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RealPot: an immersive virtual pottery system with handheld haptic devices

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Abstract In the last two decades, virtual pottery has become an interesting topic in computer aided design. Although existing works allows user to create pottery intuitively, aiming for simulation trainning, it is unclear whether the increased display and interaction asepects of fidelity can impact the usability of the system. To investigate the effects of display and interaction fidelity in virtual pottery systems, we present **RealPot**, a high fidelity immersive virtual pottery system with haptic feedback that can train novice users to design pottery works by bimanual interactions using hand-held motion controllers. In this paper, a realistic pottery creation workflow is proposed and functionalities are developed. Our goal was to gain a better understanding of the effects of fidelity on the user in a virtual environment. The results of our study indicate that both display fidelity (e.g. haptic feedback and immersion) and interaction fidelity (e.g. workflow and functionalities) significantly affect performance and user experience. In particular, the system with rich functionalies and haptic feedback has significant positive than other conditions.

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

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1 Introduction and motivation

// 1 VR on Computer Aided Design (CAD), immersive 3d modeling

// 2 as an interesting area, virtual pottery has drawn research interest recent years

// virtual pottery systems Unlike general purpose CAD tools (Maya [3], 3ds Max [2], etc.) which have powerful toolsets and rich features, virtual pottery systems are specifically designed with more intuitive user interfaces, usually allows rotational symmetric deformation.

// there are some existing virtual pottery systems [26,20,9] use gestures, camera based interaction

// however, limitations -

// low interaction fidelity - not close to real world, the workflow is over simplified

// low display fidelity - not realistic, no immersion, no haptic

// weak functionality - not fully support creativity, no parameter control

There are several desktop CAD systems which are specifically developed for pottery design [15,16], which can generate 3D pot 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 [26,20,9], 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. (1) Although freehand interactions in these systems are simple, the imprecision of user inputs from depth cameras hinders work efficiency and user experience. (2) In terms of reality, immersion or haptic feedbacks are missing in these systems, where the user experience is less realistic. Moreover, these systems overlook some visual features of clay, namely shape irregularity, thickness, etc., which undermines realistic look and feel in the pot design process. (3) The deformation parameters cannot be adjusted interactively by the users, which restricts various possible effects of deformation.

!!! how immersion and influence usability of virtual pottery system?

// we aim to

increasing virtual pottery system's fidelity to real world.

In this paper, we present RealPot, an immersive virtual pottery system with haptic feedbacks that allows users to design pottery models using hand-held motion controllers.

There are three major design goals for RealPot: (1) design an interface with high interaction fidelity which reproduce the realistic interactions in pottery (2) build an virtual pottery system with immersions and haptic feedbacks based on spatial interactions and (3) provide helpful features such as parameter control, undo/redo to support creativities in virtual pottery design.

// display and interaction fidelity - mcmahan

//Both display and interaction fidelity significantly affect strategy and performance, as well as

// mcmahan: increased fidelity can often have positive effects on the user experience.

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 RealPot 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 RealPot 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) develop a virtual pottery system with high interaction fidelity, realistic workflow (2) present high display fidelity, including immsersion and haptic feedback, enabling novice users to understand and learn pottery production pipeline via simulation training and (3) conduct user studies to investigate the effects of increased fidelity of virtual pottery system.

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.

// how helpful this research to the field

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, we set up two comparative user studies and Section 5 shows the results of the experimental results. Finally, discussions for the system are given in Section 6, followed by the conclusions in Section 7.

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 interactions can be classified into two categories: barehanded interactions and instrument-based interactions.

There are a great number of research efforts [32,6,26,20,9] on barehanded interactions using depth camera such as Kinect, Leap Motion, etc. Cuenestics [32] 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 freehand 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 barehanded 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 [33, 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 VE, 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 [18] 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 VE, where users can enjoy the creation process in an 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 [9] presented an audiovisual interface, where pottery shapes deformed by hand motions are translated into musical sound. In AR Pottery [8], augmented reality

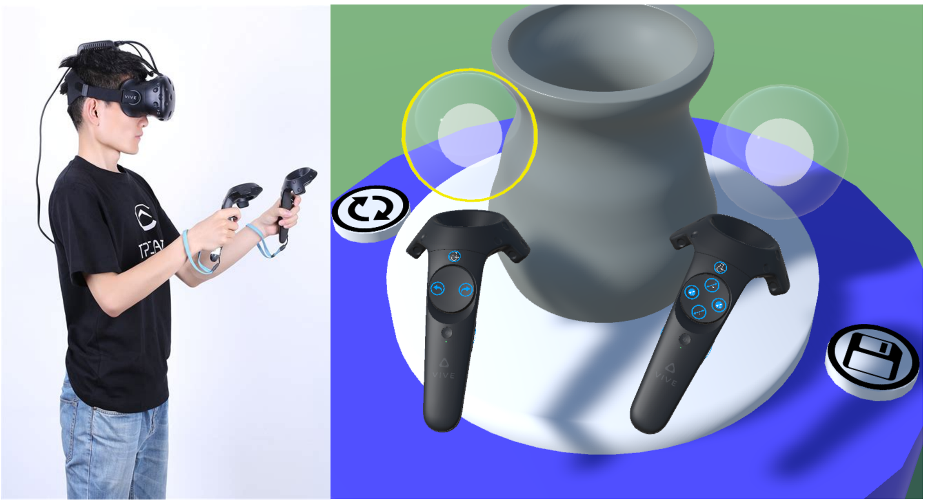

Fig. 1 A user is using our system to create virtual pots.

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 more 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 VE.

3 Interactive Modeling for Virtual Pottery in VR

3.1 System Overview

RealPot 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. RealPot 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.

3.1.1 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

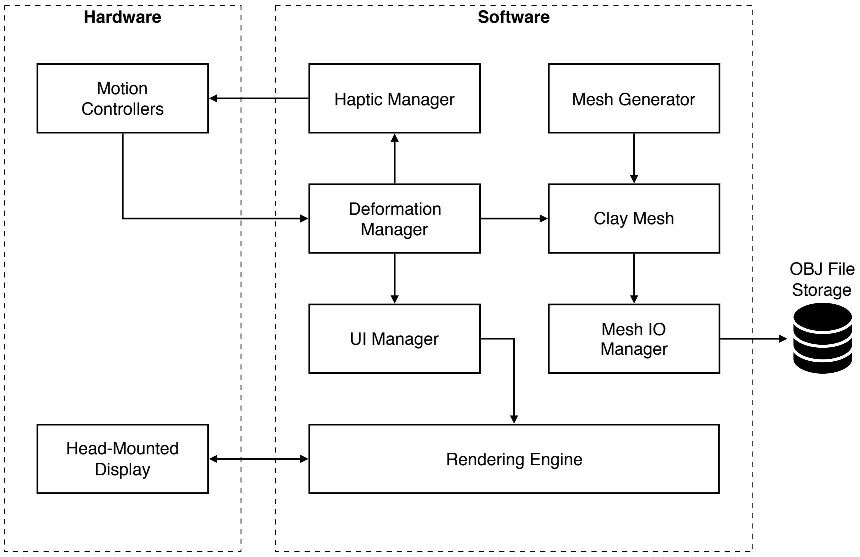

Fig. 2 The system architecture of RealPot.

via the rendering engine. Once the creation is done, the mesh IO manager will convert the meshes into OBJ files and save them.

3.1.2 Workflow

In real life, the pottery creation process on a pottery wheel is called *throwing*, where a ball of clay is placed in the center of a turntable wheel-head, and shaped by a potter. Some interaction metaphors are used in RealPot, which simulates the operations on real-life pottery. To illustrate the pipeline of pottery creation in our system, an example workflow using RealPot is described as follows.

When a user starts to use RealPot, a realistic clay mesh is automatically generated with Perlin noise (Figure 3a, Section 3.2). 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 *centering* (Figure 3b, Section 3.3.1). 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 3.3.2). The system not only allows mesh deforming (Figure 3e, Section 3.3.3) with different deformation range parameters but also mesh smoothing (Figure 3f, Section 3.3.4), where the user can remove sharp features in the pot to get an 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.

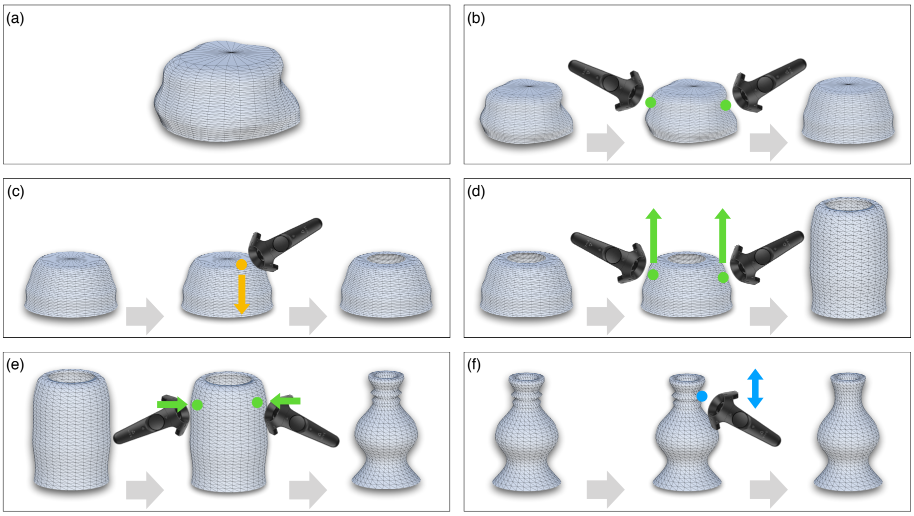

Fig. 3 The workflow in RealPot. (a) The automatically generated clay mesh with Perlin Noise. (b) The mesh is shaped into rotational symmetry by holding both hands. (c) The user controls the thickness of the mesh by pressing down the clay. (d) The user controls the height of the mesh by drawing up the 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.

3.2 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 [8, 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, RealPot 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.

3.2.1 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:

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

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

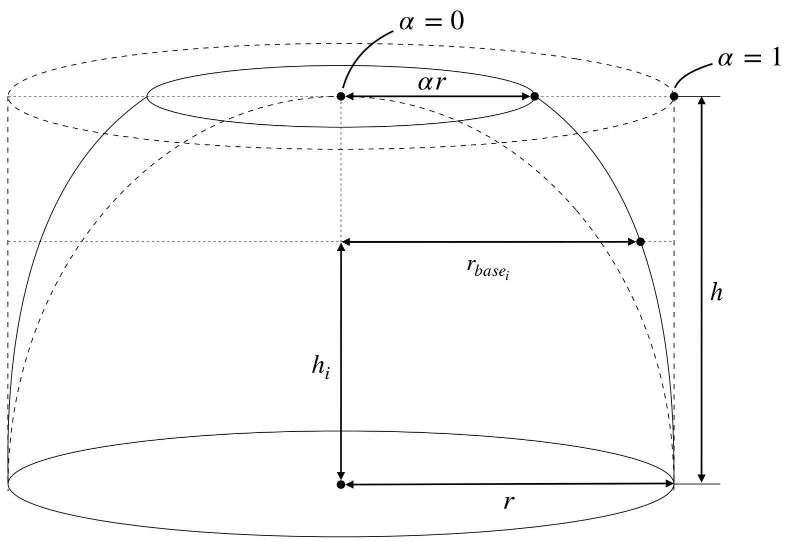

Fig. 4 The basic clay generated by our system, which is a blending shape between a cylinder and a semi-ellipsoid. α is the blending factor which controls the radius on the top.

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

3.2.2 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 treated 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 center 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 center for each circular section, random parameters ϕ_i and η_{c_i} are used to calculate the new center $\mathbf{O}_i$:

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

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

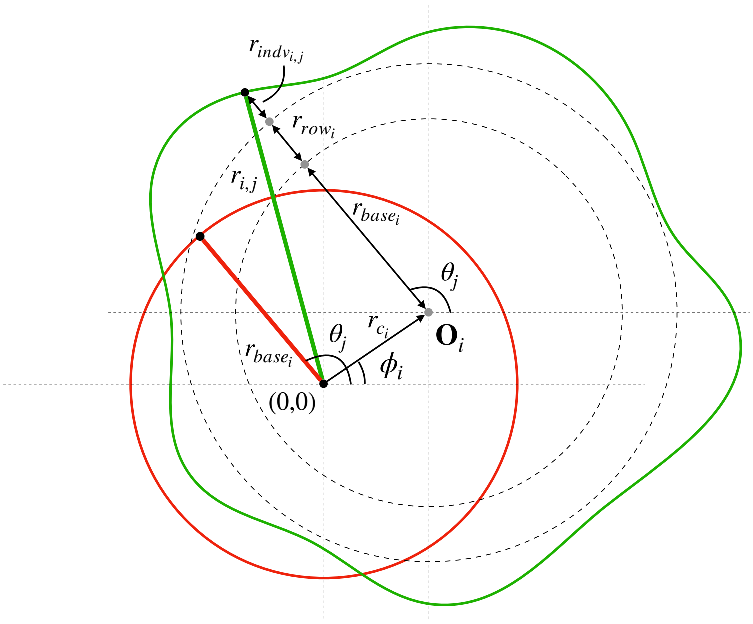

Fig. 5 To get a noised radius $r_{i,j}$ (green) based on radius r_{base_i} (red): (1) Move the center from origin (0,0) to $\mathbf{O}_i$. (2)Calculate the sum: $r_{total_{i,j}} = r_{base_i} + r_{row_i} + r_{indv_{i,j}}$. (3) Find the distance to the origin, which will be the noised radius $r_{i,j}$.

$\mathbf{v}_{i,j}$ for each vertex can be computed in the follow equations:

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

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

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

3.2.3 Inner Vertices

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

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

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

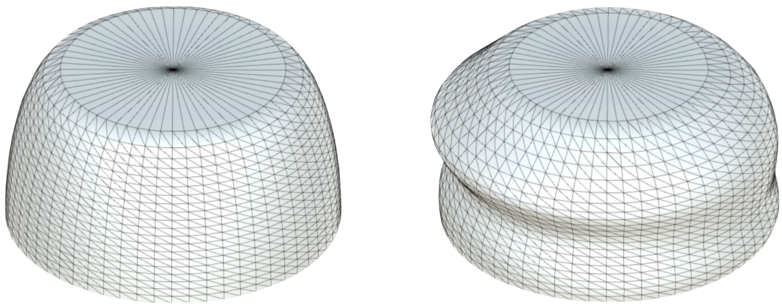

Fig. 6 The meshes generated with our system. (a) A regular mesh without adding Perlin noise. (b) A mesh with Perlin noise, which is more realistic as a clay.

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

3.3 Mesh Editing

After observing and analyzing several real-life pottery throwing videos, we put real-life clay operations into 5 categories: (1) rotational symmetry control, (2) thickness control, (3) height control, (4) mesh deformation and (5) mesh smoothing. And we propose 5 interaction metaphors in our system: *centering*, *opening*, *pulling*, *shaping* and *smoothing*, which correspond to the clay operations above. 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, RealPot 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.

3.3.1 Rotational Symmetry Control

Centering 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

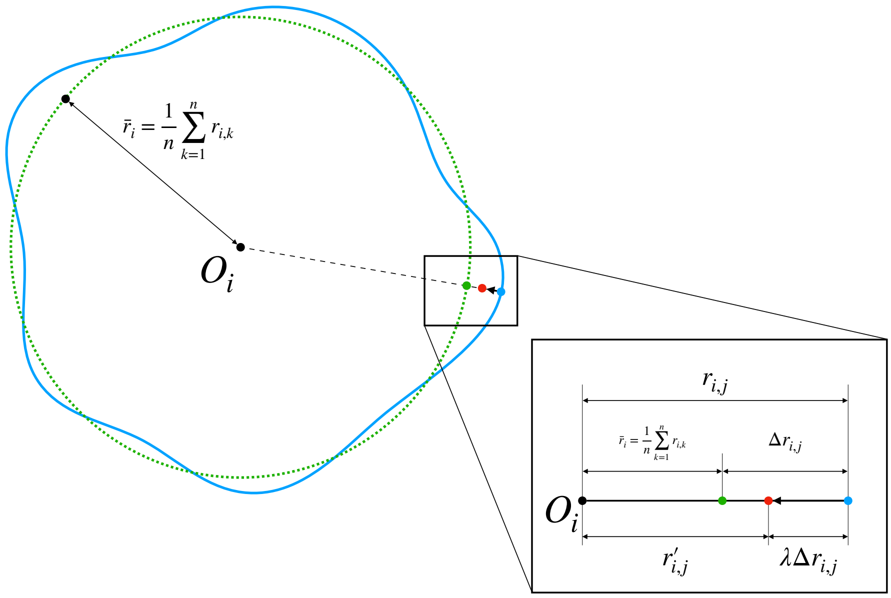

Fig. 7 Rotational symmetry control. The blue curve is the noised circular section at height h_i, and the green curve is a circle with the average radius $\bar{r}_i$. Let $\Delta r_{i,j}$ be the difference between $r_{i,j}$ and $\bar{r}_i$, then multiplied by the damping factor λ. New radius be calculated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

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.

3.3.2 Thickness and 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 center part of the clay, making a centered 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'.

3.3.3 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, RealPot 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 3D cursor position at time t_0 when the deformation starts, and we can calculate the initial radial distance of the 3D cursor from y-axis: $\rho_0 = \sqrt{x_0^2 + z_0^2}$. The new 3D cursor 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 3D cursor touches the mesh, the vertical distance $d_{i,j}$ between the 3D cursor 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 (Figure 8a). The fixed region will keep constant during the deformation, where $d_{i,j} > R_O$; the moving region will follow the movement of the 3D cursor, 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: $w_{i,j} = f(t)$, where $t = (d_{i,j} - R_I)/(R_O - R_I)$. There are many ways to select a smooth falloff functions for the weights, which needs to satisfy these additional requirements: (i) f(0) = 1 , (ii) f(1) = 0 and (iii) f'(0) = f'(1) = 0.

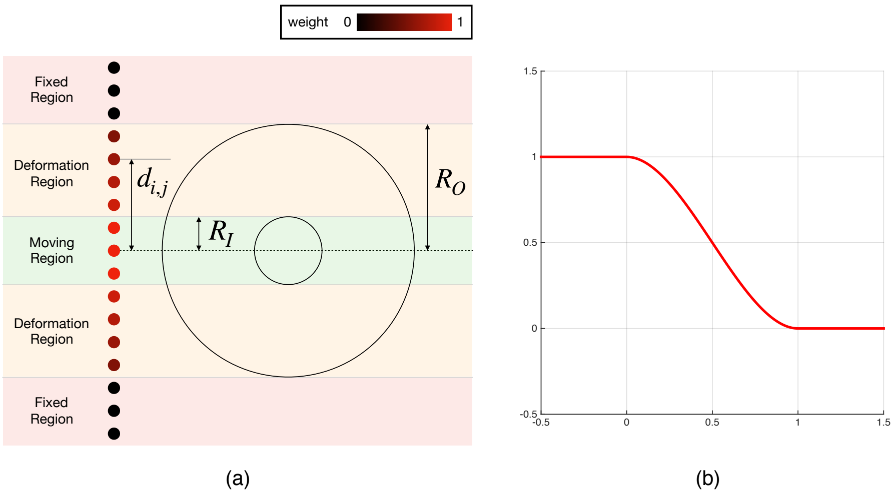

Fig. 8 (a) The concentric circles represent the 3D cursor, and R_I and R_O define the inner range and outer range respectively. $d_{i,j}$ is the vertical distance between a vertex $\mathbf{v}_{i,j}$ in the deformation region and the 3D cursor, which is used for calculating weight parameter : $t = (d_{i,j} - R_I)/(R_O - R_I)$. (b) A cubic polynomial function $f(t) = 2t^3 - 3t^2 + 1, t \in [0, 1]$ is used as the falloff curve for calculating the weight $w_{i,j}$.

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 8b).

3.3.4 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:

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

where N is the number of adjacent vertices of $\mathbf{v}_{i,j}$; $\omega \in [0, 1]$ is a factor controlling the smoothing effect. Only the vertices within the range of the 3D cursor R_O will be affected. As a result, users can control the 3D cursor position and adjust the outer range R_O of the 3D cursor to apply smoothing on specific areas interactively on the mesh.

3.4 Haptic Feedback Model

Haptic feedbacks can be crucial when touching or grasping an object in virtual environments, which are helpful for users to perceive the location of virtual objects. However, little work has been done on haptic feedbacks in the existing virtual pottery systems, due to their intrinsic barehand-based interaction mechanisms. To increase the fidelity of our system, a haptic feedback model for virtual pottery is described in this subsection. Unlike the barehand experience, RealPot provide users with rich haptic feedbacks by handheld controllers based on the proposed model.

3.4.1 Analysis of the sensation in real life pottery

In real life pottery, users can perceive forces from hands and fingers when performing various operations on the clay. Moreover, users can obtain information from these forces, such as shape and smoothness etc.

To provide realistic haptic feedbacks in our system, we analyzed the pottery throwing process in real life. In general, the haptic feedbacks from clay can be classified into two categories based on the type of forces: friction force and reaction force. When a user softly touches the clay without pushing or pulling, he/she can perceive the sensation on fingers or hands since the clay is rotating. In addition, when a user pushes or pulls to deform the clay, reaction forces are generated in the opposite direction to the movement.

From the analysis, clay various changes including...(i)friction (ii)reaction

As described in Section 3.3, there are five main mesh editing operations in our system.

By designing mechanisms that simulate the forces, we can realize a virtual pottery system with realistic haptic feedbacks. The mechanisms will be described in detail in the following subsections.

3.4.2 Friction Haptic Model

In this subsection, we describe a model to calculate the friction force, which is generated when the user touches the surface of the rotating clay.

For calculation efficiency, we assumed the friction type as kinetic friction, which is a force that opposes the relative motion between moving surfaces. The frictional force can be calculated by the following equation:

$$F_f = \mu \cdot F_n \tag{19}$$

where μ is the coefficient of friction between clay and hand, and F_n is the normal force exerted on the clay surface.

Since all the mesh editing operations in our system can be performed using handheld controllers, we use the trigger value as the input of normal force.

The trigger value ranges from 0 to 1, which indicates how much has the user pulled the trigger button.

In the HTC VIVE handheld controllers, haptic feedback is generated by the built-in vibrators. The haptic pulse intensity based on friction is calculated as:

$$k_f = k_{min} + \epsilon \cdot k_\mu \tag{20}$$

where k_0 is the minimum friction intensity when user just touches the clay, and $\epsilon \in [0, 1]$ is analog value of the trigger button. k_μ is the predefined coefficient.

3.4.3 Reaction Haptic Model

In actual pottery creation processes, users often exert forces to deform the clay by pushing or pulling.

According to Newton's Third Law, the forces between the hand and the clay exist in equal magnitude and opposite direction.

Since handheld controllers are used in our system, the reaction force exerted by hands can be calculated based on the position of the controllers.

$$\mathbf{F} = m\frac{\mathrm{d}\mathbf{v}}{\mathrm{d}t} \tag{21}$$

Since both the hand mass m and frame time interval Δt are constant, a predefined value k_ω is used in the follow equation to calculate

The reaction haptic intensity k_r in each frame can be calculated based on the consecutive controller positions in last three frames:

$$k_r = k_\nu \cdot \|\mathbf{v} - \mathbf{v}'\| = k_\nu \cdot \|(\mathbf{x} - \mathbf{x}') - (\mathbf{x}' - \mathbf{x}'')\| = k_\nu \cdot \|\mathbf{x} - 2\mathbf{x}' + \mathbf{x}''\| \tag{22}$$

Here, k_ν is a predefined coefficient; $\mathbf{x}$ is the controller position in current frame; $\mathbf{x}'$ and $\mathbf{x}''$ are the consecutive controller positions in last two frames.

The total hapic intensity is the sum of friction force and reaction force.

$$k_\sigma = k_r + k_f \tag{23}$$

From the above, the user can perceive rich haptic feedback when shaping the virtual pottery.

By providing haptic feedback based on k_σ, we can implement the sensation caused by clay deformation.

In a VE, it is not so easy for users to perceive if her hands have touched anything. Hence, our system adds visual feedback on both virtual sphere, which will be highlighted when touching the clay (Figure 9).

3.5 Interactions

RealPot is designed as a pottery studio built in a VE. In our implementation, we use a HTC Vive VR system [11], which includes a head-mounted display (HMD) and two hand-held controllers to track user head orientation and bimanual movements (Figure 10). The HMD uses head tracking to create a human-centric rather than a computer-determined point of view, and the two hand-held controller allows user to manipulate the mesh in a natural and realistic way. 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

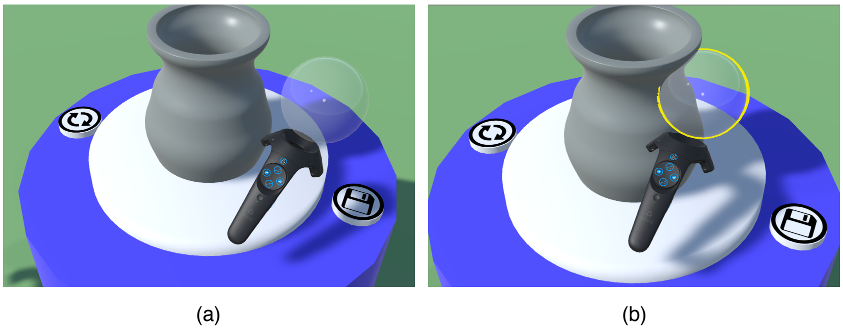

Fig. 9 The visual and haptic feedback when user touches the clay. (a) The normal state of the 3D cursor when it is not touching the clay. (b) The highlight state of the 3D cursor when a user has touched the clay, with a haptic pulse to the corresponding hand.

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 immediate visual feedback from the size of the sphere.

Undo/Redo RealPot 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.

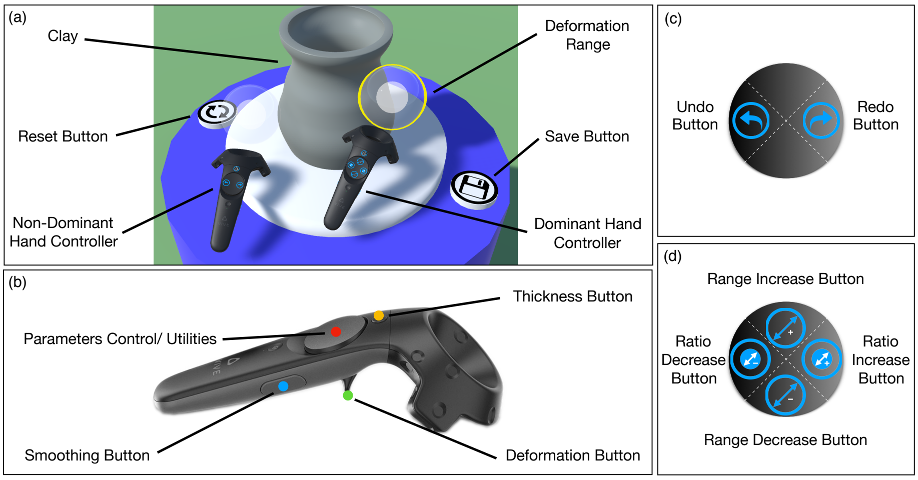

Fig. 10 The user interface of our system. (a) The pottery wheel in the virtual space. (b) The controller button configuration of RealPot. (c) The button layout of left controller pad. (d) The button layout of right controller pad.

Table 1 The random parameters based on Perlin Noise.

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

3.6 System Configurations

We have implemented RealPot using Unity3D [31] game engine. RealPot 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, RealPot 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 centering parameter λ, height parameter γ and smoothing parameter ω 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 realistic look of the clay. Table 2 demonstrates statistics based on different mesh solutions. Higher resolution requires 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 RealPot.

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

Fig. 11 The virtual pots designed by our system, which are real-time rendered in Unity3D.

4 User Studies

4.1 User Study 1: Haptic Models

The goal of our first user study was to investigate how different haptic models can impact user experience. Although McMahan et al. found that display fidelity significantly affect performance in virtual environments [19], they only focused on the visual aspects, not haptic aspects. To increase experimental control and reduce confounds, we adopted a systematic approach that utilizes RealPot while investigating haptic fidelity. As the independent variable, haptic fidelity had three levels (No Haptic Model, Basic Haptic Model and Advanced Haptic Model) and varied within subjects. The presentation order of the three conditions was counterbalanced between subjects.

4.1.1 Appartus

In order to evaluate different levels of display fidelity, we used HTC Vive Virtual System, which contains a head mounted display (HMD) and two wireless motion tracked controllers. The HMD has a resolution of 2160 x 1200 (1080 x 1200 per eye) and a refresh rate of 90 Hz. The wireless motion tracked controllers have multiple input methods including a track pad, grip buttons, and a dual-stage trigger, which can generate pulses to provide haptic feedbacks.

4.1.2 Participants

36 participants were participated in our user study, 23 males and 13 females, whose age ranged from 24 to 41 years. 8 of the subjects are familiar with VR systems (?%); 2 of the subjects have experience with 3D modeling tools (?%); 4 of the subjects have amateur pottery throwing experience in real life (?%).

4.1.3 Experimental Design

The participants were required to perform 5 tasks with 3 different haptic models.

No Haptic Model : In this condition, there was no haptic model applied. In the case without haptic model, RealPot did not provide any haptic feedback, even if the cursor touches the virtual clay.

Basic Haptic Model :

Advanced Haptic Model : In the case with the basic haptic model, the system provided haptic feedback that change according to the amount that user pulled the trigger on the handheld controller.

tasks

4.1.4 Procedure

Each participant was required to fill out a background survey, which collected general demographic information and experiences of VR, real pottery and 3D modeling tools. In the next phase, each participant experience a quick VR training for five minutes. Since it is possible that the participants are first time users to virtual reality, that subjective may be influenced by Hence, we hoped VR familiarity could eliminate "wow-factor" situations.

The order of the three different conditions (i.e. no haptic model, basic haptic model and advanced haptic model) and the five tasks was assigned at random for each participant.

the order of ... was counterbalanced between subjects.

evaluate the components of A and B while controlling other components

4.1.5 Metrics

For usability and preferences, we developed our own usability questionnaire consiting of seven-point Likert-scale items (See Appendix A)

Each participant evaluated the basic and advanced model using a seven-point Likert scale, with 1 being the most negative score, 7 the most positive and 4 the baseline with no haptic model.

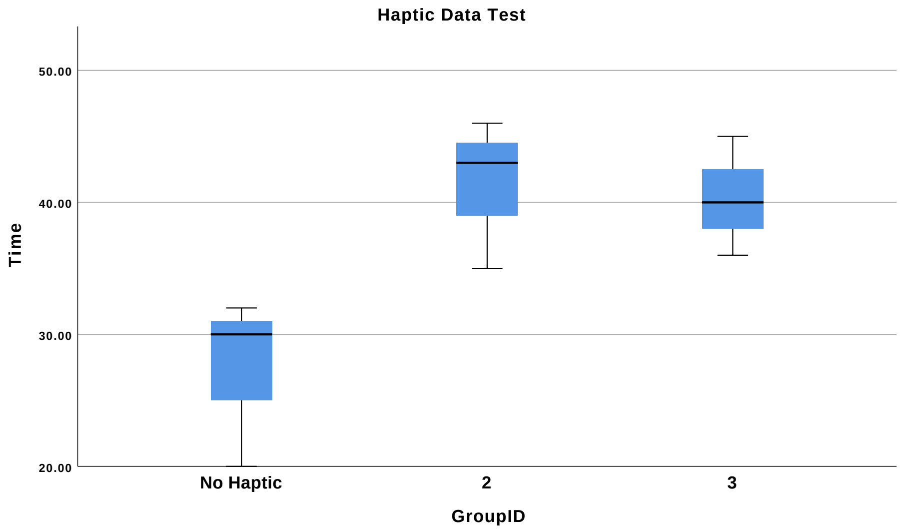

Fig. 12 user study 1 result here

To evaluate the overall performance of the two systems, we collected metrics related to objective user performance and subjective judgments of usability and presence. For user performance, we measured completion time and accuracy. The accuracy was the correlation coefficient between the user-created shape data and the target shape data.

For perceptions of presence, we used Slater-Usoh-Steed (SUS) Presence Questionnaire after each trial. To measure the usability of pottery systems, we developed our own usability questionnaire consisting of seven-point Likert-scale items (see Appendix A).

4.1.6 Study Results

For completion times, we performed a one-way ANOVA and the results showed two systems had a significant effect ($F(1, 23) = 82.3503, p < 0.0001$). For accuracy, we performed a one-way ANOVA and the results showed two systems had a significant effect ($F(1, 23) = 82.3503, p < 0.0001$). For subjective presence questionnaire, we performed a one-way ANOVA and the results showed different haptic models had a significant effect ($F(1, 23) = 82.3503, p < 0.0001$). For subjective usability questionnaire, we performed a one-way ANOVA and the results showed different haptic models had a significant effect ($F(1, 23) = 82.3503, p < 0.0001$). To determine if participants' backgrounds hand any significant effects on our results, we computed Pearson correlation coefficients to assess the relationships between objective metrics and participants' real pottery experience and VR experience.

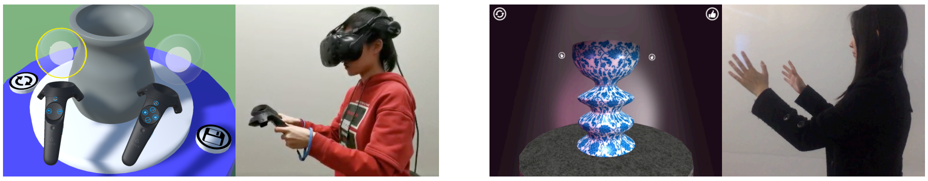

Fig. 13 The systems used in our user study. (a) RealPot: the proposed immersive virtual pottery system based on handheld haptic motion controllers (b) DigiClay: a representative of barehand based virtual pottery systems.

Table 3 A comparison of the two systems used in our user study.

System	Platform	Input Method	Immersion	Haptic Feedback
RealPot	PC	Hand-held Motion Controllers	Yes	Yes
DigiClay	PC	Barehand	No	No

4.2 User Study 2: RealPot vs barehand based systems

2nd: compare RealPot with other virtual pottery systems To investigate the usability of RealPot, we compare RealPot with other barehand based virtual pottery systems. We used DigiClay, a representative of barehand based virtual pottery systems [7].

4.2.1 Appartus

The two evaluated systems were as follows:

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

DigiClay : DigiClay uses Kinect, Unlike the HMD which can provide immersive experience, We used a Dell 23.8" LED monitor with a 1920 x 1080 resolution and 60Hz refresh rate to provide output for low level of visual display fidelity. Kinect, which is composed of a RGB camera and a IR camera both with 640 x 480 resolution and 30 Hz refresh rate.

The interfaces of the systems are demonstrated in Figure 13, and a comparison of these systems is listed in Table 3.

4.2.2 Participants

39 participants were participated in user study 2, 10 males and 9 females, whose age ranged from 8 to 32 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%).

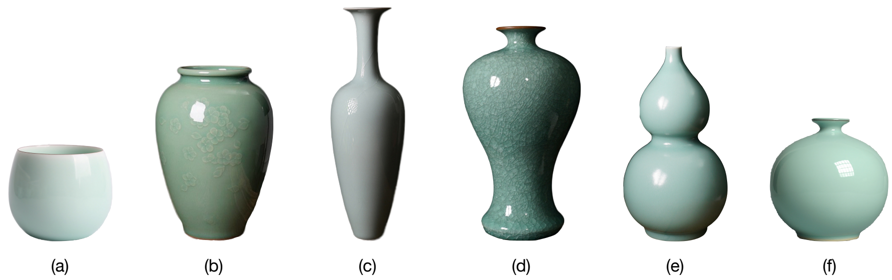

Fig. 14 The target shapes used in our user study, which have various heights and curvatures.

4.2.3 Experimental Design

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

$\mathbf{T}_2$: 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.

When doing tasks $\mathbf{T}_1$ and $\mathbf{T}_2$, a total of six target shapes were presented to subjects in a randomized sequence (Figure 11).

4.2.4 Procedure

Each participant was required to fill out a background survey, which collected general demographic information and experiences of VR, real pottery and 3D modeling tools. In the next phase, each participant experience a quick VR training for five minutes. Since it is possible that the participants are first time users to virtual reality, that subjective judgments may be influenced by "wow-factors". Hence, we hoped VR familiarity could eliminate "wow-factor" situations.

After the VR exposure phase, participants proceeded through the tasks in a randomized order. There was a training session before each task, in which the experimenter explained how to interact with the given system and the participant was allowed to practice. After the practice session, participants were instructed to shape the clay according to the target shape as quickly as possible while maintaining high accuracy. Afterwards, the participants were given the usability and presence questionnaires.

4.2.5 Metrics

To evaluate the overall performance of the two systems, we collected metrics related to objective user performance and subjective judgments of usability and presence. For user performance, we measured completion time and accuracy. The accuracy was the correlation coefficient between the user-created shape data and the target shape data.

For perceptions of presence, we used Slater-Usoh-Steed (SUS) Presence Questionnaire after each trial [30]. To measure the usability of pottery systems, we developed our own usability questionnaire consisting of seven-point Likert-scale items (see Appendix A).

4.2.6 Study Results

For completion times, we performed a one-way ANOVA and the results showed two systems had a significant effect ($F(1, 23) = 82.3503, p < 0.0001$). For accuracy, we performed a one-way ANOVA and the results showed two systems had a significant effect ($F(1, 23) = 82.3503, p < 0.0001$). For subjective presence questionnaire, we performed a one-way ANOVA and the results showed different haptic models had a significant effect ($F(1, 23) = 82.3503, p < 0.0001$). For subjective usability questionnaire, we performed a one-way ANOVA and the results showed different haptic models had a significant effect ($F(1, 23) = 82.3503, p < 0.0001$). To determine if participants' backgrounds hand any significant effects on our results, we computed Pearson correlation coefficients to assess the relationships between objective metrics and participants' real pottery experience and VR experience.

5 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 creation processes. 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 change without using undo/redo shortcut provided by RealPot.

We also asked their suggestions for the future features they wanted to see in RealPot. 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 RealPot 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.

6 Conclusions

We present RealPot, an immersive virtual pottery system in VR. Closely linked to pottery creation experience in real life, our system enables users to manipulate the mesh in real time with two hands, allowing them creating a variety of pottery models from realistic generated clay meshes. As an educational tool, RealPot 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 RealPot 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.

Appendix: Usability Questionnaire

1. Rate how easy
2. Rate how natual
3. Rate how much fun
4. Rate how tiring
5. Rate how much skills you gain from the virtual pottery training

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