Wowtao: A personalized pottery-making system

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Abstract

We present Wowtao, an easy-to-use pottery manufacture system to take digital creativity into the real world. Our approach is able to create customized pottery virtually on mobile phones or tablet computers interactively and quickly. Our work takes integration of the customer in product personalization into consideration to support personal design in pottery manufacture field.

Different from other virtual pottery design systems, our approach simulates the entire physical pottery design process, such as modeling, painting, seals, firing and customization, and provides the ability to have the designed results fabricated by real artists or a 3D printer. To make the designed results manufacturable by artists, our approach imposes some industrial constraints (both geometry and decorations) when the user designs his/her personalized potteries. Our method only requires simple and intuitive interactions, so even novices can follow the workflow to create pretty potteries easily. We optimize the design process to perform real-time operations. Our informal user study shows that a first-time user typically masters the operations within 10 minutes, and can construct interesting and satisfactory 3D pottery models within minutes.

Keywords: Industry 4.0, Pottery-making, Personalized design, Mobile platform, Parametric model, 3D end-product

1. Introduction

Pottery is the process of forming and manufacturing vessels and other objects with clay and other ceramic materials. As a traditional culture and handcrafted artwork in China since ancient times, pot-tery was used to serve people in daily life [1], and it gradually spreads around the world. The advances in the Internet technol-ogy and mobile devices make it possible to revitalize the practical pottery industry from offline to online. On one hand, Computer Graphics (CG) and Virtual Reality (VR) are filling the gap between the cyber and physical world [2], and these technologies can sim-ulate the designing and manufacturing processes before they are physically carried out [3]. On the other hand, additive manufactur-ing and 3D printing bring about a revolution in the way products are manufactured and distributed to end users [4–7]. As a result, manufacturers are capable of transforming today's manufacturing paradigm to online personalized manufacturing with the help of the accumulated big data and knowledge [8]. Inspired by this concept, we reproduce the visual art of Chinese pottery in a virtual environment by learning the preset pottery knowledge of master potters during the interactive design processes. Moreover, real pottery art, virtual environment, and real pottery products form a closed loop in our system, which makes it easy to manufacture the designed virtual potteries into real products if necessary.

Nowadays, a lot of design tools previously depending on tradi-tional manual operations have been replaced by digital operations. Using Computer-Aided Design (CAD) to improve the design produc-tivity has become an irresistible trend. Digital simulation enables the designed products to be predicted and previewed before being industrially manufactured, and thus the design data can be exchanged more directly and conveniently between designers and potters. Pottery design, which consists of 3D modelling, texture mapping, and human computer interaction, also attracts many attentions in Computer Graphics.

Significant developments have been made on 3D modelling sys-tems like Igarashi's work [9]. As a branch of them, pottery design obtained many achievements as described in the works on mod-elling by Vinayak et al. [10,11] and Chiang et al. [12], the research on reconstruction and decoration by Willis and Cooper [13], and the review on colloidal processing by Lewis [14]. These researches mainly focusing on the virtual display, modeling or part of the whole process have the limitation of creating potteries in reality.

Our work expands the modelling and decoration part to a complete workflow for designing pottery products, considers the industrial constraints and offers personalized customization parts like adding photos and bottom seals design. Through intuitive human com-puter user interactions, Wowtao is able to simulate the whole industry stream process of pottery design for constructing final 3D end-products, with the help of a computer aided parametric design method similar to Chu [15]. Without complicated operations, even novices can create nice potteries within minutes as shown in Fig. 1, which can be further fabricated by real artists or a 3D printer. Fig. 2 shows one user is creating pottery via Wowtao in a virtual potter-making experience zone.

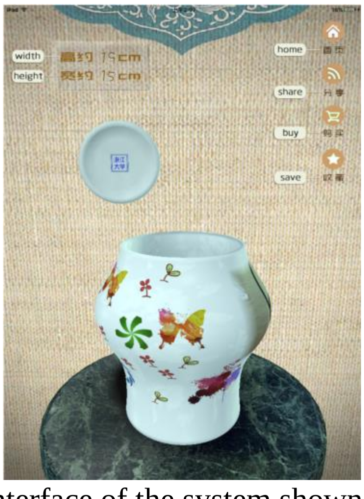

Fig. 1. The interface of the system shown on tablet computer.

Nowadays, some manufacturing companies are running their business by integrating mobility and customers in the product design, which can be further deployed on mobile devices

[16]. From a mass customization and personalization view, Mourtzis et al. [17] discussed the challenges in the design and planning of manufactur-ing networks. Inspired by their work, we develop Wowtao for the rapid construction of virtual pottery products. Given initial models and painting decorations, our system allows real-time interactive rendering on mobile phones or tablet computers without dedi-cated 3D rendering hardware. Moreover, the designed models can be saved for future refinement.

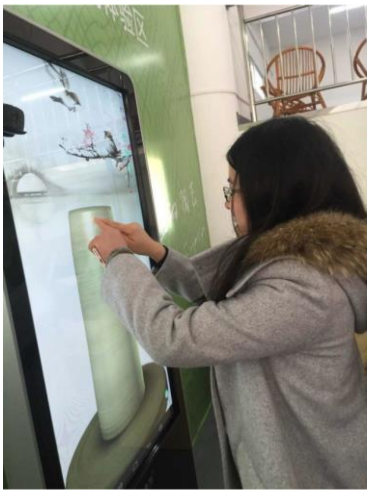

Fig. 2. A novice user is creating virtual pottery using Wowtao.

Our contributions can be summarized as follows:

1. We develop a real-time, interactive, and easy-to-use virtual pot-tery design system, which is available as Apps in Android and Apple stores.
2. We present a large amount of pre-collected classic models and painting decorations for design reference.
3. A novel pottery shape deformation method is designed for touch-based devices with industrial constraints derived from real pottery-making industry, which guarantees that the designed pottery models are manufacturable in practice.

The paper is organized as follows. After describing the related works in Section 2, we introduce our user interface and system operations in Section 3. Section 4 describes the structure represen-tation and constrained deformation algorithm for pottery models. The implementation details and the user study are presented in Sections 5 and 6, respectively. Finally, we conclude our work and discuss future work in Section 7.

2. Related work

2.1. Personalized design

In recent years, Industry 4.0 has been introduced as a popular term to describe the trend towards digitization, automation and customization of the manufacturing environment. It is a widely dis-cussed topic which has the potential to affect entire industries by transforming the way goods are designed, manufactured, delivered, and paid [18,19]. Industry 4.0 increases the flexibility to manufac-ture products with a level of customization (or personalization) similar to the era of crafts manufacturing. As addressed in [20], personalized design is becoming a trend in the field of consumer products. To bridge the gap between virtual and physical products, Virtual Reality and Computer Graphics provide a new means to design personalized product intuitively and interactively with a flexible experience [5]. Chu et al. [20] propose a computational framework for personalized design of the eyeglass frame based on parametric face modeling. Such a personalized design may add new values to a product according to personal preference. To fabricate designed virtual products, additive manufacturing and 3D printing technologies [21] can be employed to print functional product design. 3D printing changes the way that people design and man-ufacture products, and lots of tools are developed for different 3D printable designs with customization [22,5–7]. Different from their work, we focus on pottery design and manufacturing. Our sys-tem supports personalized design using parametric modeling with mobile touchscreen devices, and the product design is rigorous, short, and sufficiently manageable [23]. Moreover, we impose some industrial constraints on the design in order to make the designed pottery fabricable and 3D printable.

2.2. Modelling system

A design system can simulate the real manufacturing process, or create models from a sketch-based method [24–26], freehand-drawing [27], and associated models [28]. There have been many pottery modelling tools such as the approaches based on web or Kinect cameras [29], and the work of Lee et al. [30] for desktop PC. Vinayak et al. [10] present an interactive system for rapid 3D shape exploration through natural hand and arm motions. It proposes a paradigm of natural and exploratory shape modeling through 3D interactions for creating, modifying and manipulating 3D shapes (the three components of shape exploration) in 3D space. Vinayak et al. [31] also propose a paradigm of shape-gesture-context inter-play wherein the interpretation of gestures in the spatial context of a 3D shape directly deduces the designer's intention and the subsequent modeling operations. Dangeti et al. [32] introduce a technique called digital wheel-throwing to create digital potter-ies using certain number-theoretic techniques of digital geometry. Through this work, thick-walled potteries can be created success-fully and efficiently to have the final product ultimately resembling a real-life pottery. The method is robust, efficient, and easy for implementation. However, the work cannot be deployed for man-ufacture due to lacking industrial constraints and complete design steps like decoration and firing process. Apart from the articles which propose detailed methods of pottery modelling, there are several design platforms for virtual pottery modelling. The system developed by Gao et al. [33] presents an interactive installation for virtual potteries, which adopts intuitive in-air hand interac-tions with the help of motion sensing technology. Once a virtual pottery work is completed, it can be shared to a social network automatically, and the mesh data will be saved for future use like 3D printing. The pottery-making training system presented by Chiang et al. [12] allows users to create customized pottery pieces based on the models. It provides simulated exercises as well as problem-solving tasks designed in accordance with the design principles. However, these works do not add standard rules of pottery man-ufacturing. Our system is inspired by the previous gesture-based modelling system with which 3D pottery modelling can start with a predefined state and use a homogeneous cylinder to represent the transformable pottery structure. In addition, our method provides a complete framework with classical preset models and a variety of in-store decorations. Wowtao creates virtual potteries with per-sonalized operation modules and industrial constraints, which is easy-to-use for novices and suitable for factories to manufacture real potteries.

2.3. Interaction

The fusion between real world and artificial information needs to be taken into consideration like Marino's work [34]. Interaction is very important for a virtual design system, and it should provide users with enjoyable experiences. Most of the works concentrate on hand-gestures or touch-screen based interaction. Zheng et al. [35] try to understand hand gestures in daily life. Jeannerod [36] iden-tifies two functional requirements of finger grip during the action of grasping: (a) adaptation of the grip to the size, shape, and use of the object to be grasped and (b) coordination between the rela-tive timing of the finger movements with hand transportation (i.e., whole hand movements). In addition to the hand gesture, Mapes and Moshell [37] simulate the input devices by emulating a pair of 3D mouse and a keyboard, which is relatively simple and effective. Boulic et al. [38] use digital glove and take into consideration of deriving a visual restitution consistent with the user manipulative intentions while respecting the integrity of solid interaction with friction. In this paper, we adopt the touch-screen based interac-tion method because our system is installed on mobile phones and tablet computers, which are available for ordinary people.

3. User interface and system operations

This section describes the detailed process of Wowtao. Through real-time touch-screen based interface, Wowtao simulates differ-ent stages of the pottery manufacturing process. More than forty different types of pottery images are collected and displayed in the reference sample database, which can be further supplemented or updated by users themselves. In industry, pottery design usually consists of the following sequential phases: preparing clay, pot-tery molding, firing, painting (or stamping), and glazing. Our mobile device based system supports pottery molding, firing, painting (or stamping), and sealing, which are executed in real time. Even users without any 3D modelling experience are able to create virtual potteries with simple operations. In addition, Wowtao provides a trading platform between users and pottery manufacturers, where the designed works by users can be uploaded online to factories for production, and the fabricated potteries are delivered to them by mail within seven days.

3.1. Overview

The whole framework of Wowtao is displayed in Fig. 3. Users begin with deforming and shaping a predefined pottery model through single-touch interactions. After the automatic firing phase, users then paint or add decorations on the surface and the bottom of the deformed pottery model. Finally, users can preview the fin-ished product and save it or submit the data online via Internet to factories to fabricate real potteries. The following subsections demonstrate each process of the system.

3.2. Creating a new pottery

In this initial pottery molding phase, users can create their desired potteries through touch-screen based interactions. Pre-collected classical models such as vases, flowerpots, etc., are presented as references at first as shown in Fig. 4. The virtual pottery models can be deformed and reshaped following the users' fingertip within given manufacture constraints provided by pottery industry factories. Fig. 5 shows an example of pottery with the radius and height changed. Concrete operations can be described as below, leftward sliding makes radius smaller in contrast to rightward slid-ing. Upward sliding makes the circular ring higher in contrast to downward sliding.

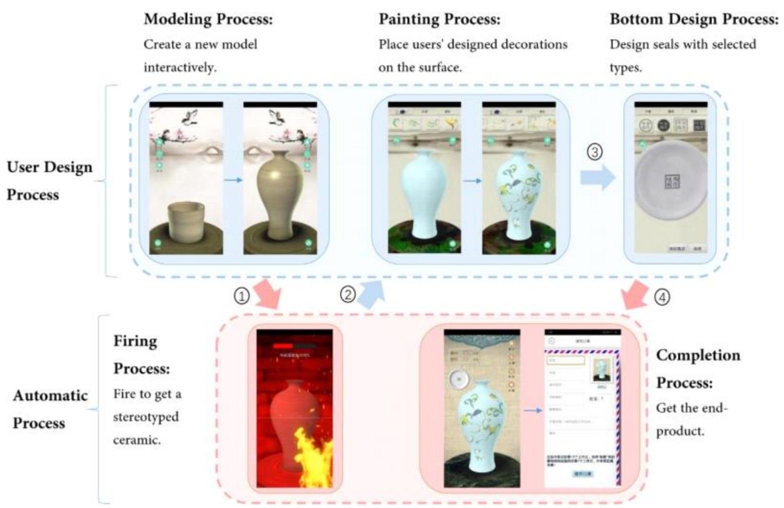

Fig. 3. The complete workflow of Wowtao which includes five stages: modeling process, painting process, bottom design process, firing process, and completion process. Modeling process, painting process, bottom design process are user design processes and firing process, and completion process are automatic processes that users not involved.

Fig. 4. Part of classical samples offered by the system.

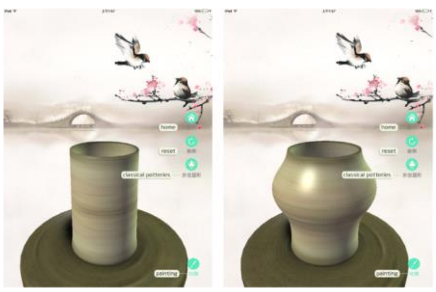

Fig. 5. Modeling process: the left one shows the origin model and the right one is the result after deforming.

3.3. Painting on the surface and bottom design

In the painting phase, users can decorate the deformed pottery models with textures shown in our provided icons, part of which are shown in Fig. 6, or their own phone albums on the surface every-where by touch-rotation based operations as shown in Fig. 7, as well as erasing them. The pottery model is a scaled version of a real object, with the same scale applied to its decoration, which ensures the finished pottery from our system can be manufactured with the standard decoration decals. Touch operations outside the pottery will be regarded as changing the viewpoint by rotating the pottery. Bottom painting is an optional part for carving words. We provide several fonts and color choices, and design the layout of the stamp mark to deal with input words of different lengths as shown in Fig. 8. The designed models are sent into the automatic firing module for generating the virtual end-products and saved for future refinement or real manufacture.

Fig. 6. Part of decorations for reference offered by the system.

4. Algorithm

In this subsection, we describe how the system constructs a 3D pottery in the view of algorithm details. A pottery model is represented as a polygonal mesh in the initial phase. Each editing operation modifies the mesh for conforming to the specified shape according to the user's input. The initial and final models are always topologically equivalent to double-layer cylinders. Our designed algorithm can be deployed in the mobile platforms for virtual model generation, which is adaptive for real manufacture and 3D printing.

Fig. 7. Painting process: the left one shows the original model and the right one is the result after painting. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

4.1. Structure representation

We divide our pottery structure into three parts: side, bridge and bottom. The side part is described as a vertical sequence of n circular rings, as shown in the right part of Fig. 9. It consists of two simple and homogeneous cylinders (inner and outer) defined by $P_{n,m} = \{(h_i, R_i, r_i) \mid R_i = R(H_i), r_i = r(h_i), h_1 < ...h_n \in R\}$, where R_i and r_i are outer and inner radii of circular ring C_i, respectively. Based on the definition, the vertices' positions of the side part can be easily obtained by

$$\vec{v}_{i,j,w} = \left[-r_{i,w} sin\left(\frac{2j\pi}{n}\right), h_i, -r_{i,w} cos\left(\frac{2j\pi}{n}\right)\right]^T \quad (1)$$

where w ∈ {0, 1} denotes vertices.

Fig. 8. Two different types of seals.

The left part of Fig. 9 shows the bridge component. It is a sequence of sector clips, linking the top circular ring's inner andouter vertices. Defining θ as the clip angle, the bridge vertices can be determined by

$$\vec{v}_{i,j,w,k} = \vec{v}_{oc} + Rcos(k\theta)\vec{n}_{oc} + Rsin(k\theta)\vec{n}_{\perp} \quad (2)$$

Here $\vec{v}_{oc} = \frac{1}{2}\sum_{w}\vec{v}_{i,j,w,k}$, $\vec{n}_{oc}$ is the normalization of $\vec{v}_{oc}$, and $\vec{n}_{\perp}$ is the normal vector perpendicular to $\vec{v}_{oc}$.

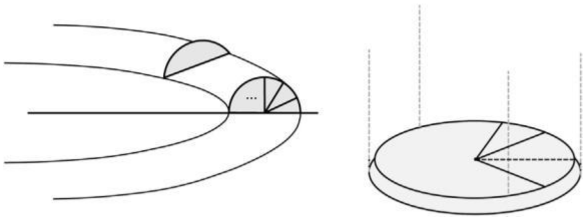

Fig. 9. The top section (left) and the side part (right) of our model.

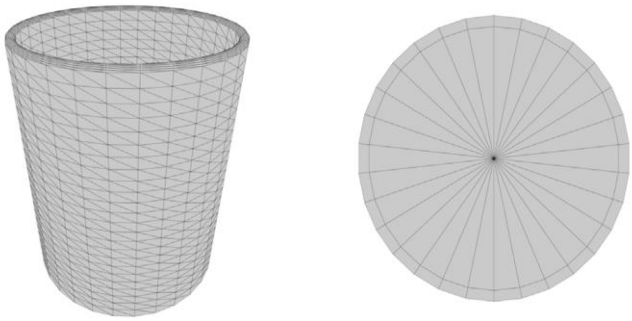

Fig. 10. Structure of our model: the whole structure (left) and the bottom (right).

As demonstrated in the right part of Fig. 10, the component con-sists of two circles, and each circle contains m + 1 vertices: one is at the center, and the other is from the outer circle. The left part of Fig. 10 shows the whole structure of the pottery mesh.

4.2. Deformation models

Different from the method of Agathos et al. [39], which drives the deformation of the input model indirectly using a simplified control mesh, our method first generates a predefined rough or classi-cal model, and then deforms it directly by touch-based operations without employing such a control mesh. Fig. 11 shows the flowchart of our pottery modeling algorithm. According to the homogeneous cylinder structure, the deformation of our virtual pottery model is conducted by deforming the profile curve, i.e., by modifying the radius of each section. Since the deformation of the profile is akin to Gaussian distribution, we choose Gaussian function to constrain deformation. Suppose we put a force on circular ring C_i, the defor-mation formula of its inner radius to become fatter can be written as

$$r_i = r_i + s_0 \arctan(r_{max} - r_i) * \frac{1}{\sqrt{2\pi\theta}} e^{-\frac{r_i - \bar{r}}{2\theta^2}} \quad (3)$$

and to become thinner can be written as

$$r_i = r_i + s_0 \arctan(r_i - r_{min}) * \frac{1}{\sqrt{2\pi\theta}} e^{-\frac{r_i - \bar{r}}{2\theta^2}} \quad (4)$$

Here, r_{max} and r_{min} are the maximum and minimum radii, respectively, r is the radius of the selected circular ring, s_0 is the scale factor, and decides the deformation range: the larger is, the wider the range is.

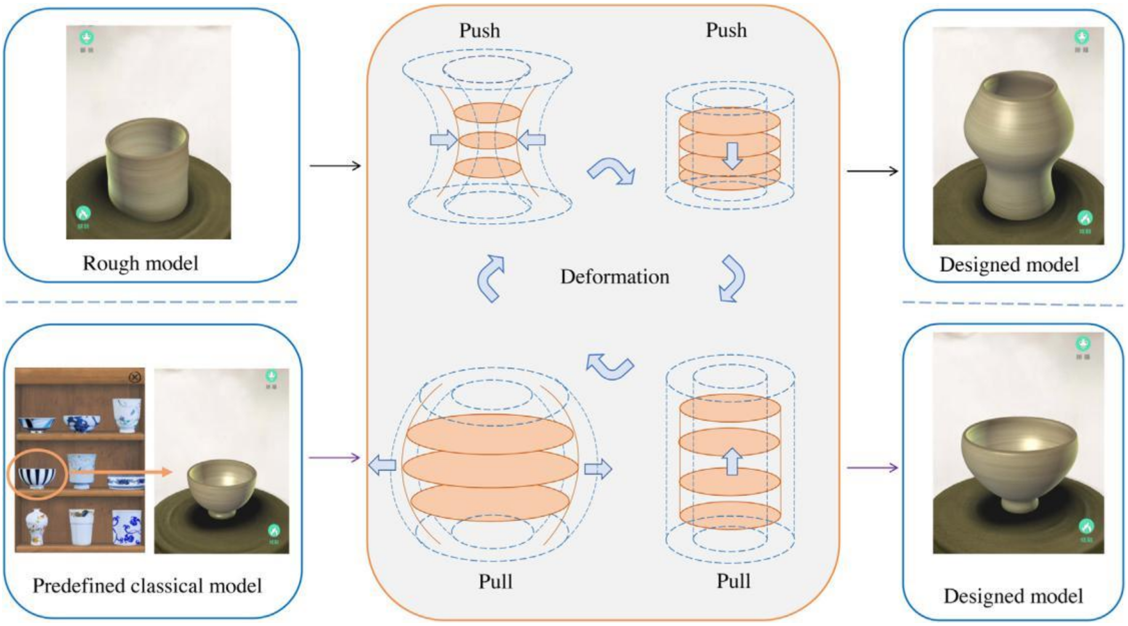

Fig. 11. The flowchart of our pottery modeling algorithm. Our system starts from a predefined rough or classical model, and then the user designs a new pottery model via touch-based pull/push deformations

Considering the characteristics of touch-screen based mobile devices, we deform the pottery by grabbing or pulling one section to change its radius via the input point, on which the deformations of the adjacent sections depend. Thus, we can easily get the horizontal section of the pottery model and deform it. Moreover, when users grab or pull via mobile device screen, the touched point will generate a white pan as a response. Fig. 12 shows the deformation process.

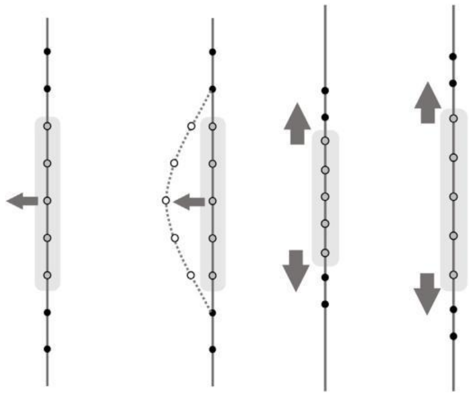

Fig. 12. Deformation process: the left one and right one parts are the structures before operation, the left two and right two parts are the deformation processes

4.3. Deformation constraints

To ensure the manufacturability of the designed models, we introduce some industrial constraints derived from real pottery-making industry into our system. Let h be the height of the pottery, r_i be the radius of the pottery at section i, n be the number of sections, l be the number of local maximum points of the profile curve, and s be the number of local minimum points of the curve. We also define r_1 as the radius at pottery mouth section, and r_n as the radius at pottery bottom section. Fig. 13 illustrates the symbols defined above. Then, the rules summarized by potters can be described as follows:

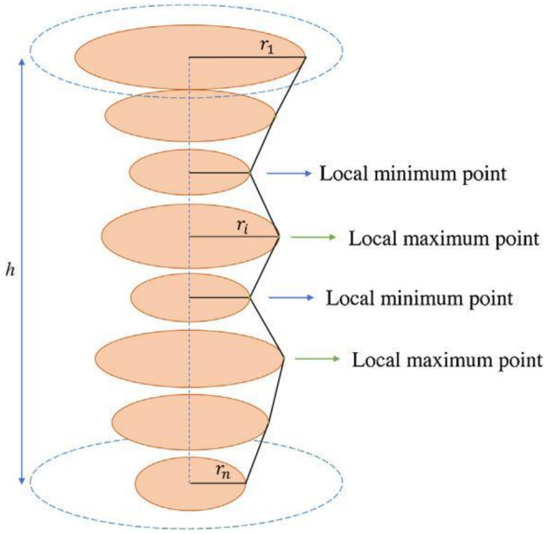

Fig. 13. The symbols used for our deformation constraints.

Fig. 14. Two end products created by our system.

1. 3.5 cm < h < 26 cm.
2. $\max(\frac{7}{52}h, 1.4cm) \leq r_i \leq \frac{9}{26}h.$
3. For a section i which is a local minimum point, if there is no local maximum point above it, the system should follow r_1 <2.16 * r_i.
4. For a section i which is a local minimum point, if there is an adja-cent local maximum point j above it, the system should follow r_j <1.7 * r_i.

5. For a section i which is a local minimum point, if there is an adjacent local maximum point j above it and an adjacent local maximum point k below it, then the system should follow $r_k < 1.4 * r_j$.
6. If the pottery mouth is hyperbolic open, l and s should be less than 4, respectively, otherwise less than 3.

5. Implementation

Our system is implemented as a smart-phone (tablet computer) application on the Android and iOS systems without any input device, which is running at 60 fps on the latest Android and iOS systems. Fig. 14 shows some final virtual potteries created with Wowtao by an experienced user. Please refer to the accompanying video for the live demo.

The geometric shapes, textures, bottom seals of a designed pot-tery can be exported in a standard data format and uploaded to a server. Thus, factories can use them for manufacture or 3D print-ing. Fig. 15 shows a 3D printed end-product which is identical to the physical product. The top left part of Fig. 16 shows the virtual pottery generated by our system and the top right part shows the corresponding product manufactured by factories according to this designed model. The bottom part of Fig. 16 shows another pair.

Fig. 15. A real 3D printing product generated based on designed models via Wowtao

Fig. 16. Two pairs of real products (right) and associated designed virtual pottery models (left) created via Wowtao

6. User experience

We evaluate the efficiency and effectiveness of our Wowtao sys-tem through intensive experiments. Three groups of participants in their twenties, randomly invited from a university where the male to female ratio is roughly the same, attended our experiments. The first experiment is performed to test the efficiency of our system (see Section 6.1) by inviting two groups of participants: Group A and Group B. Group A consists of twenty novice users; Group B consists of five experienced participants. All the participants in two groups were asked to design three self-satisfied models similar to three reference pottery models (see Fig. 17). The second experiment is designed to test the effectiveness of Wowtao (see Section 6.2). In this experiment, another twenty participants, which is call Group C, were asked to evaluate the generated pottery models created by Group A and Group B.

6.1. Efficiency of Wowtao

In the first experiment, we compared the time cost for finishing the design of three given reference pottery models by novice and experienced users.

As shown in Table 1, given a reference pottery model, it took from 360.2 to 408.9 seconds for Group A and from 292.5 to 301.9 seconds for Group B on average to design a satisfactory simi-lar model, respectively. Interestingly, the modelling time for two groups were similar. However, it cost more time for novices to find required decoration textures in the painting procedure as they are unfamiliar with the system. Therefore, we can conclude that even novices can master the design procedures of Wowtao efficiently.

6.2. Effectiveness of Wowtao

In the second experiment, by presenting the reference pottery products and the designed models from Group A and Group B to Group C simultaneously, we evaluated the effectiveness of Wow-tao system to test its usability. Each participant from Group C was required to assess the similarities between the reference product and the two corresponding designed pottery models. The question-naire is designed as follows: the result of Group A is better, the result of Group B is better, and both are similar. In addition, participants were asked to provide a five-level score (1 represents completely different and 5 represents most similar) to each presented pottery model in order to judge the similarity. A reference model along with two corresponding designed pottery models by Group A and Group B were randomly chosen five times to each participant from Group C for assessment. Thus, 300 times evaluations were conducted in total.

From Fig. 18 and Table 2, we can find that the qualities of the designed pottery models from the novice users were rather similar to those from the experienced users. In addition, there is almost no difference between the designed models and the reference pottery models. The second experiment shows that our Wowtao system is very easy to use to design a satisfactory pottery model.

In summary, the above two experiments validated that Wow-tao is intuitive and easy-to-use even for novice users, and users can design satisfactory pottery products quickly. Moreover, par-ticipants commented that Wowtao makes it possible for them to understand the pottery production process intuitively, and they can create their own virtual pottery products similar to physical ones easily.

Table 1

The time cost for finishing the design of virtual potteries according to the reference pottery models.

Average time cost (s)	Modelling		Painting		Total time	
	Group A	Group B	Group A	Group B	Group A	Group B
Ref 1	124.5	100.3	284.4	192.2	408.9	292.5
Ref 2	110.2	99.4	272.4	194.1	382.6	293.5
Ref 3	103.5	101.2	256.7	200.7	360.2	301.9

Fig. 17. Three given reference pottery models presented to the participants in the experiments. We use Ref 1 (left), Ref 2 (middle), and Ref 3 (right) to represent three reference models, respectively

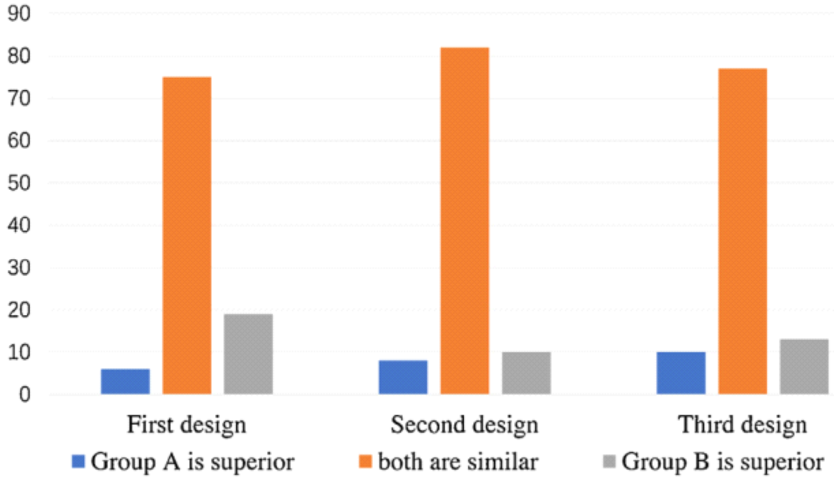

Fig. 18. Evaluation of similarity comparison according to the reference pottery models.

Table 2
Similarity comparison of designed results from two groups.

Average scores	Ref 1	Ref 2	Ref 3
Group A	4.08	4.12	4.11
Group B	4.24	4.13	4.16

7. Conclusions and future work

We have presented Wowtao, a virtual pottery design system deployed in mobile devices, just like spinning clay on a real pot-tery wheel. It provides a new means for novices with a creative genius to design custom-to-made potteries at any place and any time, through simple shaping and painting operations. Casual users can use their creativity to design their own piece of pottery based on some classical pottery models and texture decorations created by master artists. Besides enjoying the virtual pottery design, users can also buy the designed potteries by having them fabricated by real artists or a 3D printer.

However, the current system is unable to generate irregular pot-teries such as the ones with non-homogeneous deformations or a teapot-like shape with a handle since the representation of our pot-tery models is constrained by a homogeneous cylinder. Moreover, the raise-up and push-down gestures were implemented using proportion-based deformation, which may violate the law of con-servation of mass.

In the future, we plan to design more flexible algorithms to deal with more types of potteries, such as potteries with handles, while keeping the user interactions as simple as possible. We are also considering to supplement more reference samples so that users can create interesting products more easily. In addition, introduc-ing haptic interaction or even volume soft sensor [40] will further enhance the experience of pottery-making. By making the above extensions in the upcoming version, Wowtao system will be more efficient, robust and controllable. We believe that it can stimulate users to design more creative works and be contributive to the pottery manufacture industry.

Authors’ contributions

Ruifan Cai: Methodology; Software; Writing – Original draft preparation; Data curation; Visualization; Investigation.
Yingying Lin: Writing – Original draft preparation.
Yuzhen Zhu: Investigation; Visualization.
Xiangjun Tang: Investigation.
Honglin Li: Writing – Reviewing and Editing.
Yanjun Weng: Methodology; Data curation.
Lihua You: Writing – Reviewing and Editing.
Xiaogang Jin: Conceptualization; Methodology; Validation; Writing – Reviewing and Editing.

Declaration of interest statement

The authors declare that they have no known competing finan-cial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.compind.2020. 103325.

References

Wu, J., Zhang, M., Hou, T., Li, Q., Wu, J., 2015. Analysis of the celadon of the tang and the five dynasties unearthed from Nan Kiln and Lantian Kiln site of Jingdezhen, China. Ceram. Int. 41 (5), 6851–6857, http://dx.doi.org/10.1016/j.ceramint.2015. 01.134.

Lu, S., Mok, P., Jin, X., 2017. A new design concept: 3d to 2d textile pattern design for garments. Comput.-Aided Des. 89, 35–49, http://dx.doi.org/10.1016/j.cad.2017. 03.002.

Ong, S.K., Nee, A.Y.C., 2013. Virtual and Augmented Reality Applications in Manu-facturing. Springer Science & Business Media, http://dx.doi.org/10.1007/978-1-4471-3873-0.

Gao, W., Zhang, Y., Ramanujan, D., Ramani, K., Chen, Y., Williams, C.B., et al., 2015. The status, challenges, and future of additive manufacturing in engineering. Comput.-Aided Des. 69, 65–89, http://dx.doi.org/10.1016/j.cad.2015.04.001.

Zhao, H., Wang, J., Ren, X., Li, J., Yang, Y.L., Jin, X., 2018. Personalized food printing for portrait images. Comput. Graphics 70, 188–197, http://dx.doi.org/10.1016/j. cag.2017.07.012.

Zhao, H., Hong, C., Lin, J., Jin, X., Xu, W., 2016. Make it swing: fabricating personalized roly-poly toys. Comput. Aided Geom. Des. 43, 226–236, http://dx.doi.org/10. 1016/j.cagd.2016.02.001.

Davia-Aracil, M., Hinojo-Pérez, J.J., Jimeno-Morenilla, A., Mora-Mora, H., 2018. 3d printing of functional anatomical insoles. Comput. Ind. 95, 38–53, http://dx.doi. org/10.1016/j.compind.2017.12.001.

Tao, F., Qi, Q., Liu, A., Kusiakc, A., 2018. Data-driven smart manufacturing. J. Manuf. Syst. 48, 157–169, http://dx.doi.org/10.1016/j.jmsy.2018.01.006.

Igarashi, T., Matsuoka, S., Tanaka, H., 1999. Teddy: a sketching interface for 3D freeform design. SIGGRAPH'99: Proceedings of the 26th Annual Conference on Computer Graphics and Interactive Techniques, 409–416, http://dx.doi.org/10. 1145/311535.311602.

Krishnamurthy, V.R., Murugappan, S., Piya, C., Ramani, K., 2012. Handy-potter: rapid 3d shape exploration through natural hand motions. International Design Engi-neering Technical Conferences and Computers and Information in Engineering Conference, 19–28, http://dx.doi.org/10.1115/DETC2012-71427.

Krishnamurthy, V.R., Ramani Jr., K., Jasti, K.L.R., 2014. zPots: a virtual pottery expe-rience with spatial interactions using the leap motion device. CHI'14 Extended Abstracts on Human Factors in Computing Systems, 371–374, http://dx.doi.org/ 10.1145/2559206.2574834.

Chiang, P.Y., Chang, H.Y., Chang, Y.J., 2018. Potterygo: a virtual pottery making train-ing system. IEEE Comput. Graphics Appl. 38 (2), 74–88, http://dx.doi.org/10.1109/MCG.2018.021951634.
Willis, A.R., Cooper, D.B., 2008. Computational reconstruction of ancient artifacts. IEEE Signal Process. Mag. 25 (4), 65–83, http://dx.doi.org/10.1109/MSP.2008. 923101.
Lewis, J.A., 2000. Colloidal processing of ceramics. J. Am. Ceram. Soc. 83 (10), 2341–2359, http://dx.doi.org/10.1111/j.1151-2916.2000.tb01560.x.
Chu, C.H., Song, M.C., Luo, V.C., 2006. Computer aided parametric design for 3D tire mold production. Comput. Ind. 57 (1), 11–25, http://dx.doi.org/10.1016/j. compind.2005.04.005.
Mourtzis, D., Doukas, M., Vandera, C., 2014. Mobile apps for product customisation and design of manufacturing networks. Manuf. Lett. 2 (2), 30–34, http://dx.doi.org/10.1016/j.mfglet.2014.01.002.
Mourtzis, D., Doukas, M., 2014. Design and planning of manufacturing networks for mass customisation and personalisation: challenges and outlook. Proc. CIRP 19, 1–13, http://dx.doi.org/10.1016/j.procir.2014.05.004.
Oesterreich, T.D., Teuteberg, F., 2016. Understanding the implications of digitisation and automation in the context of industry 4.0. Comput. Ind. 83, 121–139, http://dx.doi.org/10.1016/j.compind.2016.09.006.
Hofmann, E., Rüsch, M., 2017. Industry 4.0 and the current status as well as future prospects on logistics. Comput. Ind. 89, 23–34, http://dx.doi.org/10.1016/ j.compind.2017.04.002.
Chu, C.H., Wang, I.J., Wang, J.B., Luh, Y.P., 2017. 3D parametric human face modeling for personalized product design: eyeglasses frame design case. Adv. Eng. Inform. 32, 202–223, http://dx.doi.org/10.1016/j.aei.2017.03.001.
Gao, W., Zhang, Y., Nazzetta, D.C., Ramani, K., Cipra, R.J., 2015. Revomaker: enabling multi-directional and functionally-embedded 3D printing using a rotational cuboidal platform. UIST'15: Proceedings of the 28th Annual ACM Symposium on User Interface Software & Technology, 437–446, http://dx.doi.org/10.1145/ 2807442.2807476.
Zhang, Y., Kwok, T.H., 2017. An interactive product customization framework for freeform shapes. Rapid Prototyp. J. 23 (6), 1136–1145, http://dx.doi.org/10. 1108/RPJ-08-2016-0129.
Lloret-Climent, M., Nescolarde-Selva, J., Mora-Mora, H., Jimeno-Morenilla, A., Alonso-Stenberg, K., 2019. Design of products through the search for the attractor. IEEE Access 7, 60221–60227, http://dx.doi.org/10.1109/ACCESS.2019. 2915678.
Zeng, L., Liu, Y.J., Wang, J., Zhang, D.L., Yuen, M.F., 2014. Sketch2jewelry: seman-tic feature modeling for sketch-based jewelry design. Comput. Graphics 38 (1), 69–77, http://dx.doi.org/10.1016/j.cag.2013.10.017.
Liu, Y.J., Ma, C.X., Zhang, D.L., 2011. Easytoy: plush toy design using editable sketch-ing curves. IEEE Comput. Graphics Appl. 31 (2), 49–57, http://dx.doi.org/10.1109/MCG.2009.147.
Kyratzi, S., Sapidis, N.S., 2011. 3d object modeling using sketches. Inf. Resour. Manag. J. IRMJ 24 (4), 27–49, http://dx.doi.org/10.4018/irmj.2011100102.
Wang, C., Zhang, Y., Sheung, H., 2010. From designing products to fabricating them from planar materials. IEEE Comput. Graphics Appl. 30 (6), 74–85, http://dx.doi.org/10.1109/MCG.2009.155.
Zhou, Y., Peng, S., Liu, X., Liu, S., Tang, J., 2018. A novel method to generate the tooth surface model of face-milled generated spiral bevel gears. Int. J. Adv. Manuf. Technol. 102 (5), 1205–1214, http://dx.doi.org/10.1007/s00170-018-2951-4.
Krishnamurthy, V.R., Ramani, K., 2015. Extracting hand grasp and motion for intent expression in mid-air shape deformation: a concrete and iterative exploration through a

virtual pottery application. Comput. Graphics 55, 143–156, http://dx.doi.org/10.1016/j.cag.2015.10.012.
Lee, J., Han, G., Choi, S., 2008. Haptic pottery modeling using circular sector element method. Haptics: Perception, Devices and Scenarios. 6th International Confer-ence, EuroHaptics 2008, 668–674, http://dx.doi.org/10.1007/978-3-540-69057-3 84.
Krishnamurthy, V.R., Murugappan, S., Liu, H.R., Ramani, K., 2013. Shape-it-up: hand gesture based creative expression of 3D shapes using intelligent generalized cylinders. Comput.-Aided Des. 45 (2), 277–287, http://dx.doi.org/10.1016/j.cad. 2012.10.011.
Dangeti, S., Chen, Y.V., Zheng, C., 2016. Comparing bare-hand-in-air gesture and object-in-hand tangible user interaction for navigation of 3D objects in mod-eling. TEI'16: Proceedings of the TEI'16: Tenth International Conference on Tangible, Embedded, and Embodied Interaction, 417–421, http://dx.doi.org/10. 1145/2839462.2856555.
Gao, Z., Li, J., Wang, H., Feng, G., 2018. Digiclay: an interactive installation for virtual pottery using motion sensing technology. ICVR 2018: Proceedings of the 4th International Conference on Virtual Reality, 126–132, http://dx.doi.org/10.1145/ 3198910.3234659.
Menozzi, M., Hofer, F., Näpflin, U., Krueger, H., 2003. Visual performance in aug-mented reality systems for mobile use. Int. J. Hum.-Comput. Interact. 16 (3), 447–460, http://dx.doi.org/10.1207/S15327590IJHC1603 4.
Zheng, J.Z., Rosa, S.D.L., Dollar, A.M., 2011. An investigation of grasp type and frequency in daily household and machine shop tasks. IEEE International Conference on Robotics & Automation, 4169–4175, http://dx.doi.org/10.1109/ICRA. 2011.5980366.
Jeannerod, M., 1986. The formation of finger grip during prehension. A cortically mediated visuomotor pattern. Behav. Brain Res. 19 (2), 99–116, http://dx.doi. org/10.1016/0166-4328(86)90008-2.
Mapes, D.P., Moshell, J.M., 1995. A two handed interface for object manipulation in virtual environments. Presence: Teleoper. Virtual Environ. 4 (4), 403–416, http://dx.doi.org/10.1162/pres.1995.4.4.403.
Boulic, R., Rezzonico, S., Thalmann, D., 1996. Multi-finger manipulation of virtual objects. Proceedings of the ACM Symposium on Virtual Reality Software and Technology, 67–74, http://dx.doi.org/10.1145/3304181.3304195.
Agathos, A., Azariadis, P.N., 2015. Parametric-based reconstruction of 3d mesh models; towards the generation of a parametric human foot biomodel. In: Euro-graphics Workshop on Visual Computing for Biology and Medicine, VCBM, pp. 221–222, http://dx.doi.org/10.2312/vcbm.20151232.
Yoon, S.H., Huo, K., Zhang, Y., Chen, G., Paredes, L., Chidambaram, S., et al., 2017. Isoft: a customizable soft sensor with real-time continuous contact and stretching sensing. Proceedings of the 30th Annual ACM Symposium on User Interface Soft-ware and Technology, 665–678, http://dx.doi.org/10.1145/3126594.3126654.