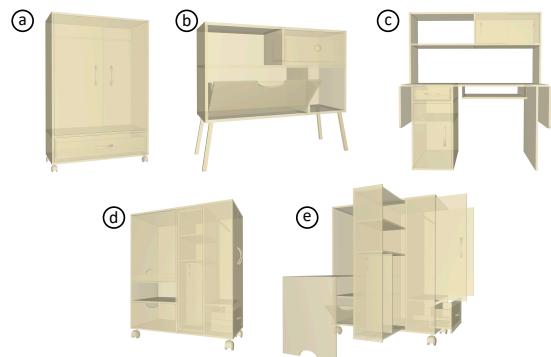


Figure 16: The four models we showed to the users for reconstruction. (a-b): Two cabinets. (c): A composite desk. (d-e): A multi-functional cabinet in compressed state (d) and expanded state (e).

6.1.3. Semi-Structured Interview

Upon completion of all the modeling tasks, we used questionnaires and a semi-structured interview to collect qualitative feedback about our system. The first questionnaire asked users to rate

how much they liked each hand gesture and each functional characteristic of our interface, on a 5-point Likert scale. The second questionnaire presents some statements about our system and we asked users to rate how much they agreed with each of them on a 5-point Likert scale. We then performed a semi-structured interview to ask about their feelings and suggestions for our system.

6.2. Results and Discussion

6.2.1. Gestures and Natural Motions

Our system involves ten kinds of motions for dynamic component creation, six kinds of motions for static component creation, and four kinds of motions for component manipulation. Ten of twelve users agreed that those gestures or motions were easy to remember (Figure 18). Users mentioned that: “*The mapping between the modeling process and the corresponding gesture is intuitive.*”(U3) and “*The hand motions can be learned by analogy easily. When I am taught using single hand motion of opening the door to create a single door, I can rightly know how to create a double door or a sliding door.*”(U5). Only U11 showed disagreement because “*I think there are too many motions. I prefer the hand-guided interface with no more than ten motions in total.*”

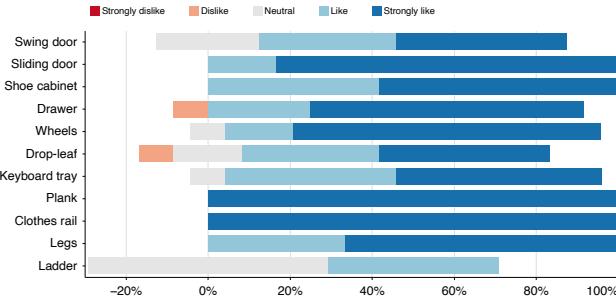


Figure 17: Preference distribution of hand gestures for each component creation. The further the bars extend to the right (relative to zero), the more users like the gesture.

The gestures for creating static components (except ladder) were liked by all the users (Figure 17). Seven users kept a neutral attitude to creating the ladder and they did not use this gesture during their user study, and the other five users showed preference after using it. The gestures for dynamic components were liked by more than 80% users. More than one user mentioned that our interface is cool: “*This kind of hand control is creative and fancy*”(U2), “*It is magic that I pull out the shelf in real world and a shelf is created and pulled out on the screen.*”(U6) and “*I have never tried this modeling methods. It is cool.*”(U12). Sometimes the user remained neutral or disliked some gesture because it went against his/her habits or the motion was likely to be out of range where the LMC could track the hands: “*I am used to pulling out the drawer with palm facing upward, but this motion is assigned to create keyboard tray.*”(U1) and “*Occasionally I forget the LMC and make big hand movement to create the door, but get nothing.*”(U3). 90% of the users liked the gestures for deleting or changing component (Figure 18). Because we also allow for mouse control for object manipulations, half of the users were used to using the mouse and kept neutral with the hand gestures: “*Using mouse to translate or scale object seems more accurate.*”(U2).

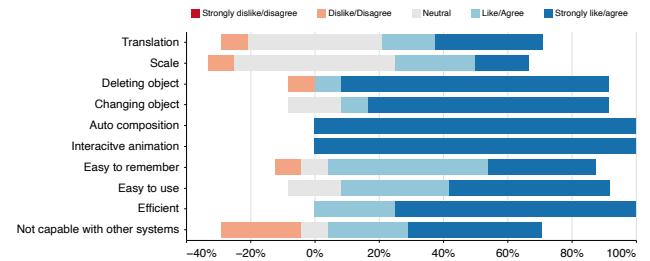


Figure 18: Preference/Agreement distribution of hand-based manipulations and other characteristics. The further the bars extend to the right (relative to zero), the more users like/agree.

6.2.2. Usability and Efficiency

All of the users finished the task of reconstructing the four models, which shows that our system is user-friendly. The average time it took the users to build model 1 to 4 are respectively 1:51 (1 minute 51 seconds), 2:48, 7:49 and 7:40, and the standard deviations are 0:40, 1:00, 2:02, 1:46. This numeric data shows the efficiency of our system: novices can use our system to create a complex furniture model within eight minutes.

According to the feedback of the post-task questionnaire (Figure 18), 90% of the users agreed that our system is easy to use. U12 said that “*The interface is very simple and it has little icons needed exploring.*” and U4 said that “*I feel easy and intuitive to use those motions to create what I want.*”. The limitation of the LMC may have an impact on the system’s usage. U9 remained neutral about the ease because “*LMC can’t track my hands precisely when my hands are far away from the center.*”

Our system fits the new component (with animation if it is dynamic) to the existing model automatically. All users strongly liked these two features, as users commented that: “*It [auto composition] really saves my time. I needn’t do any adjustment at most time.*”(U1) and “*The animation makes greater visualization of models’ function.*”(U11). Overall, 100% of the users agreed that our interface is efficient.

6.2.3. Using Other Systems

Since commercial CAD software designed for experts to do precise modeling and lightweight tools designed for novices to do conceptual design are two different goals, we did not conduct detailed comparisons with commercial CAD software. Quantitatively, it took about 2 minutes for users to model the simplest cabinet (Figure 16a) with only 5 main gesture operations and about 8 minutes to model the most complex example (Figure 16d-e) with about 20 operations. This shows that users can model a variety of 3D shapes efficiently with a small number of operations, in contrast to existing commercial CAD software. Qualitatively, when we asked our users whether they could reconstruct the 4 given models with other CAD or 3D modeling software, the two skilled users (U5 and U6) showed disagreement. However, they admitted that it would cost more time, especially in adding the full animations for the dynamic components. 8 of the 10 CAD novice users thought they were not capable of reconstructing the models with other CAD systems, while the other two thought they could make it after some short course.

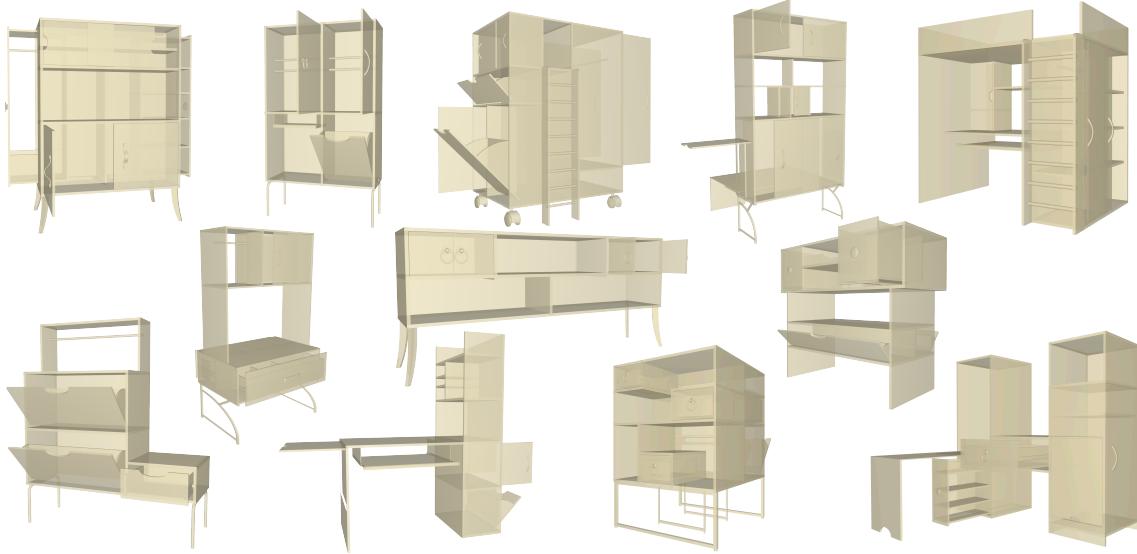


Figure 19: Various 3D furniture models (model opacity = 0.8) that users chose to design themselves with our system.

6.2.4. Diversity

With our modeling system, users are able to create various 3D furniture models ranging from a dressing table to a composite-bed with desk and cabinet (Figure 19). The limited number of components did not constrain the users' free conceptual design, and personalized furniture structures and functions can be achieved.

7. Discussion, Limitations, and Future Work

We designed and implemented a “motion-guided” 3D modeling user interface for conceptual furniture design. While we were able to successfully demonstrate this idea, there are some limitations.

First, although users can create various designs (Figure 19) by different arrangements of the components, the modeling results are restricted by the predefined components. For example, because “revolving door” is not included in our component database, users could not add it into their designs. Our component database currently only considers the typical dynamic functionalities of furniture. To scale it to a richer set, we could follow the same approach of an elicitation study to find out the users’ corresponding natural motions. However, as the types and complexity of users’ motions increase, our tree-based recognition logic may be overwhelmed, and learning-based motion recognition methods may work better. Additionally, the trade-off between the variety of motions and the user-friendliness of the interface can be further explored in future work.

In this work, we chose the Leap Motion Controller as our hand tracking device. It is a lightweight tool and it captures users’ hands without additional wearable sensors, so it does not affect the user’s hand comfort like the wearable devices (such as the MANUS glove). However, because the LMC’s tracking is based on images obtained from the binocular infrared cameras, its range is limited by the LED light propagation through space, which means large motions will cause the tracking to fail. Moreover, its hand tracking ability will drop in bright light environments or when the hands

are self-occluded, and hence our motion recognition quality would drop correspondingly. For future work, we can improve our system with other and/or better hand tracking devices.

Furthermore, our user interface is proposed for the conceptual design of furniture, which focuses more on the furniture structures and their dynamic or interactable functions, and our system does not provide precise modeling of the furniture models. An easy-to-use interface is what we aimed for and built, and the trade-off for this is that precise or detailed modeling is not possible.

Finally, our work only covers “hand” motions in a desktop environment, but “hand” or “full body” interactions are also highly relevant and intuitive in immersive environments such as AR and VR. Moreover, we focus on furniture with dynamic components to illustrate our idea of a “motion-guided” 3D modeling user interface. In theory, our “motion-guided” idea should work in more general 3D modeling, if the 3D shapes to be built include some type of “motion”. For example, in the modeling of interior design or car design, there are many transformable dynamic structures, which induces various motions. For future work, more elicitation studies would be needed to extend our idea to these broader contexts in more immersive environments.

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