PotteryGo: A Virtual Pottery Making Training System

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This article presents a pottery-making training system with a focus on teaching fundamental knowledge and practical techniques in a virtual-reality environment. Gesture analysis makes it possible to correct the learner's actions via visual feedback. Our results demonstrate the efficacy in assisting beginners with learning the gestures used in pottery-making.

Pottery refers to the production of clay vessels. Mastering the requisite skills for crafting pottery eludes most novices due to the need for extensive practice, which requires access to a suitably equipped pottery studio and materials. In this study, we developed a novel instructional system referred to as PotteryGo, which integrates sensor-based gesture recognition with 3D modeling techniques within a virtual-reality environment, as shown in Figure 1. Deformations in the virtual vessels are controlled using hand gestures detected by motion sensors.

Several studies have addressed the issue of virtual pottery-making. Kumar et al. generated 3D pottery models by manipulating control points and 2D generatrixes;[1] however, the vessels produced using their method tend to be excessively symmetrical; i.e., they are not accurate representations of real-world clayware. Cho et al. proposed a digital pottery system in which vessels are manipulated by the user's hand.[2] Vinayak et al. achieved delicate shape deformations using polygon meshes with precise control over the surface of the model.[3-5] Unfortunately, these studies focus on the appearance of the model without taking into account the computer-human interaction associated with the study of pottery-making in the real world. Overall, a lack of variety in gestures and insufficient visual feedback make these systems unsuitable to pottery instruction.

We sought to overcome these shortcomings by creating an interface and set of gestures modeled on traditional hand-throwing techniques (the technique that produce an artisan craft by working clay on a potter's wheel), with a focus on teaching fundamental techniques, providing practice in the use of those techniques, and creating customized pieces of pottery.

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These objectives are achieved by 1) providing tutorials on the fundamental techniques used in pottery-making; 2) providing step-by-step visual guidance and feedback while users practice creating pieces based on specific models; 3) allowing users to create custom pottery pieces based on the models. We also developed a series of games to provide motivation based on the G/P/S (Gameplay/Purpose/Scope) model proposed by Djaouti et al.[6] The proposed training system provides simulated exercises and problem-solving tasks designed in accordance with the design principles outlined by Susi et al.[7] The instructional content comprises basic information on the hand-throwing process and editable hand gestures. A visual feedback mechanism provides user guidance and corrections for erroneous hand gestures. PotteryGo also enables instructors (users) to record and playback their throwing techniques and share them with students (peers) or use them as a reference. PotteryGo provides a step-by-step approach to developing the skills used in the art of handmade pottery.

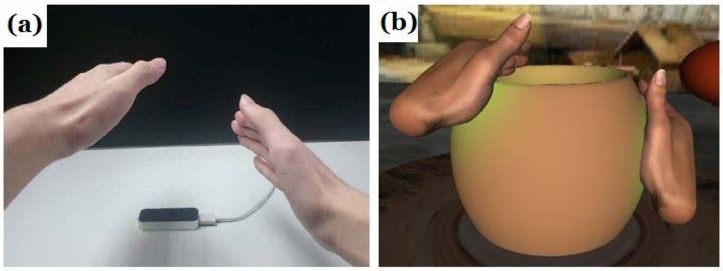


Figure 1. Manipulating virtual pottery via hand gestures: (a) detecting hand gestures using a motion sensor; (b) the corresponding gesture rendered in real-time in a virtual-reality environment.

The effectiveness of PotteryGo and user experiences of the system were evaluated in a three-phase user study with participants who possessed no prior pottery experience. Our results demonstrated the following: 1) After receiving the tutorial, participants were able to make a ceramic base in fewer attempts than before the tutorial. 2) Participants who received guidance through visual feedback required fewer attempts than did those who received no visual guidance. 3) Participants who underwent this training were able to produce an actual ceramic base as easily as individuals who received instruction in a real-world pottery studio. 4) Participants rated their experience with PotteryGo as highly satisfactory.

PREVIOUS WORK

Our main objective was to develop an effective interactive training system using feedback and guidance based on the design concepts and principles developed in previous studies on human-computer interactions.

Igarashi et al. proposed prediction and suggestion mechanisms for use in a 3D drawing system.[8] When users draw a stroke on the screen, the system analyzes the geometric properties and suggests subsequent operations in an array of small thumbnails. The system also allows users to preview their drawing result and provides suggestions in real-time while accelerating the process by omitting repetitive operations. Tsang et al. extended the design concept of by adding contour-drawing suggestions and 3D volume maps for guidance.[8-9] Rather than starting from a blank canvas, users complete a 3D image by copying contours suggested by the system in real-time. The multiple segment styles and spatial guidance substantially reduces the time and effort required to create 3D images while ensuring that the finished products possess the correct proportions. Paczkowski et al. developed an interactive 3D paper-folding system in which users perform folding, cutting, and curling using simple finger gestures on a tablet PC.[10] The screen displays circles in various colors to suggest finger combinations for various operations as well as arrows to guide the user's actions. This system greatly accelerates the process of learning origami, and the same steps can be used to reproduce the virtual models with actual pieces of paper.

In this study, we adopted the concepts outlined in the research of the suggestive interface.[8-9] We did not adopt employ haptic feedback because we wanted to avoid a situation where users would be required to purchase additional equipment. To lower the learning curve and facilitate the use of the virtual pottery training system, we incorporated gesture suggestions and guidance as a vision-based feedback mechanism. We also adopted the approach proposed by Paczkowski et al. and incorporated learning elements within an interactive system to enable users to model pottery and learn skills at the same time.[10] Interactivity has been shown to improve learning efficiency. It was our intention that users would be able to apply the techniques they learned in the creation of handmade ceramic items in the real world.

Surface Deformation

Lee et al. proposed the Circular Sector Element Method to simulate the shape deformations employed in pottery,[11] wherein collision detection is applied in circular sectors of the virtual pottery model to calculate the direction of external forces and immediately render their effects. Unfortunately, the final model exhibits what appear to be raised layer lines on the surface. We sought to develop a more sophisticated sectoring method to avoid this problem. Gautam et al. proposed a number-theoretic approach to produce perfectly symmetrical models,[1] wherein the profile of the model was defined by control points in user-defined positions (i.e., points with 2D coordinates) with the curve between two control points calculated using a spline interpolation matrix. The efficiency of this method was demonstrated by the small number of control points required for surface rendition; however, the final models are overly symmetric in appearance, such that they do not resemble real-life handmade pottery. Cho et al. proposed a digital pottery system capable of taking into account manipulation by the user's hand.[2] However, that system simply detects the positions of the user's hand for collision detection, as opposed to gestural changes. Model deformation is conducted via collisions between hands and the voxelized model, whereupon the finished surface is reconstructed using the marching cubes algorithm. Vinayak et al. proposed a modeling and surface-manipulation system based on intelligent generalized cylinders.[3] The range of the virtual pottery model is defined by layers of generalized cylinders, and surface smoothing is achieved by spline interpolation. Deformation of the cylinders can be used to render the surface of the model as concave and convex. This system is able to produce a diversity of results due to the ability to deform the generalized cylinders section by section. However, an inability to edit the surface on the y-axis prevents the mimicking of clay-centering and hole-opening functions in actual the creation of handmade pottery. Vinayak et al. proposed a mesh-based system for shape deformation.[5] Following the selection of mesh vertices on the surface using specific hand gestures, the system defines the cylindrical range of influence and all vertices within the range are subject to deformation. When users move the vertices to the target position using hand gestures, the system immediately generates symmetrical mesh deformations on circular sections. This method creates excellent finished models; however, the shape manipulation process differs from the process of making handmade pottery in the real world.

In this study, our deformation functions enable surface real-time deformations of an object rotating at a constant speed (the speed of the spinning wheel). In seeking to mimic the deformation methods used in actual handmade pottery while taking into account the fluidity of operations and aesthetics, we adopted the scheme proposed by Vinayak et al. in which mesh vertices are employed as the basic deformation unit to obtain accurate results for surface deformation.[5]

The above review reveals that most of the existing systems used for model deformation and sculpture focus on the appearance of deformation and strive to produce perfect pieces of art. None of these systems were designed specifically to promote the development of skills pertaining to the hand throwing of pottery pieces in the real world. The proposed interactive human-computer system includes a set of learning and guiding functions aimed at enhancing user experience and learning efficiency.

DESIGN PRINCIPLES

Our design objectives of the virtual pottery training system, including respect for traditional pottery techniques, principles of serious gaming, extensible learning content and real-time visual feedback, are detailed in the following:

Respect for traditional pottery techniques. We deemed that the pottery-making pipeline, gestures, and overall instrumentation must adhere to existing real-world practices. The system therefore emulates traditional pottery manufacturing techniques to enable users to use much the same gestures when crafting handmade pottery after training.

Principles of serious gaming. Serious games emphasize the learning experience of users while engaged in playing the game. This means that instructional content is an indispensable element in any learning system. Well-designed content can help users understand the importance of compliance with operational rules by experiencing the effects of reckless actions (e.g., over-lifting virtual pottery or excessive depressions causing collapse).[7] One crucial indicator of design success is whether the games assist users in problem solving. PotteryGo teaches basic knowledge of handmade pottery (tutorial) while continually providing visual prompts and messages to correct mistakes (interactive training). This helps users understand key elements of pottery-making. It also helps them to quickly become sufficiently accustomed to these actions to allow them to create real-world handmade pottery.

Djaouti et al. classified serious games using the G/P/S model, in which gameplay classifies games based on rules and objectives;[6] purpose classifies games based on message broadcasts, training, and data exchange; and scope classifies games according to their target market and audience. Table 1 compares the proposed system with those pottery systems using G/P/S model classification.[2,4] The latter two are classified as play-based, as they lack goals. The proposed system has a competitive advantage over the other two systems from the perspective of education because the inclusion of simulated training, virtual pottery procedures, and customizable manipulation gestures grant the system goals, purpose, and a targeted scope.

Extensible learning content. PotteryGo enables step-by-step instruction through gesture recording and playback. For example, an instructor could use the recording function to record the gestures required to create a ceramic cup, including raising the model to the appropriate height, digging into the top of the model, and pushing the edges to protrude. Students can then learn these steps using the playback function, and try to replicate the cup by following them.

Real-time visual feedback. It is expected in any field that beginners will experience a variety of mistakes and setbacks. We sought to mitigate the negative consequences of mistakes by providing a real-time visual feedback mechanism, including assistive hand shadows, distance spotlights, and status labels. This makes it possible for users to complete gesture learning and error correction using a variety of visual aids. Triggering a gesture function allows the user to immediately see the corresponding shape deformation in his/her piece.

Table 1. Comparison between systems based on G/P/S model.

	Vinayak's[4]	**Cho's[2]**	**Ours**
Gameplay	Play-Based	Play-Based	Game(Goal)-Based
Purpose	No educative message broadcast and no training	No educative message broadcast and no training	Educative message broadcast and training
Scope	Entertainment for general public	Entertainment for general public	Culture & Arts for general public

SYSTEM OVERVIEW

As Figure 2 shows, the main features of the proposed system include the learning path (for students), the teaching path (for instructors), and the free creation path (for experienced users).

The learning path contains a tutorial module and an interactive training module. The tutorial module provides educational elements with detailed descriptions and instructions, where users can preview learning objectives and key operational methods. Users can enhance their impressions of the procedure and gestures using demonstration videos and examples of system operation. The interactive training module provides comprehensive visual guidance and feedback to assist users in familiarizing themselves with basic gestures. Once users become familiar with the operation of these gestures, they can move on to the free creation path. This path allows users to complete the pottery creation process by combining hand gestures and eventually painting the surface of their finished work. We discuss the details of gesture-based modeling techniques in the section on "Gesture Recognition." The teaching path allows instructors to record specific processes to extend training in the creation of finished products.

Once users exhibit an understanding of the basic operational gestures and become familiar with the production process, they can move on to advanced learning based on prerecorded videos showing the gestures required to make specific examples of pottery. This also makes it possible for experienced users to record and share their work.

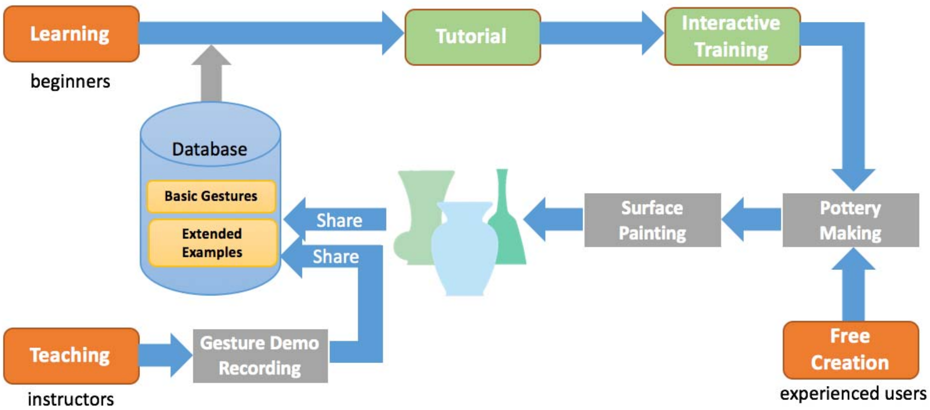


Figure 2. System overview: The learning path allows users to experience a full tutorial on the pottery-making process as well as training in the use of interactive gestures. The teaching path allows instructors to record processes and share them for extended learning. Experienced users can freely play and (optionally) share their work for extended learning.

VISUAL FEEDBACK DESIGN

A clear and informative user feedback design is required to allow users to quickly master the operating environment. Our objective in this study was to construct an easy-to-use virtual learning environment for pottery-making; therefore, it was imperative to analyze the type of user feedback mechanisms appropriate for guidance. Thus, we designed a tutorial system for educational purposes in conjunction with an interactive training scheme to give the users the experience required for skill mastery. We adopted the classification system proposed by Renaud,[12] in which user feedback is classified as archival or immediate, as Figure 3 shows.

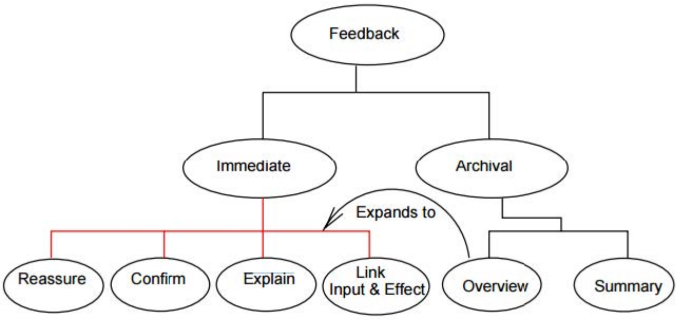


Figure 3. Design of user feedback system.[12]

Archival feedback is similar to an instruction manual or a system overview that allows users to preview system operations. Our tutorial module is classified as archival feedback. In addition to the detailed instructions provided before the start of each learning stage, users are also provided with prearranged educational content and gesture operating procedures. Immediate feedback involves real-time prompts, such as cautions and confirm buttons. Our interactive training module is classified as immediate feedback.

We adopted design concepts and feedback mechanisms commonly used in gesture-learning and interactive games,[13] the efficacy of which (particularly in an interactive environment) have been demonstrated in experiments. We also adopted the verification method for use in confirming the benefits of the feedback mechanism when applied to our virtual pottery training system. The following two modules outline the main design content of the tutorial and interactive training system.

The tutorial module provides comprehensive coverage pertaining to system operation and learning content, as shown in Figure 4(a). A demo video illustrates how to edit virtual pottery using hand gestures, and a corresponding real-life video shows how this is done in the real (physical) world. The guide book in the left panel presents the procedures used in pottery-making: 1) wetting hands for preparation; 2) five basic hand gestures (dig, raise up, push down, push surface, and pull surface; and 3) painting the surface of a finished workpiece. The tutorial gives the users an overall idea of the process. During interactive training, the same content can be displayed in the panel on the right, as shown in Fig. 4(b).

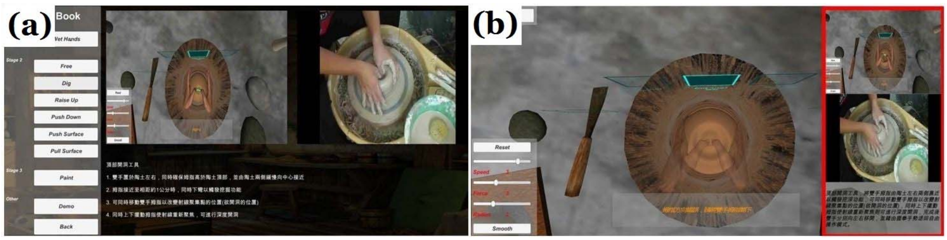


Figure 4. Tutorial videos used as preview of pottery-making pipeline.

The interactive training module provides visual guidance and feedback as users practice the gestures. The objective in providing visual guidance is to accustom users to the hand gestures. The objective in providing visual feedback is to provide users with immediate responses to their actions and to keep them notified as to the active range of manipulation, area of deformation, and manipulation status. We developed four categories of visual guidance/feedback, the motivation and objectives of which are detailed in the following:

1. Trigger spotlight: The fact that our system does not provide haptic feedback makes it difficult for users to orient their hands with regard to the virtual clay. As shown in Figure 5(a), the trigger spotlight provides immediate visual feedback of the relative

distance between the user's hands and the virtual clay. It also uses a green light to indicate whether the user's hands are within range to manipulate the virtual clay, and a red light to indicate that they are out of range.

2. Thumb ray and deformation spotlight: Hole-digging involves the use of the thumbs together to dig a hole into the top of a pot as the other fingers grasp it, as shown in Fig. 5(b). On-screen, light rays are emitted from each thumb in the direction they are pointed. The intersection of the two rays indicates the center of the hole. A green spotlight is used to highlight the area around this point. This gives the user an intuitive sense of how their gestures affect the pot, and thereby helps them to avoid undue deformation.
3. Hand shadow: The hand shadow function is a novel contribution of the present study, allowing users to quickly comprehend various hand gestures and their spatial relationship with the virtual clay. As shown in Fig. 5(c), the system displays assistive hand shadows where the hand should be and how the gestures should appear. The hand shadows make it easier to learn the gestures by reducing the time required to get used to the operating space. Without this guidance function, users would have to spend additional time figuring out their hand locations, which could lead to a frustrating learning experience (as stated by participants in our experiment).
4. Text labels indicating gesture status: When users encounter a problem, a label explains the current status and provides solutions via brief text descriptions, as shown in Fig. 5(d). This feedback function eliminates misunderstandings and helps to resolve difficulties.

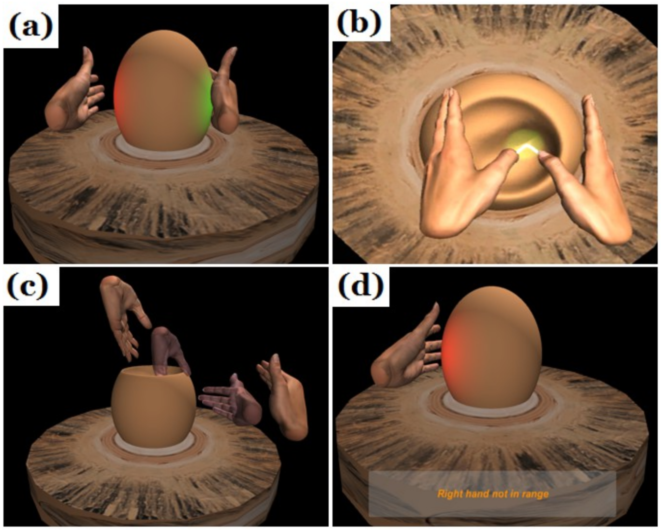


Figure 5. Elements of visual feedback in proposed interactive training system: (a) trigger spotlight; (b) thumb rays and deformation spotlight; (c) hand shadow; (d) text label indicating gesture status.

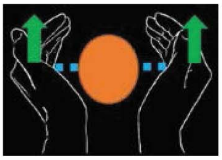
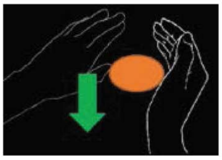
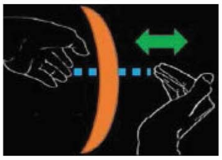
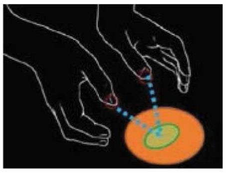
The proposed system also provides visual feedback related to deformation in real-time by synchronizing data related to the mesh and collision boundaries following each gesture operation. This makes it possible for users to immediately view their results on-screen, thereby enhancing the learning experience.

GESTURE RECOGNITION

Gesture Definition

The most common gestures were demonstrated in a variety of ways. We collected a number of online demonstration videos and conducted demonstrations by several professional instructors. Table 2 defines the important gestures raise up, push down, side push, side pull, and top dig.

Table 2. The Basic Gestures and Their Descriptions

Gesture	Definition of the gesture	Illustration
Raise Up	1. Both hands are positioned near the sides of the mold 2. Fingers point toward the front 3. Palms are aligned 4. Both hands slowly rise to trigger the raise up command	
Push Down	1. Left hand is placed on top of the mold 2. Right hand is placed to the right of the mold 3. Fingers point toward the front 4. Left hand slowly pushes the mold down to trigger the push down command	
Side Push & Pull	1. Place left hand inside the mold and right hand on the right side 2. Align both middle fingers 3. Right or left middle finger presses the mold to trigger side manipulation command 4. Hold the gesture to sustain manipulation	
Top Dig	1. Both hands are placed on the top of the mold 2. Thumbs are aligned fairly close together 3. Both thumbs are bent down to trigger top dig command 4. Maintain the gesture to sustain manipulation	

The green arrows in the figures on the right indicate the movement of each operation. First-time users may struggle to develop a spatial sense of working with virtual clay. To familiarize them with our learning approach, we developed real-time shape deformation techniques with particular strategies for their presentation. For the raise-up and push-down gestures, users place both of their hands close to the mold surface and slowly move them to produce shape deformations; i.e., the mold deforms upward or downward, respectively. Side-push and side-pull gestures involve moving the hands close to the virtual clay without actually touching it. This makes it possible to observe changes in the mold without covering the surface. For the top-dig gesture, we assume a viewing angle above the pot to make it easier to observe the process. The virtual hand is displayed at a slight distance from the mold to avoid an overlap between the viewing angle and the mold. This makes it possible for the user to observe his/her hand movements as well as deformation of the virtual clay.

To differentiate among the various gestures, we adopted the categorizations proposed by Deshayes,[14] who categorized similar gestures to reduce the complexity of a gesture recognition system . Virtual buttons are used to switch among the various gestures. Furthermore, the user can make fists with both hands to end the manipulation process, whereupon the system returns to its default state.

Hand Information and Depth Sensors

Simulating the creation of a handmade ceramic base requires highly sensitive detection of the user's gestures. In this study, we used a somatosensory depth sensor, Leap Motion, for the detection of hand gestures. This device can detect the vector of each finger, the position of each finger, the position of the palm and the normal vector of the palm, and use this information to determine whether the gesture matches our definition and whether it triggers a mold manipulation function. A user need only sit on a chair and perform the hand movements as he/she would in the creation of real-world pottery.

Mesh Deformation

We developed a real-time mesh deformation function to visualize how the surface of the mold changes according to hand gestures. In interactive training mode, the system uses detected hand gestures to define the region and shape of mesh deformations. When a gesture is presented correctly, the mesh deformation function is activated and continuously updates the shape of the mold within the region of deformation. The effective range of deformation is defined by the relative position of the user's hand with regard to the virtual clay. Deformation of the mold surface is determined using the Gaussian falloff equation.

Region of Deformation

While in interactive training mode, the surface of the mold undergoes continuous changes as long as the user maintains his/her hands in that gesture and the ray intersects to the surface. In each time frame, a region of interest (ROI) for the desired shape deformation must be designated, and only mesh vertices within the ROI are moved. In Figure 6(a), the ROI for each time frame was defined by center and a radius. The center is where the user's finger is pointing. We employed the ray cast method to project the finger toward the mold surface in order to find the center, as expressed in (1).

$$C = RaycastHit(f_{pos}, f_{\vec{N}}) \qquad (1)$$

where

f_{pos} and $f_{\vec{N}}$ respectively denote the position and the direction in which the finger is pointing. C refers to the center of the deformation region. The system automatically configures finger f according to the selected manipulation tool. When the top-dig tool is selected, f denotes a thumb; when the side-push or side-pull tool is selected, f denotes a middle finger.

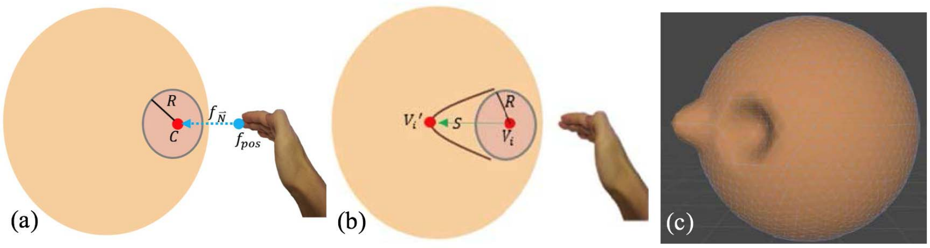


Figure 6. Mesh deformation: (a) definition of deformation region; (b) falloff deformation model designed to move vertices in the center the most (to) and those at the boundaries move the least; (c) examples of changes in mold surface using falloff model.

At present, the proposed system is unable to detect finger pressure. Thus, radius R of the deformation region is defined by a user-adjustable parameter via a slider on the interface. We limited the size of the region to less than the radius of the mold in order to prevent distortion.

To deform a region of the surface, our system used C designates the center of region, $f_{\vec{N}}$ is the surface normal at C and R is the radius of the region. The mesh vertices in the center move the most whereas those at the deformation boundary move the least. In each calculation, the deformed mold surface presents a smooth bell-shape (see Figure 6(b)). For example, the finger should create smooth dents/bumps on the surface when using the side push/pull gesture, as Figure 6(c) shows.

Calculating Mesh Deformations

We employed a linear falloff equation as in Equation 2 and a modified Gaussian falloff equation as in Equation 3 to define the normal and falloff values of each vertex V_i in the region.

In the linear falloff equation,

$$LinearFalloff(V_i) = m \cdot (\| V_i - C \|) + n, \quad (2)$$

Where m represents the slope on the two sides of the direct falloff model, n represents the peak height of the falloff model, and C represents the center point.

In our modified Gaussian equation,

$$GauessFalloff(V_i) = a \cdot U - \left(\frac{\| V_i - C \|}{R} \right), \quad (3)$$

where a represents the peak height (an adjustable deformation strength as determined by a user through a user interface); U denotes a raise-up constant; R denotes the radius of the region of deformation (i.e. bottom width of the falloff model); C represents the center point; and P influences the peak smoothness of the falloff model. P and U are the main parameters affecting the appearance of the falloff model.

We modified the original Gaussian function as expressed in Equation 3,[15] since the original is unable to produce an ideal bell-shaped deformation. A smooth falloff shape can be obtained from Equation 3 by setting P at 2.5 and U at 100. However, the falloff value is not equal to zero at the boundary (although it approaches zero). Thus, the boundary will be smoothed using discrete laplacian smooth function as shown in Equation 4 to avoid discontinuity.

$$V_b = \frac{\sum_{v_j \in N_b} v_j}{num(v_j)}, \quad (4)$$

Where V_b is the boundary vertex of Region R, N_b is the set of vertices adjacent to V_b, and $num(V_j)$ is the total number of V_j.

Finally, our Gaussian falloff function is used to determine the amount of falloff associated with each vertex in the region of deformation to produce a bell-shaped deformation. The new position of each vertex within the region of deformation can be obtained using Equation 5.

$$\begin{cases} V_i' = V_i + \vec{S}(V_i), \\ \vec{S}(V_i) = \vec{N}_{AVG} \cdot GaussFalloff(V_i), \\ \vec{N}_{AVG} = \frac{1}{n} \cdot \sum (\vec{N}_{V_i} \cdot LinearFalloff(V_i)), \end{cases} \quad (5)$$

where V_i and V_i' respectively denote the original position of the vertex and the new position after deformation. $\vec{S}(V_i)$ represents the direction and magnitude of a vertex's displacement. $\vec{N}_{AVG}$ represents the average of the normal vectors of all vertices in the deformation region, which can be obtained using the linear falloff function to calculate the components of the normal vector of each vertex in the direction of the central point, and then averaging all of the components. n denotes the total number of vertices in the region of deformation, and $\vec{N}_{V_i}$ denotes the normal vector at V_i.

Surface Painting

Following completion of the pottery-making process, the workpiece can be painted and glazed using a size-adjustable brush and a color palette. After the user selects a brush and a color, the system determines the size of the corresponding color patch for use as a basic coloring unit. Various color patches are created according to the current selected color and brush along the way where the user painted. The color patch is translucent, which means that it can be applied multiple times in the same place to produce a thicker layer of color. When a piece is being colored, the system projects the coordinates of the fingers onto a UV map of the surface, such that the corresponding UV coordinates of each color unit can be identified. The system reads the color on the UV map and then combines the currently selected color with the previous color in that surface region. The painting results are then updated on the UV map. Finally, the system maps the color on the UV map to the surface of the piece.

EXPERIMENT RESULTS

The proposed system was implemented using Unity3D, running on a desktop computer (Intel Core i7-3770 CPU, 12 GB RAM, NVIDIA GeForce GTX 750 Ti) in conjunction with a Leap Motion sensor (Software development kit 2.3.1) configured at a visual angle of 150 facing directly upward for gesture tracking (detection distance of 25 mm to 600 mm). The average time required to learn how to operate the system and finish a piece was 20 to 30 min. Figures 7(a_1)~(a_4) present a number of original projects, whereas Figures 7(a_5)~(a_8) are imitation works.

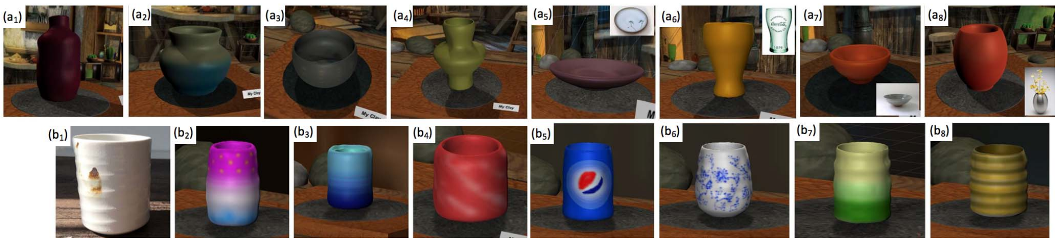


Figure 7. Virtual pieces produced using proposed system: (a_1) ~ (a_4) created freely and (a_5) ~ (a_8) imitation works; (b_1) is the sample, (b_2) ~ (a_8) were virtual cups made by seven beginners after two training sessions.

User Studies

We conducted three experiments to assess the efficacy of PotteryGo in helping novices to learn the skills associated with pottery making. In the first experiment, we examined the number of attempts the participants required to make a ceramic cup by following a tutorial on basic gestures. We also examined the influence of visual feedback on learning performance. In the third experiment, beginners who received training in the first study were invited to make a copy of a specific ceramic container using the gestures they had learned. In the third experiment, participants from the first two experiments were asked to make an actual piece of pottery.

Experiment One

In this first experiment, we were primarily interested the effectiveness of PotteryGo in facilitating the development of basic skills (gestures) used in pottery-making. Our particular focus was on the effectiveness of visual feedback. We recruited 22 users aged 18 to 55 years to participate (8 women and 14 men). The participants possessed basic knowledge concerning the operation of computers, but they had no knowledge related to the creation of a handmade ceramic base, nor experience in operating a gesture-based computer-human interactive system. We randomly divided the 22 participants into two groups (A and B), each of which comprised 11 participants. Participants in both groups participated in two trials. In the first trial, Group B participants received visual feedback during the gesture tutorial, whereas Group A participants did not. In the second trial, Group B participants did not receive visual feedback in the tutorial whereas Group A did. Each participant was required to make a ceramic cup using five basic pottery gestures in the following order: raise-up, top-dig, side-push, side-pull, and push-down. We recorded the number of attempts and the amount of time participants required to complete the cup during each trial. We ran a mixed-effect linear regression model with *number of attempts* as the dependent variable, and *trial number* and *inclusion of visual feedback* as independent variables. We included participants as a random factor to account for individual variance. We also included in the model an interaction effect between trial number and visual feedback.

The results of this study presented the main effects of trial number and the presence of visual feedback on the number of attempts, respectively. As shown in Figure 8, we observed a strong main effect exerted by the presence of visual feedback (coefficient estimates= -6.18, $t(20) = -2.8$; $p=.01$) on the number of attempts. When they received visual feedback, Group A underwent a significant reduction in the number of attempts, i.e., from M=6.6 (SD= 1.9) to M=14.0 (SD= 2.0). Note that the order of receiving *feedback* played no role. The main effect of the trial number indicated a negative correlation with the number of attempts (coefficient estimates: -2.27, $t(25) = -2.9$; $p<.001$). This suggests that participants in the second trial required fewer attempts (M=9.18, SD=3.08) than they did in the first trial (M=11.18, SD=3.47). These results show that PotteryGo did help the participants to learn pottery-making skills. However, even after completing one trial, participants in Group B still required more attempts without visual feedback (M=11.7, SD=1.9) than they did when given visual feedback (M=8.4, SD=1.4). These results suggest that PotteryGo helped the participants to learn pottery-making skills and more importantly that the visual feedback helped the participants to complete the task in fewer attempts. The regression results presented no interaction effect between the trial number and the inclusion of visual feedback (coefficient estimates = 0.5455, $t(20)=0.371$, $p=0.71436$), which means that most of the differences in the number of attempts can be explained by the inclusion of visual feedback and trial number alone.

Participants were asked to rank four features of the visual feedback in terms of how helpful they were in promoting learning. The features were text label (description), spotlight, tutorial video, and hand shadow. From a total of 10 points, each participant awarded 4 points to the top-ranked item, 3 to the second, 2 to the third, and 1 to the lowest. As shown in Fig.8(b), the items were ranked from highest to lowest as follows: hand shadow (75), tutorial video (54), spotlight (54), and text label (37). The hand shadow was most often ranked the most helpful feature (13 out of 22 participants). Qualitative feedback revealed that most of the participants found the hand shadow to be useful in solving problems concerning the use of gestures. Text labels were considered less helpful, and difficult to read during operations. Participants felt that pottery training via VR simulation was no less effective than practice in a ceramics studio. They expressed that the gestures resembled the skills used in actual molding situations and were useful in learning how to make a ceramic base by hand. Participants appreciated the design of the visual feedback system in helping them to make sense of how to perform the various gestures. For example, one participant said,

> *"For beginners, the gesture function is extremely helpful. After a little practice, I can remember the positions very well."*

Another participant said,

> *"The use of lights and the hand shadow to provide clues was interesting and helpful."*

On the other hand, they also suggested a number of improvements that could be made to the PotteryGo system. One participant recommended shortening the description in the tutorial. One participant wanted a more distinguishable color between deformation regions and distance indicators. Another participant found the text labels distracting. We asked the participants for qualitative feedback and their level of satisfaction with the system after the two trials. As shown in Figure 8(c), the participants gave the overall system an average usability rating of 4.5 (SD=0.6). They gave the usefulness of visual feedback an average rating of 4.6 (SD=0.5), and an educative value of 4.5 (SD=0.7).

Putting these results together, Study One showed that Pottery Go was effective for helping participants learn the gestures of pottery making. In addition, the visual feedback of PotteryGo could further enhance its effectiveness. Overall, participants thought that the tutorial of PotteryGo was satisfactory and useful for them to learn the basic gestures of pottery making. Participants used fewer attempts at making a cup after receiving the tutorial. In addition, participants needed fewer attempts with visual feedback than without visual feedback.

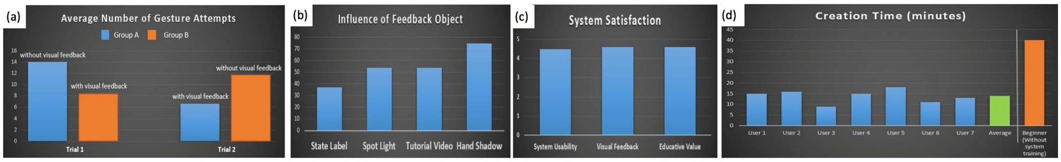


Figure 8. Experiment results: (a) effects of providing visual feedback; (b) ranked score of each visual feedback item; (c) satisfaction level of participants; (d) time required to make a simple cup.

Experiment Two

Experiment Two was meant to assess the learning outcomes of the participants who underwent PotteryGo training in Experiment One. This was done by asking the participants to create a ceramic base without any help from the tutorial. We downloaded several pictures of ceramic bases from the Internet and invited participants to make a copy of a ceramic base of their choice.

Seven out of the 22 participants opted to participate in Experiment Two. Our primary concern was the speed with which they could complete a ceramic container of their choice. It would be impossible for participants to make an identical copy; therefore, we deemed that a participant had successfully completed the task when the body of their work and the target ceramic base presented a similar outline. (To evaluate the similarity of the manual model and target image, we selected the initial front view of manual model, and normalized its size to fit the target image. After center alignment, we computed the area of non-intersection as part of the similarity evaluation.)

All seven participants completed the task, spending between 9 and 20 minutes (average: 13.9 minutes) to complete the task, as Figure 8(d) shows. Adding this time to the time spent training in Experiment One, these participants spent between 17 and 27 minutes completing the container (M=24.5, SD=3.67). This is a remarkably short amount of time for beginners to create a ceramic container. It is noteworthy that 5 out of these 7 participants were among the top 10 in terms of performance in Experiment One; i.e., they required the fewest number of attempts in the two trials. Thus, their learning outcomes may be representative of more effective learners. Nonetheless, even P2 and P9 (15th and 17th in learning performance in Experiment One) took only 25.7 and 26.7 min in total, respectively.

Experiment Three: Pottery Field Test

Six participants from Experiment Two were asked to make an actual ceramic base by hand in a pottery studio. Our objective in this experiment was to determine whether PotteryGo training would enable beginners to learn how to make a typical ceramic base at least as quickly as beginners receiving training in a pottery studio. The six participants spent on average 24.2 minutes (SD=3.7) completing a typical ceramic base using the gestures they learned using PotteryGo, which is approximately 10 minutes longer than they required in PotteryGo. This was not surprising because they had not experienced haptic feedback from actual pottery material and therefore required time to become accustomed to it. In addition, we asked six new participants who did not have any related experience to make the same ceramic base after 13 minutes of training. The average time for completing the task was 1 hour and 3 minutes (SD=9.7) because they constantly forgot the corresponding gestures. Even if we include the 8-13 minutes of training time, participants who underwent tutorials using PotteryGo required no more time to complete the ceramic base than did those learning in a studio. Furthermore, PotteryGo does not require any pottery materials or access to a pottery studio. Our results demonstrate the feasibility of using virtual reality with visual feedback to learn manual skills.

CONCLUSIONS, LIMITATIONS, AND FUTURE WORK

In this paper, we presented a virtual-reality pottery training system called PotteryGo, which uses gesture recognition to help novices develop the skills used to handcraft pottery. PotteryGo provides tutorials on the basic techniques used in pottery-making. It provides step-by-step guidance for users in learning new skills as well as continual monitoring and visual feedback as they practice these skills. Finally, it enables users to create pottery based on their own designs. PotteryGo enables instructors and learners alike to record the pottery-making process for instructional purposes, review and evaluation, or sharing. The instructional content, manipulation methods, and the learning space emulate those found in a traditional pottery studio. Experiments demonstrate the efficacy of PotteryGo in helping novices learn the manual skills of pottery making as well as the applicability of these skills when applied in a pottery studio.

Nevertheless, PotteryGo has a number of limitations. First, the basic mold used in the simulations (4553 vertices and 9082 facets) lacks the delicacy required for highly detailed surface sculpture functions, such as text or pattern carving. Unfortunately, simply increasing the resolution of the simulations would incur heavy computational overhead that could degrade rendering performance and thereby undermine the user experience. Thus, any refinement of the local meshes will require optimization of the mesh deformation algorithm.

Second, the deformation method used in the proposed system was not designed for use with a mesh structure. As a result, the raise-up and push-down gestures are implemented using proportion-based deformation, which can result in exaggerated deformation; i.e., violating the law of conservation of mass. We therefore added the side push-and-pull mechanism to the deformation process in order to rectify this discrepancy. In the future, we will incorporate some of the concepts used in as-rigid-as-possible studies to maintain the mass of the mold during deformation. Third, the somatosensory depth sensor is limited in its ability to recognize gestures. Gestures with feature points on one hand overlapped by the other hand cannot be recognized because they are partially obscured. This necessitated a slight modification to the angle of these gestures (±20°) to ensure that they would be recognized. This solution proved satisfactory in the initial implementation; however, it detracted from the correctness of the gestures and will therefore have to be resolved using an alternative approach in future work.

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