CONTRIBUTED PAPER

Virtual Handcrafting: Building Virtual Wood Models Using ToolDevice

This paper introduces a number of new physical world tools to manipulate virtual objects and the research behind their construction.

By Ryan Arisandi, Mai Otsuki, Asako Kimura, *Member IEEE*, Fumihisa Shibata, *Member IEEE*, and Hideyuki Tamura

ABSTRACT | Most 3-D modeling software are difficult for beginners to learn. The operations are often complicated, and the user is required to have prior mathematical knowledge. Therefore, we developed a simple modeling system using ToolDevice to simplify such operations. ToolDevice consists of a set of interaction devices, which use metaphors of real-life hand tools to help users recognize each device's unique functions. Using TweezersDevice, KnifeDevice, and HammerDevice, we developed a mixed reality (MR) 3-D modeling system that imitates real-life woodworking. In the system, TweezersDevice is used to pick up and move objects, while KnifeDevice and HammerDevice are, respectively, used to cut and join virtual objects represented as wood materials. In this study, we describe the motivation for developing the system, the available interactions, and the procedures for creating 3-D models in the system. We also present the results of a user study in which we compare user performance in our system and a common 3-D modeling software. Finally, we discuss the contributions and limitations of this study and future work.

KEYWORDS | Augmented reality; human–computer interaction; tangible device; virtual reality

I. INTRODUCTION

It is not easy for beginners to learn how to operate a 3-D modeling software package. The user interface of the software is often complex and requires users to have prior knowledge of geometry, which many users may lack. Moreover, the operations are done on a 2-D display using a mouse and a keyboard, which are also 2-D. Skilled people may be capable of designing fine 3-D virtual models using these devices; however, many people prefer more intuitive and easy-to-learn methods. Various studies have been conducted to solve this problem [18], [20]. Fig. 1 shows our approach, which:

1) employs a hand tool metaphor for interactive devices (ToolDevice) that are commonly used in everyday life;
2) uses a mixed reality (MR) space as the working space, which merges the real and virtual worlds;
3) implements a woodworking metaphor to make a modeling method similar to that of the real world.

First, ToolDevice is a set of interaction devices that offers two key features:

- it employs the familiar shapes and tactile sensations of hand tools that are commonly used in everyday life;
- it is based on the idea that different tools are used for different purposes.

By developing devices whose shapes resemble real-life hand tools, such as tweezers [20], knife and hammers [18], and brushes [14], [17], [18], users are better able to learn how to use the devices. In addition, users can apply these devices to digital operations in a manner similar to real-life operations.

Second, our focus is to help users who have difficulty in performing spatial work, such as layout designing and 3-D

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R. Arisandi and **F. Shibata** are with the Department of Information and Communication Science, Ritsumeikan University, Kusatu, Shiga 525-8577, Japan (e-mail: arisandi@rm.is.ritsumei.ac.jp).
M. Otsuki and **H. Tamura** are with the Research Organization of Science and Technology, Ritsumeikan University, Kusatu, Shiga 525-8577, Japan.
A. Kimura is with the Department of Media Technology, Ritsumeikan University, Kusatu, Shiga 525-8577, Japan.

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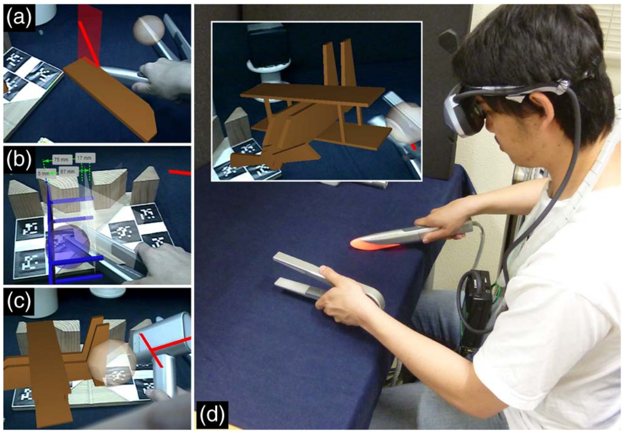

Fig. 1. ***MR handcrafting system, (a) Cutting a virtual object with KnifeDevice. (b) Measuring an object using miter box. (c) Aligning objects on the miter box and joining them with HammerDevice. (d) A user manipulating virtual objects with ToolDevice.***

modeling, by using a traditional 2-D display and mouse. For this reason, our devices are used in MR environments.

Finally, to make the system even more intuitive, we implement a woodworking metaphor because we believe that most people are familiar with the operations of real-life woodworking. For simplicity, we generalized the operations of woodworking into three tasks: picking up and moving, cutting, and joining. We developed one device for each task:

- TweezersDevice that imitates tweezers used for picking up and moving virtual objects [Fig. 2(a)];
- KnifeDevice that imitates a knife for cutting virtual objects [Fig. 2(b)];
- HammerDevice that imitates a hammer for joining virtual objects [Fig. 2(c)].

Using these devices, we develop an MR modeling system to help novice users create 3-D models.

MR and augmented reality (AR) are often used interchangeably. They both augment or enhance the real world by electronic data; in visual terms, by superimposing computer-generated images on the real-world scene. Originally, MR has a broader meaning than AR, which is included in MR itself. According to the definition by Milgram and Kishino [13], who denominated the term, in addition to AR, MR also includes augmented virtuality (AV) that augments the virtual world with real-world data. In other words, MR = AR + AV.

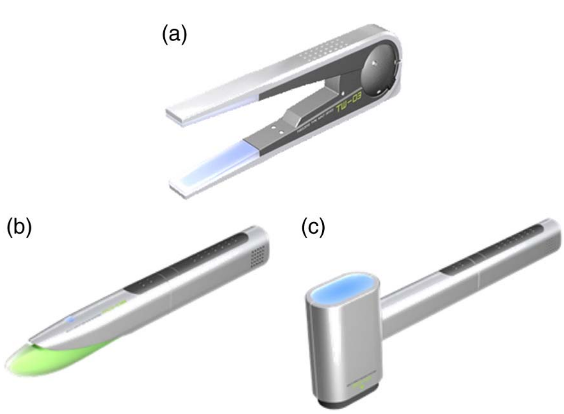

Fig. 2. ***ToolDevice. (a) TweezersDevice. (b) KnifeDevice. (c) HammerDevice.***

However, in recent years, there is a tendency to distinguish AR and MR, such that AR roughly augments the real world by superimposing simple graphic data, such as letters or arrows, while MR seamlessly merges the real world and the virtual world such that real objects and virtual objects cannot be easily distinguished. Simply speaking, AR is "rough augmentation" and MR is "seamless fusion." Obviously, MR requires precise geometrical registration and photometrical registration and also technologically more difficult. Our research group has been using the term MR instead of AR, because our aim is to develop an immersive modeling system in which the real world and the virtual world are seamlessly merged.

II. RELATED WORK

Complicated user interfaces make traditional 3-D modeling software difficult for novice users to learn. Various approaches have been suggested to make the operation more user friendly. The challenge is to find a method that is intuitive, easily controllable, and applicable in real-world environments.

A. Novel Input Methods

One approach involves the use of a specially built device or tool [6], [7], [11]. TapeWidget [6] is a high degree-of-freedom (DOF) input device that is made of rubber with a flexible spring steel core, where users can create and edit virtual objects by performing gestures. Llamas *et al.* [11] proposed a method of manipulating virtual objects using a pair of rigid handles, each having three buttons. Han *et al.* [7] developed AR Pottery, which is a system in which users can manipulate the shape of virtual objects using a tool with an AR marker on it.

Another approach involves the use of body parts such as fingers [12], [16]. Virtual Clay [12] is a system that enables users to manipulate the shape of virtual objects using a finger tracked by a haptic device called PHANToM. Similarly, Sheng *et al.* [16] developed an interface that employs a motion capture system to enable users to directly manipulate the shape of virtual objects using multiple fingers. Cho *et al.* [4] developed Turn, a system that enables users to create virtual pottery with their hands by using Kinect to capture hand movement.

Although these two approaches are arguably more intuitive than traditional 3-D modeling software, in that they provide different ways for users to directly manipulate virtual objects, they still use traditional 2-D displays. This limits the users' view to a planar surface (disadvantage 1). Consequently, operations often do not work as expected, especially operations involving parts that users cannot see.

B. Escape to the Real World

The use of real building blocks connected to a computer is one method of solving the above problem. Easigami [8] is a tool that enables users to create and manipulate virtual objects using a paper-folding metaphor. Users can connect real flat polygons having different shapes to create a model, after which the model is recreated in the computer. Similarly, Anderson *et al.* [2] developed a system that uses building blocks embedded with connectors that are used to communicate with each other and the main computer. The building blocks can compute its own geometry and send it to the computer to be interpreted. This approach enables users to have a full 360° view of the model in the real world. However, the models' shapes and sizes are limited to those of the available blocks (disadvantage 2a).

C. Creating 3-D Models in an Immersive 3-D Environment

Another approach involves the use of an immersive 3-D environment. Lau *et al.* [10] developed an immersive modeling system where users can "stamp" using multiple real objects, such as cubes, planks, or cylinders, to build 3-D models. This approach enables users to have a full 360° view of the model in the virtual world, but the models' shapes and sizes are limited to the available primitives (disadvantage 2b).

Choi *et al.* [5] developed a sketching system where users can create and manipulate the shapes of virtual objects, as if they were making a sketch in 3-D space, by using a wand-shaped wireless 3-D input device. This system enables users to freely create and manipulate 3-D models without any restrictions. However, the wand-like input device makes it difficult for novice users with no previous experience to understand how to operate the device, especially for manipulating shapes (disadvantage 3). Surface Drawing [15] and FreeDrawer [22] are other examples of a 3-D sketch system in an immersive 3-D environment; however, their input methods are more complex than [5].

AR-Jig [1] is a handheld tool equipped with a pin array that can be used to display 2-D curves and to manipulate the shapes of virtual objects by applying the curve in an AR environment. However, the shape of the device confuses novice users to understand its operation.

Our aim is to develop an MR 3-D modeling system that enables users to manipulate virtual objects using ToolDevice. Adopting an MR environment allows users to not only view virtual objects without any restrictions but also freely place the objects wherever they like (solution for disadvantage 1). Moreover, ToolDevice enables users to manipulate virtual objects by performing gestures and providing multimodal feedback by inner mechanisms that closely resemble real-life operations (solution for disadvantage 3). For example, by cutting and joining virtual objects, users can create new models without being restricted to the available building blocks or primitive, similar to real-life handcrafting (solution for disadvantages 2a and 2b).

III. TOOLDEVICE

We developed ToolDevice, a set of interactive devices that uses a metaphor of real hand tools to enable users to more easily recognize unique functions of each device. It is designed to be used in an immersive 3-D environment, wherein users can directly manipulate virtual objects. Here we introduce three components of ToolDevice:

1) TweezersDevice, which is shaped like a pair of tweezers, is used to pick up and move virtual objects, similar to tweezers;
2) KnifeDevice, which is shaped like a knife, is used like a cutter to cut virtual objects;
3) HammerDevice, which imitates the shape of a hammer, is used to join virtual objects by swinging it onto previously assembled virtual objects.

A. TweezersDevice

The internal mechanisms of TweezersDevice are shown in Fig. 3(a). Since the position and orientation of the device are tracked using magnetic sensors, a receiver is embedded in the device. A potentiometer is also embedded to track the opening angle of the device. This allows the system to recognize whether the device is pinched. The opening angle has 64 levels.

As for operational feedbacks, the device can provide visual, auditory, and tactile feedback. It provides visual feedback through light-emitting diodes (LEDs) embedded in its tip. When the device is pinched, the LEDs turn on, indicating that the device is in the "pinched" mode. Auditory feedback is provided through a speaker embedded in the device. When the device comes into contact with a virtual object, a "beeping" sound effect is played to alert the user. Tactile feedback is provided through vibration motors and a solenoid embedded in the base of the device. The vibration motors are briefly activated when the device comes into contact with a virtual object. The solenoid is used to adjust the opening angle of the device when pinching a virtual object.

B. KnifeDevice

The internal parts of KnifeDevice are shown in Fig. 3(b). As in TweezersDevice, a magnetic sensor receiver is embedded in the device to track the position and the orientation of the device. KnifeDevice can provide visual, auditory, and tactile feedback. Visual feedback is provided by the LEDs embedded in its tip. The LEDs, when turned on, indicate to the user that the device is in the "cutting" mode. For auditory feedback, a speaker is embedded in the device. A "cutting" sound effect is played when the user cuts a virtual object.

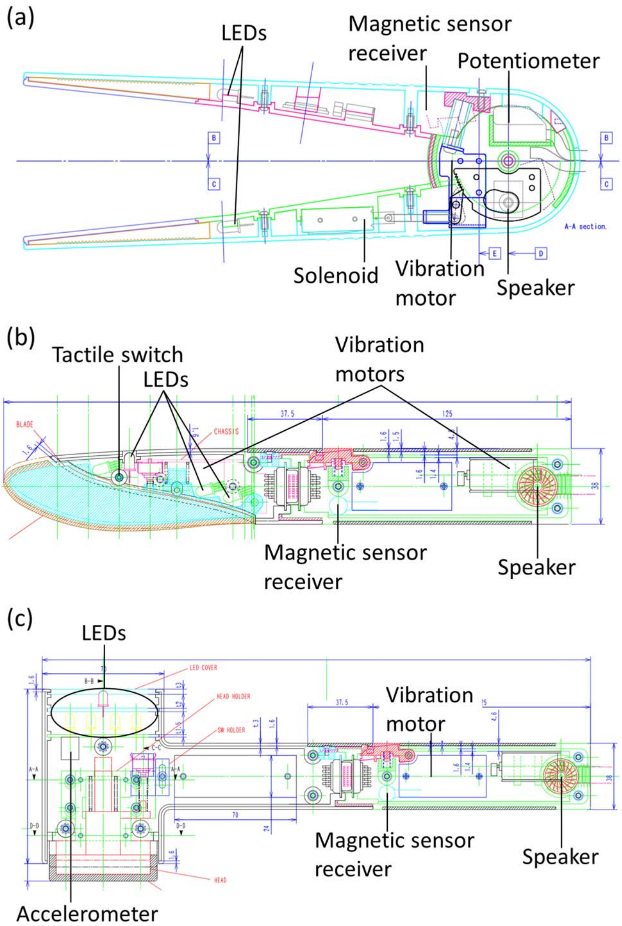

Fig. 3. *Inner part of ToolDevice. (a) TweezersDevice. (b) KnifeDevice. (c) HammerDevice.*

Tactile feedback is provided through vibration motors embedded in the knife's tip and end by utilizing the principles of phantom sensation [3]. This method changes the amplitude of two vibration motors in accordance with the angle between the device and the virtual object's surface and the contact point between the device and the object's surface. By combining this tactile sensation and visual information of touching and cutting a virtual object by a knife, this provides a sensation similar to that of real-world cutting [19].

C. HammerDevice

The internal parts of HammerDevice are shown in Fig. 3(c). As with the other devices, a magnetic sensor receiver is embedded in the device to track its position and orientation. However, unlike the other devices, HammerDevice is provided an extra weight at the head, making its total weight 250 g. This is done to give the user a feeling of holding a real hammer. An accelerometer is embedded in the hammer tip to measure the acceleration of the device when swung by the user. This acceleration is used to determine whether the user is swinging the device with sufficient speed when joining virtual objects.

As auditory feedback, when HammerDevice is swung onto a virtual object, a "hammer" sound effect is played. For tactile feedback, a vibration motor is embedded in the device. When the virtual object is successfully joined, the vibration motor is briefly activated.

IV. MR HANDCRAFTING SYSTEM

Using ToolDevice, we developed an MR 3-D modeling system that uses the metaphor of real-life woodworking. There are three basic operations: pick up and move, cut, and join. We also implemented standard digital functions, such as undo, redo, copy, and save data. In the case of digital functions, since there is no real-life metaphor for them, we simply adopt buttons and use Arduino to perform these operations.

The system configuration is shown in Fig. 4. The specifications for the main personal computer (PC) are as follows: Microsoft Windows XP OS, Intel Core i7 Ext 965 CPU, and 6144 MB of RAM. We also use a binocular video see-through HMD (Canon VH-2002), which enables users to see the scene in 3-D. The head mounted display (HMD) is connected to a video capture card (ViewCast Osprey-440), which captures input videos from the cameras built into the HMD. The NVIDIA GeForce GTX 280 graphics processor is used for image processing. The positions and orientations of the HMD and ToolDevice are tracked using Polhemus LIBERTY, a six-DOF tracking system that uses magnetic sensors. A transmitter is also used as a reference point for the sensors. We use three devices from ToolDevice, TweezersDevice, KnifeDevice, and HammerDevice. The devices are connected to the main PC through an input/output (I/O) box. The I/O box retrieves data from the devices and sends them to the main PC, which then sends back commands to control the devices.

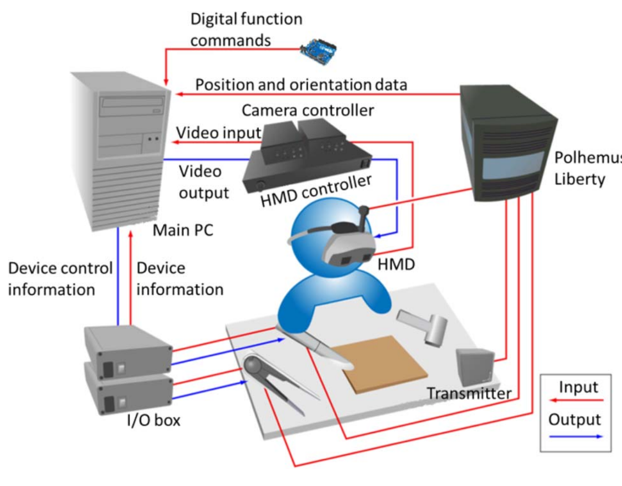

Fig. 4. *System configuration.*

All the codes in the system are written in C++/CLI in. NET Framework. We used OpenGL and the OpenGL Utility Toolkit (GLUT) for the graphics application programming interface (API). In creating the MR space, we first set the videos captured by the Osprey-440 as the background and then create a virtual viewing point in OpenGL by obtaining the position and orientation of the HMD from Polhemus LIBERTY. In doing so, users feel as if they are manipulating virtual objects in the real world.

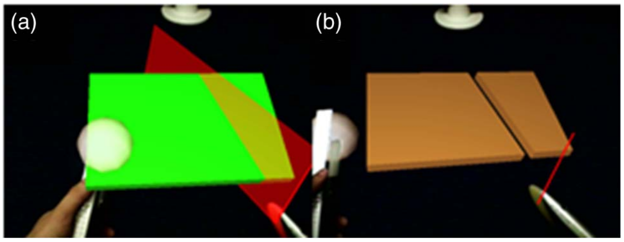

Fig. 6. ***Cutting a virtual object.***

V. USER INTERACTION

A. Basic Operations

1) Pick up and Move: Users can use TweezersDevice like real tweezers to pick up and move virtual objects. First, users have to pinch a virtual object with TweezersDevice to pick it up. Moving TweezersDevice while still holding the virtual object moves the object (Fig. 5).

To help users in assembling virtual objects, we implemented movement constraints. The algorithm is similar to that proposed by Kitamura *et al.* [9]. When a picked up object is sufficiently close to a stationary object, it will snap onto the nearest surface of the stationary object. This surface is called the constraint surface. When there is one constraint surface, users can move the picked up object along the X- and Y-axes or rotate it along the Z-axis of the constraint surface. When there are two constraint surfaces, the picked up object can only be moved along the axis that is parallel to both constraint surfaces. When there are three constraint surfaces, the picked up object cannot be moved. Users can turn this function on or off as needed. Virtual objects, the work table, and a miter box described in Section V-B can also serve as constraint surfaces.

2) Cut: KnifeDevice is used as a cutter to cut virtual objects. Users have to firmly grasp the knife until the LED in the tip turns red. They can then slide the device in the desired cutting direction. A red plane (CGI) is displayed to indicate the cutting direction [Fig. 6(a)]. After the users have decided on the cutting direction, they have to relax their grip on the device to cut the object [Fig. 6(b)].

3) Join: Users can join virtual objects using HammerDevice. They have to assemble the multiple parts by placing them so that each part touches at least one other part. After that, users have to hit the assembled model with HammerDevice to join the parts into one object (Fig. 7). Although a hammer is often used to break things, in our case, HammerDevice is used with the image of hitting a nail to join objects together.

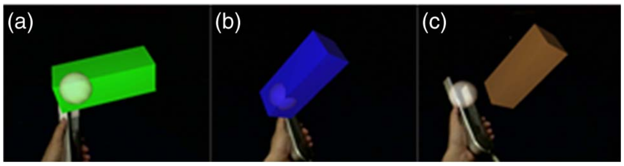

Fig. 5. ***Picking up and moving a virtual object.***

B. Miter Box

To help users more accurately align and cut virtual objects, we developed a prototype tool that is shaped like a miter box [Fig. 8(a)]. Miter box is an actual tool used by carpenters to fit and cut wood materials in a specific angle.

In this system, the miter box's position is tracked using ARToolKitPlus [21]. The tracked position is then converted into the coordinates of the magnetic sensors.

When a virtual object is placed on the miter box, the object's measurements will be displayed on the top of the box [Fig. 8(b)]. The relative position between the edges of the virtual object and the three slits on the miter box is used to calculate the virtual object's measurements.

Currently, the miter box only allows cutting in the 45° [Fig. 8(c)] and 90° directions.

C. Digital Functions

We implemented six common digital functions: copy, resize, undo, redo, save, and load. All functions are performed by pushing the corresponding buttons.

To copy an object, users first have to pinch the desired object with TweezersDevice and press the "copy" button. The new object will be automatically placed to the right of the original object.

To resize objects, users first have to select the desired object with TweezersDevice. Next, they have to press the

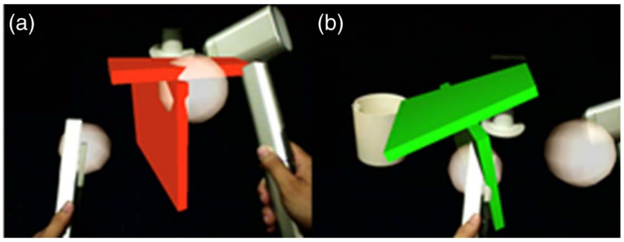

Fig. 7. ***Joining assembled virtual objects.***

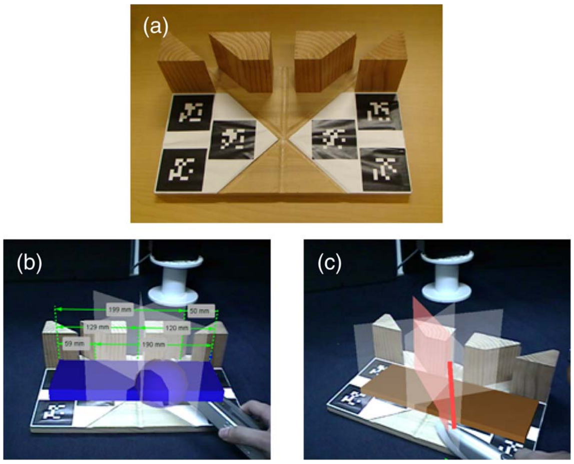

Fig. 8. ***(a) Miter box. (b) Virtual object measurement. (c) Cut in 45° direction.***

"resize" button to display three "resize" arrows that indicate the *X*-, *Y*-, and *Z*-axes [Fig. 9(a)], respectively. Users then have to pick one of the arrows with TweezersDevice and move it to resize the object along the axis indicated by the arrow. Pressing the "resize" button again will change the arrows to *XY*, *XZ*, and *YZ* arrows [Fig. 9(b)]. This time users can resize the object along the two axes indicated by the arrows. Pressing the "resize" button again will change the arrow to an *XYZ* arrow [Fig. 9(c)], and users will be able to proportionately resize the object along the *XYZ*-axis. Pressing the "resize" button once again will make the "resize" arrow disappear. Users can still move and rotate objects as usual while the arrows are displayed.

Regarding "undo" and "redo" functions, the system can undo or redo up to 50 operations. By pressing the corresponding button to save data, the scene data that contain the vertex and the face data are saved.

VI. WALKTHROUGH

In this section, we will introduce a step-by-step guide to make the chair shown in Fig. 10(a). The steps are as follows.

1) Get a plank from the set of primitives available from the start. Resize the plank to make it thin and long. Copy the resized plank five times [Fig. 10(b)].

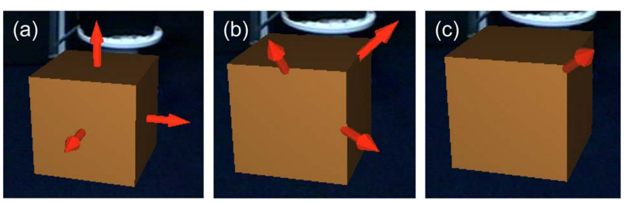

Fig. 9. ***Resize arrows: (a) X, Y, Z arrows; (b) XY, XZ, YZ arrows; and (c) XYZ arrow.***

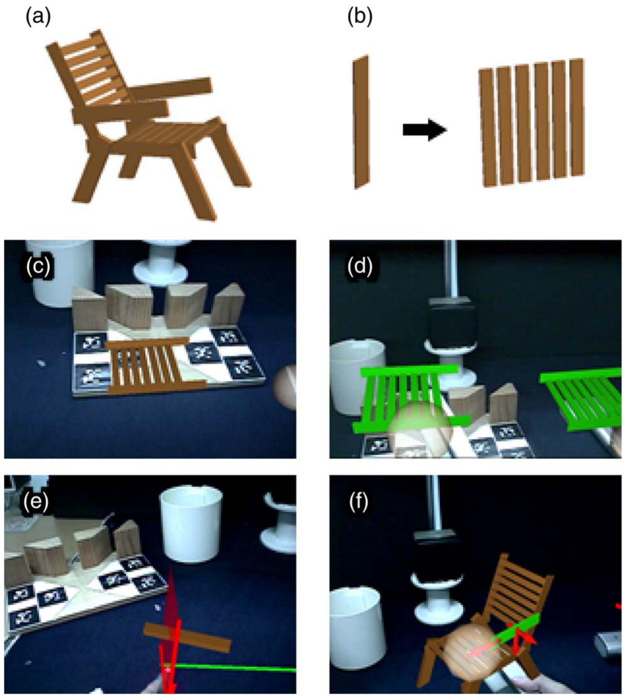

Fig. 10. ***(a) Chair. (b) Copying a plank. (c) Arranging planks. (d) Copying seat part. (e) Cutting a stick. (f) Resizing armrest.***

2) Get another plank, resize it to make it thin and long, but make it longer than the one in step 1) and copy it only once.
3) Arrange the shorter planks in parallel using the miter box and the longer planks on either side of the shorter planks, and join them using HammerDevice to make the seat part [Fig. 10(c)]. Cut the excess part after measuring the size using the miter box.
4) Make a copy of the seat part to make the backrest part [Fig. 10(d)].
5) Get another plank, cut it into a trapezoid with KnifeDevice, and copy it three times to make the legs of the chair [Fig. 10(e)]. This step can be done without using the miter box.
6) Get a stick, resize it to an appropriate size [Fig. 10(f)], and copy it once to make the armrest part.
7) Arrange all the parts and join them together with HammerDevice.

Fig. 11 shows other examples of work that was created in our MR handcrafting system.

VII. USER STUDY

A user study was conducted to verify the intuitiveness of our system. This involved a total of 12 participants (nine males and three females), aged between 21 and 23. All participants were university students, and had some

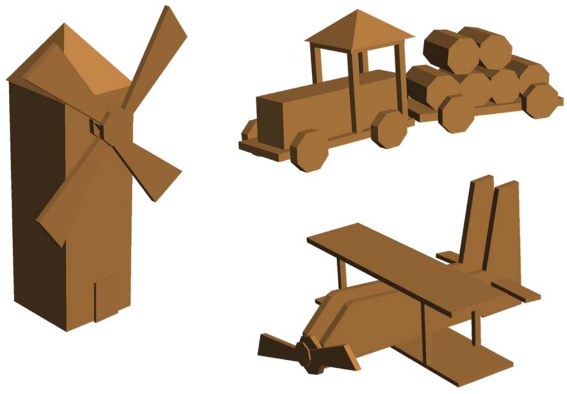

Fig. 11. *Variety of works created in the MR handcrafting system.*

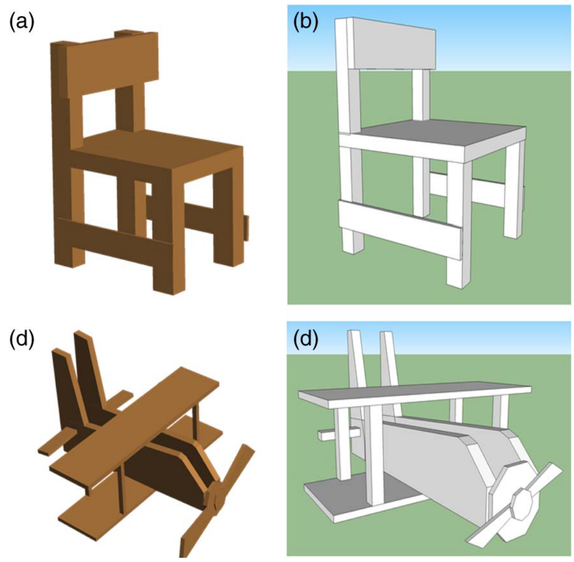

Fig. 12. *Samples used in the user study.*

previous experience in 3-D modeling, although with different levels of expertise. Prior to the study, none of the participants had used our system.

Our study aimed to compare user performance, in terms of required time and number of times each user performed the "undo" operation, when building a 3-D model. The participants were required to build the same model using our MR handcrafting system and Trimble SketchUp. We chose SketchUp as it is one of the best known 3-D modeling programs, with a reputation for being easy to use, even for beginners.

The participants were divided into two groups of six people. The first group (five males and one female) was required to build a model of a simple chair [Fig. 12(a) and (b)], while the second group (four males and two females) was required to build a relatively more complex model of an airplane [Fig. 12(c) and (d)].

The participants in each group were further divided into two groups of three people (A and B). Group A started the study with our system, while group B started the study with Trimble SketchUp.

A. Procedure

1) The study began with a demonstration session, in which the experimenter explained the operation of the modeling system (MR handcrafting system or Trimble SketchUp, depending on the group) by showing how to build a simple table.
2) The participants then built a model (chair or airplane, depending on the group) while referring to a sample that they could manipulate freely.
3) Steps 1 and 2 were repeated, having exchanged systems.
4) The study concluded by asking the participants how they felt about both systems.

The demonstration session was 5 min for the MR handcrafting system and 10 min for Trimble SketchUp. The time set for the experimental session was not limited, and the participants were allowed to freely ask questions about the operation while making the models. After each session of modeling, the participants were given a 15-min break.

B. Result

Several examples of the model created by the participants are shown in Fig. 13. The average time required for both models and the overall average are shown in Fig. 14, while the average number of times "undo" was performed and the overall average are shown in Fig. 15.

There was not much difference between the average time required to make a chair in SketchUp (14.17 min) and

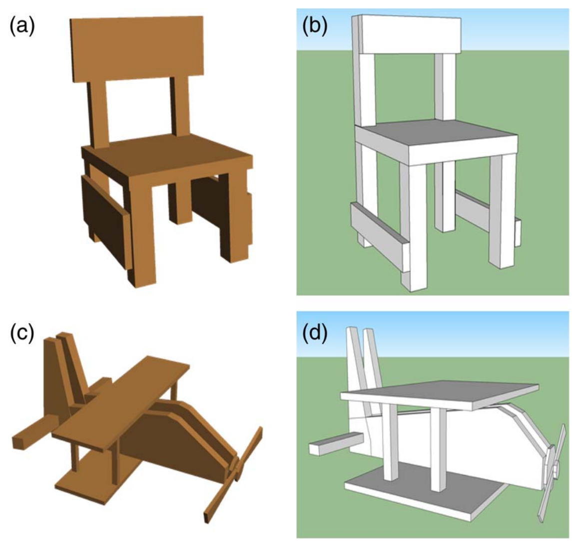

Fig. 13. *Several examples of the models created by the participants.*

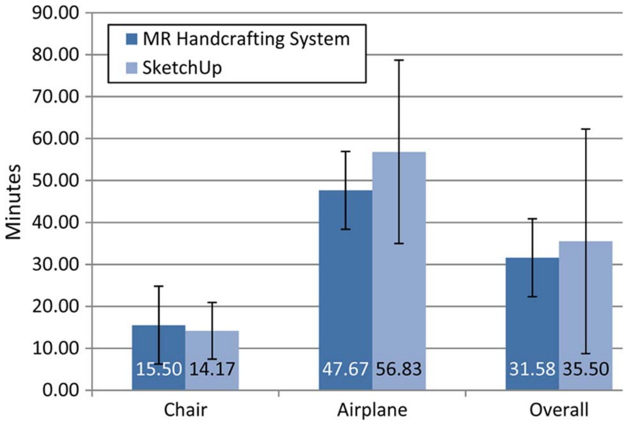

Fig. 14. ***Average time required by the participants to build a 3-D model.***

in our system (15.5 min). However, the average time required to make an airplane in our system (47.67 min) was much less than that in SketchUp (56.83 min), with only one participant requiring more time in our system than in SketchUp.

The average number of times "undo" performed was less in our system, both when making the chair (2 versus 11.17) and airplane (26.83 versus 29.33) model. No participants performed more "undo" operations in our system than in SketchUp, and only one participant performed the same number of "undo" operations in both. One participant even performed "undo" 138 times in SketchUp.

A Mann–Whitney U-test showed that, although there was no statistically significant difference between the overall average required time in our handcrafting system and SketchUp ($Z = -0.0866$ and $P = 0.46414$), there was a statistically significant difference between the overall average number of times "undo" was performed in our system and in SketchUp ($Z = -1.7609$ and $P = 0.0392$).

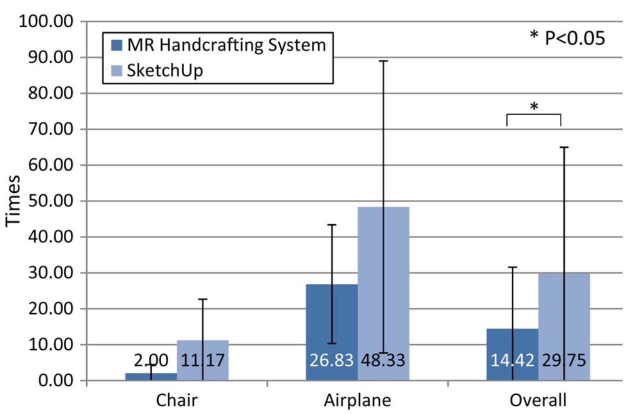

Fig. 15. ***Average number of times "undo" is performed when building a 3-D model.***

In the post-study interview, when we asked the participants which system they would recommend to a novice user, ten out of 12 participants said that they would recommend our MR handcrafting system.

C. Discussion

In this user study, we primarily focused on two parameters: the required time to build a model and the number of times "undo" is performed when building a model. Time is the standard parameter to find out which system is more easy to use. The number of times "undo" is performed also serves as an indicator whether a system is intuitive. These two parameters will be discussed in more detail below.

The results in Fig. 14 suggest that our system is comparable to SketchUp in terms of ease of understanding when building simple models. On the basis of our observation, several participants were able to build a chair by using the push/pull tool only. In contrast, in our handcrafting system, the participants had to switch between devices to perform the available functions, such as cut and join. Even then, there was not much difference in the time required to create the models.

However, when making airplanes, the results showed that the participants actually performed better when using the MR handcrafting system. We believe the reason is that, in SketchUp, the participants needed to use not just one but several other functions such as move, rotate, scale, and follow me (a function to chamfer edges). On the basis of our observation, the participants actually found it hard to remember which icon to choose from the menu to perform a specific function. In addition, the participants had to remember how to operate all these functions, which proved to be quite a challenge for them. On the other hand, our system has only three basic functions.

The results in Fig. 15 suggest that our handcrafting system is more intuitive than SketchUp. Looking at the numbers, it can be said that the participants made fewer mistakes when building models in our system than in SketchUp. We believe the reason is the shape of ToolDevice, enabling the user to operate the available functions as in real life. In contrast, all the functions in SketchUp are performed using either a mouse or a keyboard, which often makes participants confused on how to operate the available functions. For example, when rotating an object to get a better view in our handcrafting system, users can just pick an object with TweezersDevice and turn their hands around as in real life. In SketchUp, to rotate an object with the mouse, users first have to determine which axis to turn the object around, pick a point to be the central point, pick a second point to be the reference point, and, finally, move the mouse to rotate the object. This sequence of actions is rarely performed in real life, making the operation nonintuitive.

On the basis of our observations, the participants had an especially hard time understanding the operations of move, rotate, and follow me. This was later confirmed in the post-study interview, during which many participants remarked that the operations were not intuitive, since everything had to be done using the keyboard and the mouse only. On the other hand, the operations in MR handcrafting system were considered intuitive since they were similar to real-life operations. In addition, our handcrafting system handled each object in the system as a single entity, which is similar to how we handle objects in real life. On the other hand, SketchUp handles objects using the concepts of "group" and "component," which proved to be difficult for the participants to grasp.

We noted that, when building models in the MR handcrafting system, several participants build all the required parts first, before assembling the parts together in one operation. This procedure is quite similar to woodworking in real life. However, none of the participants followed this procedure when building models in SketchUp.

In the post-study interview, many participants remarked that when building a 3-D model in our system, they were able to view the model from all angles in 3-D, while in SketchUp, participants frequently failed to change the viewpoint to the one they desired. Moreover, the shapes and the feedback provided by the MR devices helped participants to quickly understand the operations and made them feel that they were really building something. In SketchUp, only visual feedback was provided, which made the experience less rich. These comments showed that our system overcame disadvantage 1 (restricted view) and disadvantage 3 (confusing operation). The use of multiple devices also did not seem to bother the participants. Although switching between devices did take more time, none of the participants complained about this.

On the other hand, many participants bemoaned the lack of precision in our handcrafting system, stating that it was difficult to line up objects precisely or to move objects slightly. In SketchUp, users could perform this task easily since SketchUp displays a measure every time the user performs an operation. Actually, we have implemented movement constraints to help users line up objects precisely, as explained in Section V. Moreover, we explained how to utilize this function to precisely line up or stack objects. However, many participants seemed reluctant to use this function because it was deemed too troublesome. Although our system lacks in precision, it is arguable that the models created by the participants in our system (Fig. 12) do not lack quality.

The post-study interview revealed that most participants would prefer to recommend our system to novice users. The reason was that the operations are simple and intuitive, so they would not have anything to remember. The participants who preferred SketchUp to our handcrafting system said the reason was that it enables users to build a more precise model.

VIII. CONTRIBUTION

The main contributions of this paper are as follows.

1) We developed ToolDevice, a set of novel interactive devices that enable users to perform spatial work in a manner similar to real life. We also implemented tactile feedback in the devices, which was shown to improve user experience.
2) Using ToolDevice, we developed an MR modeling system that uses the metaphor of real-life woodworking, and by making the operations similar to real-life operations that most people have performed in the past, we could realize an intuitive 3-D modeling system.

IX. LIMITATIONS AND FUTURE WORK

The biggest problem in the current MR handcrafting system is the lack of precision when moving or assembling objects. This prevents users from building 3-D models as they wish. This problem can be solved by displaying measurements when users move objects, or by implementing the "grid mode," in which users can move objects according to a virtual grid, making the movement more precise. Another way is to implement a snapping function, similar to that in Microsoft PowerPoint, whereby objects can snap to straight lines extending from other objects. We plan to further investigate the best way to solve this problem.

Other limitations regarding the functionality of our system also include the following.

- KnifeDevice can only be used to cut in straight lines. In addition, the miter box only allows cutting in 45° and 90° directions.
- The current system possesses only the most basic woodworking operations. Operations such as drilling a hole, grinding corners, and chamfering edges are currently unavailable.

In the future, we plan to implement the above-described functions. In addition, our long-term goal is to develop a system with which users can use the same devices while switching between wood materials, metal materials, clay, etc., and can perform operations that are appropriate for each material.

Although the results of the user study conducted in this paper show encouraging signs for our system, they only show how novice users perform in a onetime event. It is interesting to see how users perform after learning how to use the system and evaluate the time and effort to completely master our system and SketchUp. We will evaluate the learning curve in our future work.

X. CONCLUSION

In this study, we described an MR 3-D modeling system that uses a metaphor of woodworking to allow users to create 3-D models using ToolDevice. The system has three basic functions: to pick up and move objects using TweezersDevice, to cut objects using KnifeDevice, and to join objects using HammerDevice. By making the operations resemble real-life operations, we were able to realize an intuitive system. In addition, the tactile and sound feedback mechanisms, embedded in each device, significantly increased the presence of virtual wood objects. Standard digital functions, such as undo, redo, and copy, are also available. With the help of these functions, users were able to build more complex models and make the size of the models more appropriate.

We conducted a user study to confirm the usability and intuitiveness of our proposed method. All of them understood the operations after seeing a simple demonstration and were able to build models easily. ■

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ABOUT THE AUTHORS

Ryan Arisandi was born in Jakarta, Indonesia, on February 19, 1989. He received the B.E. degree in computer science from Ritsumeikan University, Kusatu, Shiga, Japan, in 2012, where he is currently working toward the M.S. degree at the Graduate School of Information Science and Engineering.

His research interests include human-computer interaction, augmented/mixed reality, and tangible devices.

Mai Otsuki received the B.E., M.E., and Ph.D. degrees in engineering from Ritsumeikan University, Kusatsu, Shiga, Japan, in 2006, 2008, and 2011, respectively.

She is a Postdoctoral Research Fellow at Ritsumeikan University. She studied human factors in mixed reality space at the University of Toronto, Toronto, ON, Canada, in 2012, as a Postdoctoral Student. Her research interests include human-computer interaction, 3-D user interface, and human perception.

Dr. Otsuki is a member of the Association for Computing Machinery (ACM), the Virtual Reality Society of Japan (VRSJ), the Information Processing Society of Japan (IPSJ), and the Human Interface Society.

Asako Kimura (Member, IEEE) received the B.S., M.S., and Ph.D. degrees in engineering science from Osaka University, Suita, Osaka, Japan, in 1996, 1998, and 2001, respectively.

She is a Full Professor at the College of Information Science and Engineering, Ritsumeikan University, Kusatu, Shiga, Japan. She taught at Osaka University from 2000 to 2003, before coming to Ritsumeikan University. She was concurrently a Special Project Associate at the Biomedical Imaging Resource Laboratory, Mayo Clinic, from 2001 to 2002, and a Sakigake Researcher of PRESTO Japan Science and Technology Agency, from 2006 to 2010. Her research interests include human–computer interaction, natural user interface, and augmented/mixed reality.

Prof. Kimura is a member of the Information Processing Society of Japan (IPSJ), the Institute of Electronics, Information and Communication Engineers (IEICE), and the Association for Computing Machinery (ACM).

Fumihisa Shibata (Member, IEEE) received the M.E. degree in computer science and the Ph.D. degree in engineering from Osaka University, Suita, Osaka, Japan, in 1996, and 1999, respectively.

In 2003, he joined Ritsumeikan University, Kusatu, Shiga, Japan, where he was an Associate Professor at the College of Information Science and Engineering. He has been a Professor at the Ritsumeikan University since 2013. His research interests include mobile computing, augmented/mixed reality, and human–computer interaction.

Prof. Shibata is a member of the Virtual Reality Society of Japan (VRSJ), the Information Processing Society of Japan (IPSJ), and the Institute of Electronics, Information and Communication Engineers (IEICE).

Hideyuki Tamura received the B.Eng. and Ph.D. degrees in electrical engineering from Kyoto University, Kyoto, Japan, in 1970 and 1984, respectively.

His professional career, starting in 1972, includes a Senior Research Official at the Electrotechnical Laboratory, MITI, Japan; the Director of Media Technology Laboratory, Canon Inc.; and a member of the executive board of the Mixed Reality Systems Laboratory Inc. In 2003, he joined the Ritsumeikan University, Kusatu, Shiga, Japan, as a full Professor at the College of Information Science and Engineering. Now he is an eminent Professor of Research Organization of Science and Technology, Ritsumeikan University. His most prominent work is that he planned and conducted the Key-Technology Research Project on Mixed Reality in Japan from 1997 to 2001. He is (co)author and (co)editor of ten books, all in the field of computer vision, graphics, and multimedia, including *Mixed Reality—Merging Real and Virtual Worlds* (New York, NY, USA: Springer-Verlag, 1999). His research interest and major achievements are in the areas of pictorial pattern recognition, digital image processing, artificial intelligence, virtual reality, and multimedia systems.

Prof. Tamura served on the executive boards of several academic societies in Japan and received several awards from such societies as the Information Processing Society of Japan (IPSJ) and the Institute of Electronics, Information and Communication Engineers (IEICE). He organized the Special Interest Group on Mixed Reality, the Virtual Reality Society of Japan, and founded the basic body of the International Symposium on Mixed and Augmented Reality (ISMAR).