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EasyPot: Interactive Modeling for Virtual Pottery with Handheld Haptic Devices

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Abstract We present EasyPot, an interactive virtual reality (VR) modeling system that allows novice users to create virtual pottery works by bimanual interactions via hand-held motion controllers. Our system consists of two major components: an automatic mesh generator and an interactive model editor. The mesh generator can procedurally generate a realistic clay mesh by adding Perlin Noise. With the interactive pottery model editor, the user can shape the virtual clay in realtime intuitively to design virtual pots. The virtual pots created by our system can be exported as OBJ files and used for 3D printing. The results of our user study have shown that our system requires lower cognitive load compared with desktop modeling experience and allows more creativity than touchscreen based interfaces. Users without real-life pottery experience and 3D modeling knowledge can easily create virtual pottery works with our system.

Keywords Virtual pottery · Natural user interfaces · Mesh deformation · Haptic feedbacks

1 Introduction

Pottery is one of the oldest inventions in many civilizations in human history for thousands of years, which is made by shaping clay into heterogeneous forms. In recent years, emerging technologies such as 3D printing introduces a new way of pot design, enabling people to fabricate pots in a digital way with the help of Computer Aided Design (CAD) software and 3D printers. However, although

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professional CAD tools (Maya [3], 3ds Max [2], etc.) provide powerful toolsets and rich features for 3D modeling pipeline, these systems are formidable for novice users and children to learn due to complex user interfaces. There are several CAD systems which are specifically developed for pottery design [15, 16], which can generate 3D meshes based on the values from user keyboard and mouse input. Although having simplified user interfaces comparing with professional tools, the experience of these systems is not intuitive and the operations are far different from the pottery workflow in reality.

To address this situation, some camera-based virtual pottery systems have been developed [26, 20, 8], which provide natural and intuitive user interfaces, allowing users to design pots via freehand interactions. These works indeed provide a gentle learning curve, however, they have some common limitations. First, although freehand interactions in these systems are simple, user inputs from depth cameras lack accuracy due to jitter, hindering work efficiency and user experience severely. Moreover, freehand interactions lack haptic feedback, making it difficult for users to perceive whether they have touched anything in VR environments. In terms of reality, these systems overlook some visual features of clay, namely shape irregularity, thickness, etc., which undermines realistic look and feel in the pot design process. In addition, the deformation parameters cannot be adjusted interactively by the users, which limits the effects of deformation.

In this paper, we present EasyPot, a VR system that allows users to design virtual pottery models from their hand movement using hand-held motion controllers. There are three major design goals for EasyPot: (1) design a simple and intuitive interface for novice users to learn pottery skills with minimum cognitive load, (2) create a virtual pottery system that can generate realistic clay meshes with refined haptic feedbacks based on bimanual spatial interactions and (3) provide helpful functionalities such as parameter control, undo/redo to support creativities in virtual pottery design.

In order to achieve the design goals, we take the human-centered design approach in our research. Oviatt concluded that human-centered design can minimize users cognitive load, which effectively frees up mental resources for performing better while also remaining more attuned to the world around them [23]. The natural behaviors in real-life pottery creation is fully considered in our system, so that the interface of EasyPot can be more intuitive, easier to learn, and freer of performance errors. In addition, Jacob et al. [12] summarized that the designer's goal should be to allow the user to perform realistic tasks realistically, to provide additional non real-world functionality, and to use analogies for these commands whenever possible. Hence, while EasyPot is designed based on pottery creation process in reality to minimize the effort, convenient functionalities should be provided in our system for efficiency as well.

The main contributions of our works are: (1) propose a simple virtual pottery system with hand-held controllers which can generate pot models for 3D printing from user spatial interactions, (2) present a virtual pottery workflow by providing realistic look and feel with haptic feedback, enabling novice users to understand and learn pottery production pipeline via simulation training and (3) conduct an user study showing the comparison results among three modeling systems. The results have shown that our system is easier to use compared with traditional 3D modeling tools and provides more creativity than touchscreen apps.

The paper is structured as follows: Section 2 introduces the related work about virtual pottery. In Section 3 the overall system is demonstrated and the technical details are discussed in Section 4. Section 5 shows the results of the experimental results and we set up a comparison user study in Section 6. Finally, discussions for the system are given in Section 7, followed by the conclusions in Section 8.

2 Related Work

2.1 Bimanual Interactions

Bimanual interactions has been a popular research field, which can accomplish a variety of tasks in both physical and virtual environments. In terms of mechanisms, bimanual interaction can be classified into two categories: bare-hand based interactions and instrument based interactions.

There are a great number of research efforts [31,6,26,20,8] on bare-hand based interactions using depth camera such as Kinect, Leap Motion, etc. Cuenestics [31] is a design space for hand-gesture based mid-air selection techniques using a depth camera Kinect, where users can select contents on interactive public displays with their gesture inputs. Cui et al. [6] proposed a modeling system with natural free-hand interactions using a Leap Motion controller, allowing users to grab and manipulate objects with one or two hands intuitively. While these works provide accessibility to users, they have some common limitations: The inputs are inaccurate due to many factors such as lighting condition, occlusion, etc., which could handicap work efficiency and cause user frustration. In addition, these methods do not provide haptic feedbacks, which hinders the realistic feel for users in the interaction process.

Unlike bare-hand based interactions, instrument based interactions provide more control precision, haptic feedback and unambiguity. Surface Drawing [28] is a system for creating organic 3D shapes using tangible tools such as data gloves, where users can define strokes with the path of hands wearing data gloves. Hinckley et al. [10] investigated two-handed virtual manipulation with a point design of a prop-based system, which allows users to view a cross section of a brain with interface props. These works have a common issue that the usage of these instruments are limited to a lab context that very few users can access. With the commercialization of gaming devices, some motion controllers such as Wii Remote and HTC Vive have become accessible to consumers, which are also used in scientific studies for 3D user interfaces [32,21]. In our project, HTC Vive system is used in our system, which provides precision, haptic feedback and well accessed by consumers.

2.2 Art and Design Tools in VR

Virtual reality has shown great potential for art and design, which not only provides immersive and intuitive interfaces for user, but also creates new art medium, new art form and novel experience [17].

CavePainting [13] is a 3D artistic medium in a fully immersive environment, which enables artists to create spatial paintings with physical props and gestures.

Agrawala et al. [1] developed an interface for painting on polygon meshes using a 6DOF space tracker, which provides a natural force-feedback for painting, allowing users to place colors on meshes intuitively. MAI Painting Brush++ [22] is a brush device for virtual painting of 3D virtual objects, where users could take a physical object in the real world and apply virtual paint to it with visual and haptic feedback. Virtual Clay [19] is a sculpture framework based on subdivision solids and physics-based modeling, which is equipped with natural, haptic based interaction, providing users with a realistic sculpting experience. Sheng et al. [29] proposed an interface for virtual 3D sculpting, which uses camera-based motion tracking technology to track passive markers on the fingers and prop, enabling users to apply operations such as deforming, smoothing, pasting and extruding.

To leverage the novel experience brought by VR, the setup of our system is based on a virtual environment, where users can enjoy the creation process in a immersive way.

2.3 Virtual Pottery Systems

Several systems have been specifically developed for virtual pottery design in the recent past. One of the earliest virtual pottery systems is CHINA [14], where users can create pottery works wearing digital gloves and stereoscopic glasses. Ramani et al. proposed a series of freehand systems based on depth cameras, where point cloud data is analyzed to extract user design intent [25–27]. Handy-Potter [20] is a rapid 3D creation tool, which tracks user skeletons with Kinect, enabling users to create potteries in several seconds based on the trails of both hands. Han and Han [8] presented an audiovisual interface, where pottery shapes deformed by hand motions are translated into musical sound. In AR Pottery [7], augmented reality has been applied to pottery design, with which users can deform a virtual pottery using a marker held by hand.

Although the interfaces provided by these systems are not difficult to learn, some realistic features are ignored and the workflow is oversimplified. In contrast to all existing works, our system provides a much realistic workflow and experience, which allows users to manipulate virtual pots through various two-handed spatial interactions, helping novice users and children to understand and learn real life pottery skills in a virtual environment.

3 System Overview

EasyPot is an interactive modeling system for virtual pottery based on handheld haptic devices in VR. Users can create pottery in our system with bimanual inputs, deforming the virtual clay in realtime. EasyPot can export the mesh data as an OBJ file when a pottery work is finished, which can be used in 3D printing. Our system provide a simulation training environment in virtual worlds, allowing novice users and children to learn pottery skills interactively.

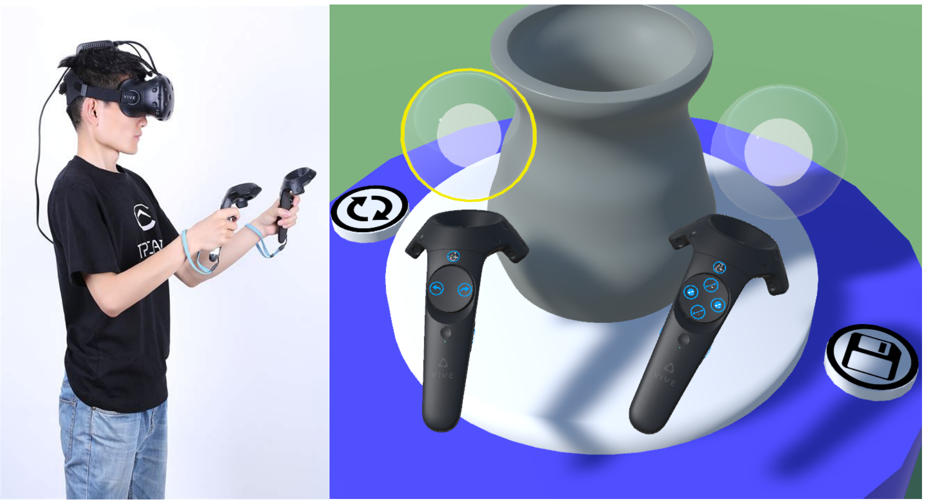

Fig. 1 A user is using our system to create virtual pots.

3.1 System Architecture

The system architecture is demonstrated in Figure 2. When the mesh generator generates a clay mesh, users can start to interact with the mesh with handheld haptic devices. The deformation manager is the core component of the mesh editor, which will deform the clay, sending information to haptic manager and UI manager. The haptic manager will send pulses to motion controller as haptic feedbacks, and the UI manager will update the UI elements, sending to the head-mounted display via the rendering engine. Once the creation is done, the mesh IO manager will convert the meshes into OBJ files and save them.

3.2 Workflow

In real life, the pottery creation process on a pottery wheel is called *throwing*, where a ball of clay is placed in the centre of a turntable wheel-head, and shaped by a potter. To illustrate the pipeline of pottery creation in our system, an example workflow using EasyPot is described as follows.

When a user starts to use EasyPot, a realistic clay mesh is automatically generated with Perlin noise (Figure 3a, Section 4.1). Similar to the operation in reality, the user first need to use both hands to make the irregular clay shape into perfect rotational symmetry, which is called *centring* (Figure 3b, Section 4.2.1). The user can control the thickness of the clay (i.e. *opening*) by pressing down the clay to create a hollow in the clay (Figure 3c), and then draw up the walls with two hands moving up together (i.e. *pulling*), controlling the height of the clay (Figure 3d, Section 4.2.2). The system not only allows mesh deformation (Figure 3e, Section 4.2.3) with different deformation range parameters but also mesh smoothing (Figure 3f, Section 4.2.4), where the user can remove sharp features in the pot to get ideal shape. After the creation process is finished, the user can export the pottery model as an OBJ file, which can be used for 3D printing.

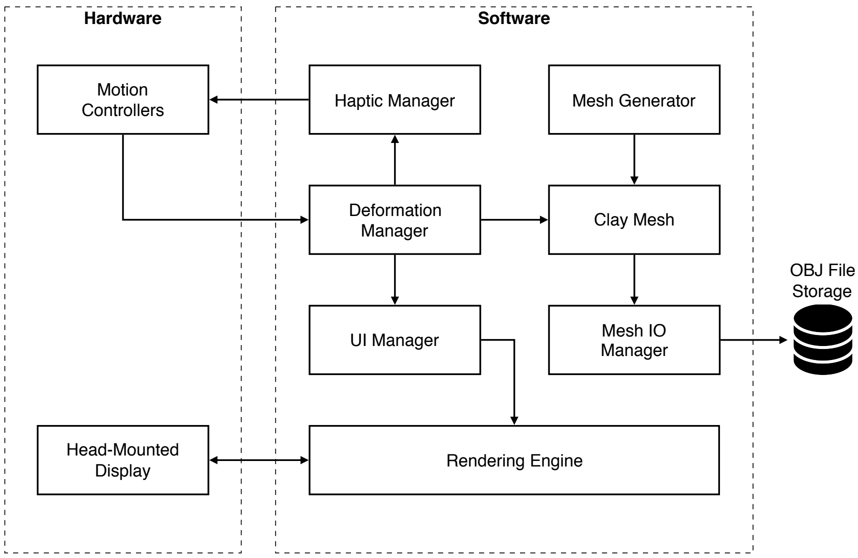

Fig. 2 The system architecture of EasyPot.

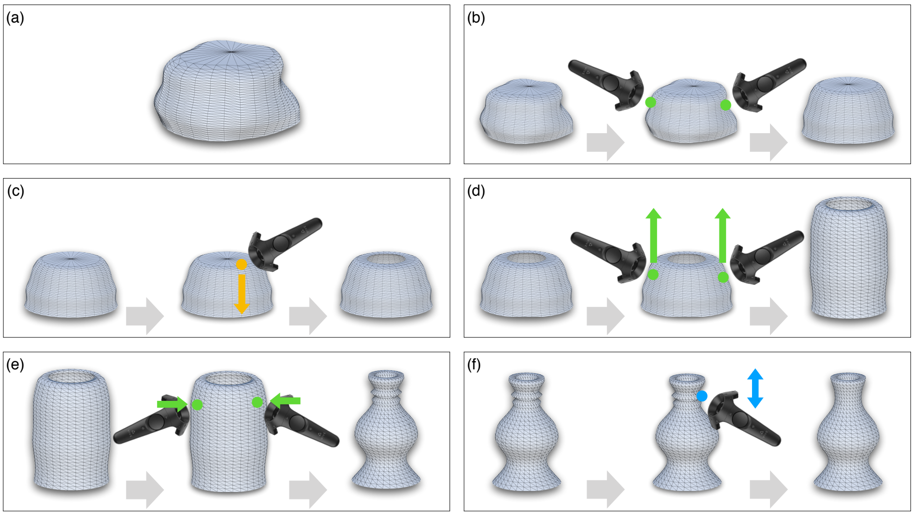

Fig. 3 The workflow in EasyPot. (a) The automatically generated clay mesh with Perlin Noise. (b) The mesh is shaped into rotational symmetry by holding both hands. (c) The user controls the thickness of the mesh by pressing down the clay. (d) The user controls the height of the mesh by drawing up the clay wall.(e) The deformation range can be adjusted to get varied deformation effect on different parts. (f) The sharp features on the upper part can be removed by mesh smoothing.

4 Interactive Modeling for Virtual Pottery in VR

4.1 Mesh Generation

Mesh generation is the first step of interactive modeling, and most of virtual pottery systems approximate the initial shape of pottery clay as a primitive cylinder shape [7,26,27]. Although this approach is simple to implement, it ignores subtle details of clay, whose irregularity needs to be handled first during the creation process in real life. Unlike the existing virtual pottery systems, EasyPot first approximates the initial clay on the pottery wheel as a blending shape of cylinder and semi-ellipsoid, then adds Perlin noises to the basic clay, in order to simulate realistic clay features in reality.

Basic Clay The clay mesh is described as a generalized cylinder, whose resolution can be defined by axis segments s_a and height segments s_h. Given radius r and height h, our system can generate primitive mesh of cylinder and semi-ellipsoid respectively (Figure 4). For each vertex in the mesh, a $m \times n$ matrix M is used to store radius values, where number of row $m = s_h + 1$ and the number of column $n = s_a$ respectively. The base radius r_{base_i} of each vertex $\mathbf{v}_{i,j}$ in row i can be calculated as:

$$r_{base_i} = \alpha \cdot \frac{r}{h}\sqrt{h^2 - h_i^2} + (1-\alpha) \cdot r \tag{1}$$

$$h_i = i \cdot \frac{h}{m-1} \tag{2}$$

where α is a factor controls the shape blending between a cylinder (when $\alpha = 0$) and a semi-ellipsoid (when $\alpha = 1$) (Figure 4).

Adding Noise Although the initial shape of clay can be roughly approximated like a rotational symmetric shape, in real life, the actual clay shape is not regular, whose irregular features needs to be specially handled during the pottery creation process. To simulate the realistic features, randomness is added to the vertices using Perlin Noise [24], which is a smooth random method proposed by Ken Perlin in 1985. In our approach, the centre positions for each circular section are randomized first, then Perlin Noise is added to the radii for each circular section and individual vertices.

To add noise to the centre for each circular section, random parameters ϕ_i and η_{c_i} are used to calculate the new centre $\mathbf{O}_i$:

$$\mathbf{O}_i = [\eta_{c_i} cos\phi_i, h_i, \eta_{c_i} sin\phi_i]^T \tag{3}$$

where $\phi_i \in [0, 2\pi]$ is a random degree, and η_{c_i} is a random radius. Then the new radii $r_{total_{i,j}}$ for each vertex can be computed by getting the sum of r_{base_i} and noise values:

$$r_{total_{i,j}} = r_{base_i} + \eta_{row_i} + \eta_{indv_{i,j}} \tag{4}$$

where η_{row_i} is the radius noise for each circular section, and $\eta_{indv_{i,j}}$ is the individual radius for each vertex (Figure 5). The radius value $r_{i,j}$, along with the position $\mathbf{v}_{i,j}$ for each vertex can be computed in the follow equations:

$$r_{i,j} = \left\| \mathbf{O}_i + \left[r_{total_{i,j}} cos\theta_j, 0, r_{total_{i,j}} sin\theta_j\right]^T \right\| \tag{5}$$

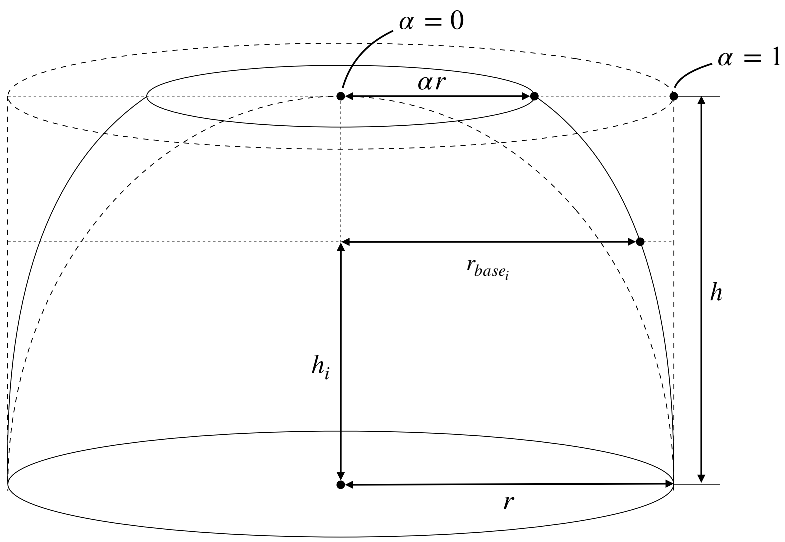

Fig. 4 The basic clay generated by our system, which is a blending shape between a cylinder and a semi-ellipsoid. α is the blending factor which controls the radius on the top.

$$\theta_j = j \cdot \frac{2\pi}{n} \tag{6}$$

$$\mathbf{v}_{i,j} = [r_{i,j} cos\theta_j, h_i, r_{i,j} sin\theta_j]^T \tag{7}$$

Inner Vertices To create 3D printing oriented pottery models, our system needs to generate watertight 3D models with thickness. To accomplish that, EasyPot generates inner and bottom sides based on the outer side mesh. The vertices on inner side can be denoted as:

$$\mathbf{v'}_{i,j} = \begin{cases} \left[0, h_i, 0\right]^T & \beta = 1 \\ \left[r'_{i,j} \cdot cos\theta_j, h_i, r'_{i,j} \cdot sin\theta_j\right]^T & 0 \leq \beta < 1 \end{cases} \tag{8}$$

$$r'_{i,j} = r_{i,j} - \max(t_{min}, r_{top} \cdot \beta) \tag{9}$$

where β is the thickness ratio of the clay, whose range is $[0, 1]$. In mesh generation phase, the default value of t is 1, which means the clay is a solid shape; in mesh deformation phase, the value of t can be adjusted by users interactively, getting a centre hollowed shape. t_{min} is a predefined value for the minimum thickness, and r_{top} is the largest radius value for the top section, which guarantees equal thickness for each part. Vertices for inner-bottom and outer-bottom sides will be then generated according to inner-side and outer-side vertices respectively. Finally,

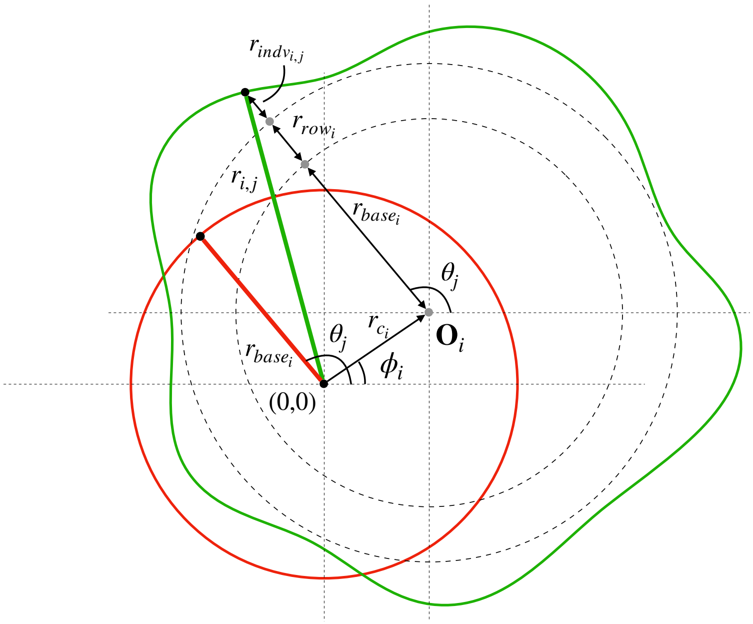

Fig. 5 To get a noised radius $r_{i,j}$ (green) based on radius r_{base_i} (red): (1) Move the centre from origin (0,0) to $\mathbf{O}_i$. (2)Calculate the sum: $r_{total_{i,j}} = r_{base_i} + r_{row_i} + r_{indv_{i,j}}$. (3) Find the distance to the origin, which will be the noised radius $r_{i,j}$.

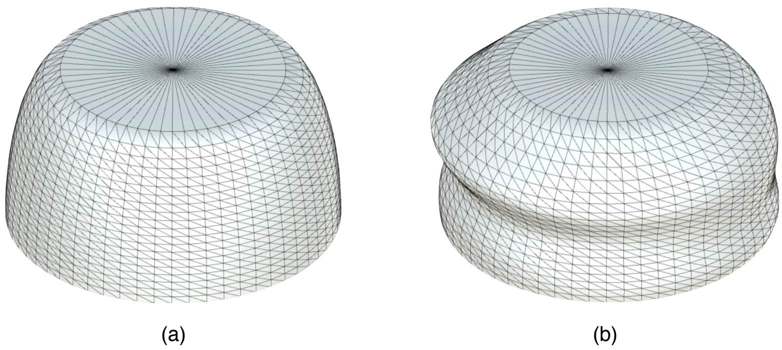

Fig. 6 The meshes generated with our system. (a) A regular mesh without adding Perlin noise. (b) A mesh with Perlin noise, which is more realistic as a clay.

a mesh can be generated by constructing triangle faces based on the vertex indices (Figure 6).

4.2 Mesh Processing

After observing and analyzing several real-life pottery throwing videos, we put mesh operations into 4 categories: (1) symmetry control, (2) height/thickness control, (3) mesh deformation and (4) mesh smoothing. These operations will be discussed in detail in the following sections. Since any clay mesh C can be generated from key parameters including height h, thickness t and radius matrix M, a mesh generation function is constructed: $C = g(h, t, M)$, which can be used to update the mesh data as well. In our approach, EasyPot first modifies key parameters of the clay according to user interactions, then updates mesh data C in realtime based on these parameters using the mesh generation function.

4.2.1 Rotational Symmetry Control

Centring is the first important operation in pottery creation in reality, where people press the ball of clay downward and inward, making the irregular clay into perfect rotational symmetry. In our system, the user can use two controllers to touch the virtual clay and pull the trigger button to achieve symmetry control (Figure 3b). The mean radius value of each row in the radius matrix is calculated and then each radius value in matrix needs updating based on the mean radius values:

$$r'_{i,j} = \lambda \cdot \frac{1}{n} \sum_{k=1}^{n} r_{i,k} + (1 - \lambda) \cdot r_{i,j} \tag{10}$$

where $\lambda \in [0, 1]$ is a damping factor controlling the rate of symmetry. The effect of rotational symmetry control is illustrated in Figure 7.

4.2.2 Thickness/Height Control

Opening (thickness control) and *pulling* (height control) are basic clay operations in pottery throwing process which are done by applying force to clay with both hands. The thickness can be adjusted by pushing down the top centre part of the clay, making a centre hollow into the clay (Figure 3c). The height can be adjusted by both hands drawing up and shaping the walls (Figure 3d). Let Δy be the mean of Δy_l and Δy_r, which are left and right vertical hand movement distance respectively. New height h' and new thickness ratio β' can be calculated in the following equations:

$$\Delta y = (\Delta y_l + \Delta y_r)/2 \tag{11}$$

$$h' = h_0 + \Delta y * \gamma \tag{12}$$

$$\beta' = \beta_0 + \Delta y / h \tag{13}$$

where h_0 and β_0 are initial height and thickness ratio values before deformation respectively; γ is a damping factor for height. And the new mesh data will be recomputed using new values h' and β'.

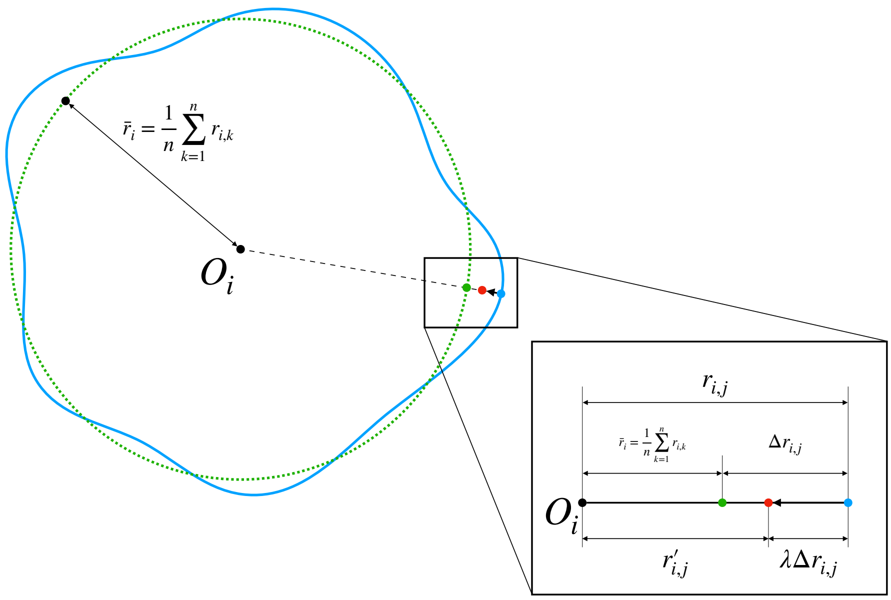

Fig. 7 Rotational symmetry control. The blue curve is the noised circular section at height h_i, and the green curve is a circle with the average radius $\bar{r}_i$. Let $\Delta r_{i,j}$ be the difference between $r_{i,j}$ and $\bar{r}_i$, then multiplied by the damping factor λ. New radius be calculated : $r'_{i,j} = r_{i,j} - \lambda \Delta r_i$, which is identical to Equation (10).

4.2.3 Mesh Deformation

In this section, interactive deformation in our system will be discussed. According to [4], this topic is challenging since complex mathematical formulations (1) have to be hidden behind an intuitive user interface and (2) have to be implemented in a sufficiently efficient and robust manner to allow for interactive applications.

In our approach, a cylindrical coordinate system is used to specify the position for each vertex, where y-axis is the reference axis. For any point P in the coordinate system, we use(ρ, ϕ, y) to denote the position, where the radial distance ρ is the Euclidean distance from the y-axis to the point P; ϕ is the azimuth; y is the height of point P from xz-plane. Due to rotational symmetry in virtual pottery, EasyPot modifies the ρ for each vertex while keeping ϕ and y constant. Thus, the deformation problem is turned into how to calculate the new radius $\rho'_{i,j}$ based on hand movement:

$$\rho'_{i,j} = \rho_{i,j} + \Delta\rho_{i,j} \tag{14}$$

Let (x_0, y_0, z_0) be the initial handle position at time t_0 when the deformation starts, and we can calculate the initial radial distance of the handle from y-axis: $\rho_0 = \sqrt{x_0^2 + z_0^2}$. The new handle position at time t_1 is (x_1, y_1, z_1), and the new radial distance is $\rho_t = \sqrt{x_1^2 + z_1^2}$. When the user presses the trigger button on the controller while the handle touches the mesh, the vertical distance $d_{i,j}$ between the handle and each vertex $\mathbf{v}_{i,j}$ can be computed as:

$$d_{i,j} = |y_0 - y_{i,j}| \tag{15}$$

where $y_{i,j}$ is the height of $\mathbf{v}_{i,j}$. In our system, outer range R_O and inner range R_I are two key parameters affecting deformation effect, which divides the mesh into three regions: fixed region, moving region and deformation region. The fixed region will keep constant during the deformation, where $d_{i,j} > R_O$; the moving region will follow the movement of the handle, where $d_{i,j} < R_I$; and the deformation region will be affected based on the weights, where $R_I < d_{i,j} < R_O$. Note that when $R_I = 0$, the deformation will go in a smooth way; when $R_I = R_O$, it is possible to create sharp features on the clay:

$$\Delta r_{i,j} = \begin{cases} \rho_t - \rho_0 & d_{i,j} < R_I \\ 0 & d_{i,j} > R_O \\ (\rho_t - \rho_0) \cdot w_{i,j} & R_I < d_{i,j} < R_O \end{cases} \tag{16}$$

A falloff curve is needed in order to get smooth deformation effect when calculating weights: $w_{i,j} = f(t)$. There are many ways to select a falloff functions for the weights, which needs to satisfy these requirements: (i) f(0) = 1 , (ii) f(1) = 0 and (iii) f'(0) = f'(1) = 0. In order to efficiently calculate the weights, we choose a cubic polynomial function $f(t) = at^3 + bt^2 + ct + d$ as the weight falloff function, we have:

$$\begin{aligned} f(0) &= 1 \\ f(1) &= 0 \\ f'(0) &= 0 \\ f'(1) &= 0 \end{aligned} \tag{17}$$

we can find the solution from Equation (17), where $a = 2, b = -3, c = 0, d = 1$. Therefore, the expression of the falloff function is $f(t) = 2t^3 - 3t^2 + 1$ (Figure 8).

4.2.4 Mesh Smoothing

As mentioned above, it is possible to create sharp features upon the clay mesh during the deformation process. In order to remove unwanted sharp features, our system uses Laplacian smoothing:

$$r'_{i,j} = \mu \frac{1}{N} \sum_{k=1}^{N} r_k + (1 - \mu) r_{i,j} \tag{18}$$

where N is the number of adjacent vertices of $\mathbf{v}_{i,j}$; $\mu \in [0, 1]$ is a factor controlling the smoothing effect. Only the vertices within the range of the handle R_O will be affected. As a result, users can control the handle position and adjust the outer range R_O of the handle to apply smoothing on specific areas interactively on the mesh.

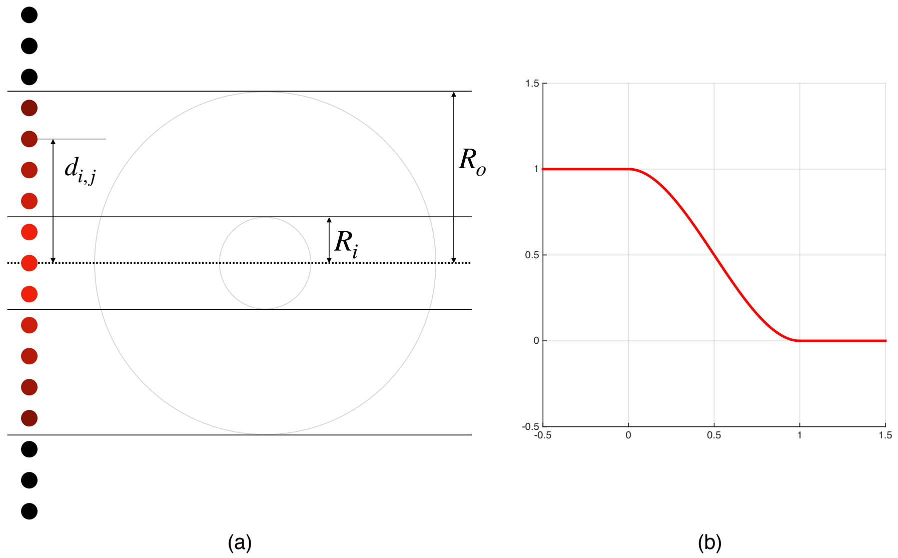

Fig. 8 (a) The center of the concentric circles is the initial position of the handle. R_i and R_o define the inner range and outer range respectively. $d_{i,j}$ is the vertical distance between a vertex $\mathbf{v}_{i,j}$ and the handle, which is used for weight calculation. (b) We use a cubic polynomial function $f(t) = 2t^3 - 3t^2 + 1$ as the falloff curve for calculating the weight $w_{i,j}$.

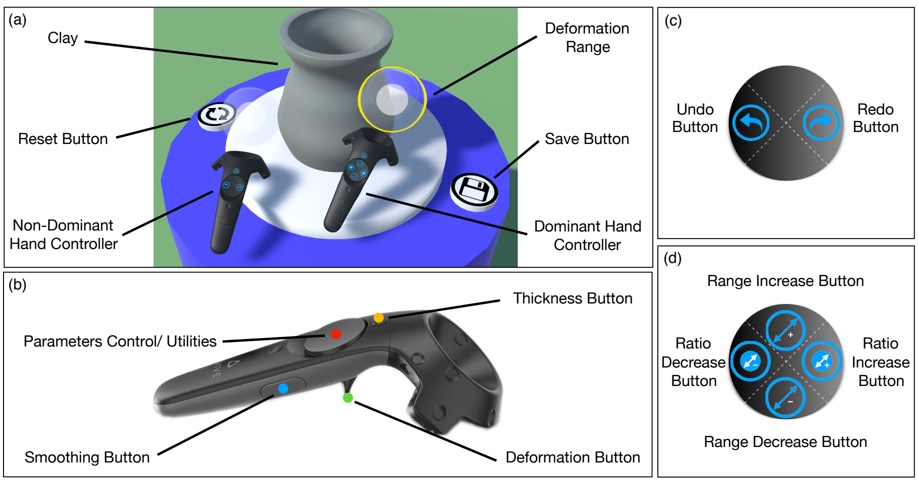

Fig. 9 The user interface of our system. (a) The virtual pottery wheel in the virtual space. (b) The controller button configuration of EasyPot. (c) The button layout of left Controller Pad. (d) The button layout of right Controller Pad.

4.3 Interactions

EasyPot is designed as a pottery workshop built in a virtual environment. In our implementation, we use a HTC Vive VR system [11], which includes a head-mounted display and two hand-held controllers to track user head orientation and bimanual movement (Figure 9). The goal of our system is not only to provide realistic experience in pottery creation, but also to provide convenient operations to improve the efficiency of pottery design. Jacob et al. [12] summarized that the designer's goal should be to allow the user to perform realistic tasks realistically, to provide additional non real-world functionality, and to use analogies for these commands whenever possible. As a result, our system offers several operations in VR for pottery design. The buttons on the controllers are assigned with different functionalities for convenience. The user can control deformation parameters with dominant hand, and perform undo and redo with non-dominant hand. The mesh reset button and mesh export button are designed on the side of the pottery wheel, as they are not frequently used during the work process, which could prevent user errors. There are three main operations supported by our system:

Parameter Adjustment Parameter adjustment allows the user to control the deformation effect. The user can adjust the outer range R_O by pressing the upper and lower part of the pad on controller, which controls the influence area. The inner range R_I can be adjusted by pressing left and right part of the pad controlling the radio of the inner range. This function is designed to activate using dominant hand since parameter adjustment is frequently used during the process. Users can adjust the inner and outer ranges while get immidiate visual feedback from the size of the sphere.

Undo/Redo EasyPot allows users to revert changes using undo and redo, which provides automatic support for recovery from user errors and misunderstandings as well as a mechanism for exploring alternatives. Undo and redo is an important interactive feature whose absence seriously degrades the usability of an interactive program [5]. Undo and redo buttons are placed on non-dominant hand controller, which allows user to revert changes made on the clay easily.

Mesh Reset/Export Mesh reset allows users to start over from the beginning. Whenever a user touch this button, the generated mesh on the pottery wheel will be reset to initial state. Since the shape is randomized, the user can keep getting a new shape until she is satisfied with the shape. When the virtual pot is finished, the mesh should be able to export for further use. Our system can encode the mesh data into an OBJ file, and save the file on the disk. The exported OBJ file can be used for 3D printing.

4.4 System Feedbacks

Effective feedbacks can notify user the current state of the system. Feedbacks in our system can be classified into two categories: visual feedbacks and haptic feedbacks.

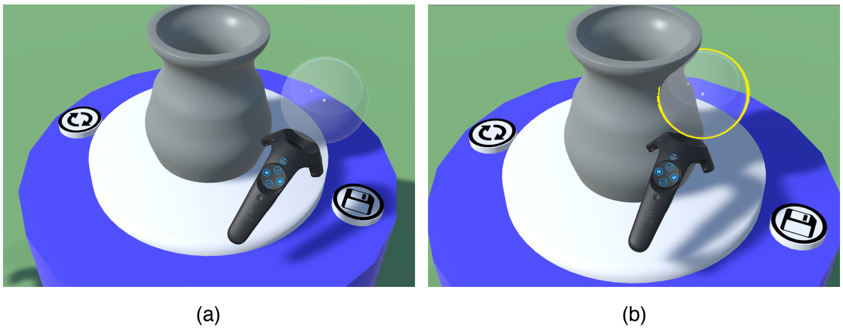

Fig. 10 The visual and haptic feedback when user touches the clay. (a) The normal state of the handle when it is not touching the clay. (b) The highlight state of the handle when a user has touched the clay, with a haptic pulse to the corresponding hand.

Visual Feedbacks In a VR environment, it is not so easy for users to perceive if her hands have touched anything. Hence, our system adds visual feedback on both virtual hands, which will be highlighted when touching the clay (Figure 10).

Haptic Feedbacks Unlike the bare hand experience, the instrument based interaction can provide haptic feedbacks, adding realistic feel in VR environments. In our system, a haptic pulse has been added to a controller when that controller has touched the clay. During any mesh editing process, we add movement resistance feedback based on the movement speed of each hand. The frequency of the haptic feedback is modeled as the following equation:

$$k = k_{min} + f_{Clamp}(\frac{\|\mathbf{p}' - \mathbf{p}_0\|}{d_{max}}) \cdot (k_{max} - k_{min}) \tag{19}$$

where k_{min} and k_{max} are predefined minimum and maximum frequency values respectively; d_{max} is predefined maximum move distance, and $f_{Clamp}(x)$ is a function that clamps the value in $[0, 1]$; $\mathbf{p}'$ and $\mathbf{p}_0$ are current and previous hand positions respectively.

5 Results

We have implemented EasyPot using Unity3D [30] game engine. EasyPot is built on a HTC Vive VR system with a PC (2.10 GHz Dual Core CPU, 16 GB RAM and NVIDIA GeForce GTX 1080 graphics card) running 64-bit Windows 10 Professional.

In order to get performance statistics of the mesh generator, EasyPot is tested to generate 4 models with different resolutions. Based on the common size of clay placed on pottery wheels, we set the height 0.2 units with the radius 0.15 units. The outer range of the handles is set to 0.2 units, and the inner range is set to 0 to get smooth deformation effect as the process begins. The centring parameter λ, height parameter γ and smoothing parameter μ are set to 0.5, 0.4 and 0.7 respectively, in order to get a more realistic deformation via damping. The parameters for Perlin noise generation are listed in Table 1. These parameters are fine tuned to get a

Table 1 The random parameters based on Perlin Noise.

Parameter Name	Value	Meaning
a_c	0.40	Centre Noise Amplitude
a_r	0.29	Row Noise Amplitude
a_i	0.18	Individual Noise Amplitude
b_c	0.81	Centre Noise Span
b_r	3.19	Row Noise Span
b_i	0.86	Individual Noise Span
b_a	3.75	Angle Noise Span

Table 2 Statistics for different axis and height segments.

Axis Segments	Height Segments	Vertices	Triangles	Generation Time (ms)
60	100	12242	24120	21.48
60	200	24242	48120	41.53
120	100	24482	48240	42.02
120	200	48482	96240	101.00

realistic look of the clay. Table 2 demonstrates statistics based on different mesh solutions. Higher resolution require more generation time, since more vertices and triangles need to be calculated and assigned. In general, the performance of mesh generator is sufficient for the requirement in EasyPot.

6 User Study

In order to compare our system with prior CAD systems that can design virtual pottery on desktop and tablet platforms, we set up a comparative user study. We chose Autodesk Maya [3] as a representative of desktop modeling systems and Let's Create! Pottery (LCP) [18] as a representative of tablet pottery design systems.

6.1 Evaluated Systems

The three evaluated systems were as follows:

EasyPot : Our virtual pottery tool based on HTC Vive VR system. The user can shape the virtual clay with bimanual spatial interaction.

Lets Create! Pottery : A touchscreen-based pottery creation tool on mobile devices. Users can interactively create pottery models by finger swiping on the screen.

Autodesk Maya : A traditional desktop 3D modeling system, which provides a set of powerful tools for professional 3D artists. The user can edit vertex, edge, face etc. with mouse and keyboard.

Although the three systems are different, we focus on comparing them based on their similarities and workflows. To investigate the influence of modeling pipeline, we compare EasyPot and Autodesk Maya since they both support 3D modeling.

(a) (b) (c)

Fig. 11 The three systems used in our user study. (a) A virtual reality system EasyPot proposed by us. (b) A touchscreen-based system Let's Create! Pottery. (c) A desktop modeling tool Autodesk Maya.

(a) (b) (c) (d) (e) (f)

Fig. 12 The target shapes used in our user study.

They differ in workflow to create and edit meshes. While EasyPot can automatically generate a mesh for deformation with motion controllers, Maya needs to create a mesh from a primitive cylinder in order to edit in vertex mode, edge mode or face mode with mouse and keyboard. On the other hand, EasyPot and LCP have similarities in their workflows with intuitive interactions. They both allow users deform the mesh interactively with natural user interfaces. While EasyPot enables parameter control and spatial interaction, LCP has no parameter control and provides touchscreen-based experience.

6.2 Participants

19 participants were participated in our user study, 10 male and 9 female, whose age ranged from 22 to 40 years. 8 of the subjects are familiar with VR systems (42.1%); 2 of the subjects have experience with 3D modeling tools (10.5%); 4 of the subjects have amateur pottery throwing experience in real life (21.1%).

6.3 Experimental Design and Procedure

Practice Each subject was given 15 minutes to get familiar with these systems (5 minutes for each). Subjects can ask questions whenever they need help.

Task 1 After the 15-minute practice of the three systems, each subject need to accomplish 3 tasks:

$\mathbf{T}_1$: Given a sequence of reference pot models as target shapes, the subjects were asked to create same pots from irregular generated meshes using EasyPot.

$\mathbf{T}_2$: Given reference pot models of the same order in $\mathbf{T}_1$, the subjects need to model these pots using Let's Create! Pottery on an iPad Pro.

$\mathbf{T}_3$: Given reference pot models of the same order in $\mathbf{T}_1$ and $\mathbf{T}_2$, the subjects need to model these pots using Maya on a PC.

When doing tasks $\mathbf{T}_1$ to $\mathbf{T}_3$, a total of six target shapes were presented to subjects in a randomized sequence (Figure 13).

Questionnaire 1 After accomplishing each task, the subjects were asked to answer a questionnaire with six questions to measure the six dimensions of NASA-TLX, which includes physical demand, mental demand, temporal demand, effort, performance and frustration. 5 additional questions were asked after they finished all tasks.

NASA-TLX has been chosen in our research because it is widely used in human factor studies which addressed questions about interface design and evaluation [9]. We selected NASA-TLX as a part of our questionnaire to assess user workload in the three systems. Since the functionalities are different among the three systems, it is impossible and unfair to compare the interactions. We intended to allow our subjects to experience those differences and similarities through these tasks and analyze which types of interactions and results were more attractive to them through our user study questions.

Task 2 After finishing tasks $\mathbf{T}_1$ to $\mathbf{T}_3$, each subject need to accomplish 3 more tasks:

$\mathbf{T}_4$: Use EasyPot to make a creative pottery model freely.

$\mathbf{T}_5$: Use Let's Create! Pottery to make a creative pottery model freely.

$\mathbf{T}_6$: Use Maya to make a creative pottery model freely.

Questionnaire 2 Each subject needs to answer the following questions after finishing tasks $\mathbf{T}_4$ to $\mathbf{T}_6$:

$\mathbf{Q}_1$: Rank the three systems according to ease of learning from high to low.

$\mathbf{Q}_2$: Rank the three systems according to their supports for your imagination and creativity from high to low.

$\mathbf{Q}_3$: Rank the three systems according to your preference from high to low.

6.4 Study Results

Figure 14 shows mean values of the six dimensions of NASA-TLX for $\mathbf{T}_1$, $\mathbf{T}_2$ and $\mathbf{T}_3$. Figure 15 shows the vote results of $\mathbf{Q}_1$, $\mathbf{Q}_2$ and $\mathbf{Q}_3$, where we count a score of 3 for the system in the highest ranking and 1 for the system in the lowest ranking.

According to Figure 14, we can get some findings. Firstly, the mental demand values of $\mathbf{T}_1$ (M = 2.52) and $\mathbf{T}_2$ (M = 2.11) were almost the same and much lower than the value of $\mathbf{T}_3$ (M = 4.92). Similarly, the temporal demand value of $\mathbf{T}_3$ (M = 5.77) was much higher than the values of $\mathbf{T}_1$ (M = 3.21) and $\mathbf{T}_2$ (M = 2.98). This indicated that EasyPot and LCP were easier to use and less time-consuming

Fig. 13 The virtual pots created by our system.

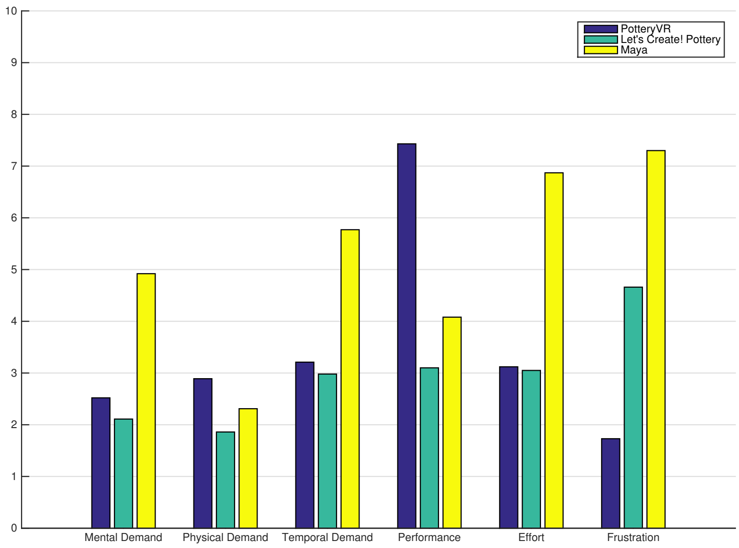

Fig. 14 Mean values of the six dimensions of NASA-TLX.

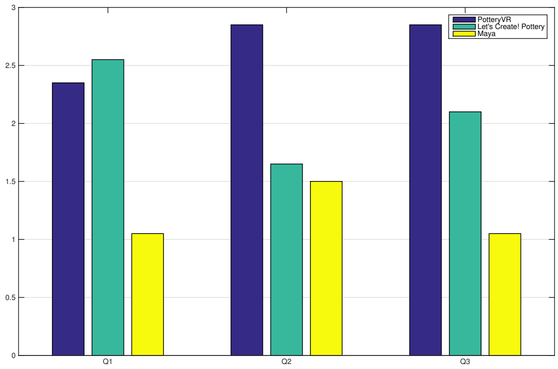

Fig. 15 Mean ranking scores of Q1, Q2 and Q3.

than Maya. Unsurprisingly, the physical demand value of $\mathbf{T}_1$ (M = 2.89) is slightly higher than $\mathbf{T}_2$ (M = 1.86) and $\mathbf{T}_3$ (M = 2.31), which means interactions based spatial movements are slightly laborious than touchscreen and keyboard/mouse interactions.

Maya showed much higher values in effort (M = 6.87) and frustration (M = 7.30) and lower value in performance (M = 4.08) compared with EasyPot and LCP. Since most subjects in the user study have no 3D modeling software experience, the complex user interface in Maya makes it challenging for these novice users to memorize where to find the commands they need, rendering a high effort. Although keyboard-mouse based interaction allows precise controls with low physical demand, many subjects struggled with selecting and manipulating vertices and faces accurately, which caused high user frustration. As a result, most subjects were not satisfied with their performances in $\mathbf{T}_3$.

Surprisingly, we found that it was not as satisfied as we predicted for the subjects using LCP in $\mathbf{T}_2$, where the performance value (M = 3.10) is lower than we expected. This is due to the limitations in LCP: Although the interaction in LCP is easy to learn, some high curvature features (Figure 12b, 12d, 12e and 12f) cannot be reached due to LCP has a fixed deformation range. Moreover, subjects cannot modify the thickness of pots, which is another limitation of LCP. Thus, the frustration value (M = 4.66) are high during $\mathbf{T}_2$.

The voting results in Figure 15 demonstrated the ease of learning, the support of creativity and overall preference of the three systems. Compared with the complex interfaces and the keyboard and mouse operations in Maya, EasyPot and LCP provides simple interfaces and intuitive interactions, allowing users get familiar with the interaction with ease. In addition, most subjects considered EasyPot stimulate their creativity and imagination the most. From their feedbacks, we found that spatial interactions in virtual reality context gave them a novel and realistic way to interact with virtual clay when using EasyPot. Moreover, EasyPot provides more powerful operations such as adjustable deformation range, thickness control and smoothing than LCP, allowing subjects creating characteristic shapes.

In $\mathbf{Q}_3$, EasyPot became the favorite virtual pottery system for the subjects. From user feedbacks, we found that EasyPot provided the subjects with most enjoyable experience among the three systems, which also has a balance of having simple interfaces and useful functionalities. In addition, the natural bimanual interactions in EasyPot are closely related to the operations in reality pottery, making it an ideal training simulation tool for pottery.

7 Discussions

We collected user feedbacks after the subjects had used our system. In summary, subjects gave many positive feedbacks when using our system to design pottery models. They spoke highly of the immersive pottery creation experience with intuitive interactions and haptic feedbacks that motivated them to design pottery works just like working on real clay. In addition, the undo/redo functionalities are quite convenient according to the subjects, which enhances the efficiency during the creation process. For those who have no real-life pottery creation experience enjoyed our system very much and would like to try real pottery someday.

During our user study, we found that the undo/redo functionality is not used frequently as we expected. The reason might be that the changes for each operation are not so difficult to revert, that some users just manually fix the chagne without using undo/redo shortcut provided by EasyPot.

We also asked their suggestions for the future features they wanted to see in EasyPot. A few subjects expressed their wishes to add coloring feature, which allows them decorate the pots with colors and patterns. At the end of our user study, many subjects said they would like to try EasyPot one more time.

Our system still has its limitations. First, the physical size of the motion controllers sometimes affect the deformation in bimanual mode, especially when the part of the clay is narrow that two controllers may collide with each other. For example, when subjects working on the neck of clay, it will be difficult to edit with two controllers. This problem can be easily solved by providing user one-hand deformation mode. We plan to use data gloves to avoid these situations in the future. Second, the potteries designed by our systems lack colors and textures. Although we focus on deformation in our study, several subjects stated that they wish to paint the pottery after designing the shape of the clay. We intend to add new features related to interactive painting on 3D objects. Another limitation of our system is that it cannot adding handles to the pottery. We will introduce more features that allow users to modify the topology of the mesh in order to create more personalized pottery works.

8 Conclusions

We present EasyPot, a realtime pottery modeling system in VR. Closely linked to the pottery creation experience real life, our system enables users to manipulate the mesh in realtime with two hands, allowing them creating a variety of pottery models from realistic generated clay meshes. As an educational tool, EasyPot can help novice users and children to learn real-life pottery creation process in virtual environments, who can fabricate their works using our system with a 3D printer. Our results have shown that EasyPot has relative advantage compared with traditional desktop 3D modeling experience (Maya) and touchscreen experience (Let's

Create! Pottery). A possible extension of our system is to support interactive coloring functionalities in the future, which can enhance the artistry of user generated pottery works.

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