Research Article

Innovative Collaborative Design of Ru Porcelain Shape Based on Digital Shape Technology

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Under the background of digital technology, computer-aided design is still in the initial stage of application in the field of design and manufacture of ceramic products. In order to improve the informatization degree of ceramic industry, advance the efficiency of product design, and satisfy the demand of personalized customization, in this paper, Ru porcelain is selected as the research object, and according to its shape characteristics, based on the 3D evolution of data combined with the image shape method and entity design, the design process of Ru porcelain shape was put forward, and the collaborative design of Ru porcelain was implemented with Yuhu spring bottle as the representative. The simulation results show that the model is highly practical and helpful to realize the convenient design of ceramic products.

1. Introduction

Innovative design of daily-use ceramics is a process of creative labor and a systematic project. Faced with the existing achievements and the ever-changing consumer demand and aesthetic demand of the public, numerous ground work has been completed by designers, including early market research, design positioning, and new product testing. As an important component of products, sculpt plays the role of transmitting information between products and consumers, designers and consumers, which can show certain personality characteristics in combination with consumers’ cognition [1, 2]. Function is the decisive factor of daily ceramic shape, and it is the purpose of daily ceramic shape. The function of daily-use ceramic is realized through shape, so its shape design occupies a dominant position in the whole design process. With the increasing demands of consumers on the function and aesthetics of daily-use ceramics, designers pay more attention to its design.

Due to the lack of innovation in ceramic design, it is losing its attraction, and because of the complexity of ceramic technology’s own manufacturing process and the combination of various techniques, in pattern design, colorful patterns require craftsmen to have enough patience and aesthetic capability. In addition, the ceramic industry is fragmented without satisfactory ecology and system model. It is mainly based on traditional small workshops, which leads to the stereotyped shapes and patterns in the ceramic market. At the same time, because of its small scale, they are unable to introduce more advanced technologies and feed them back into ceramic production, which leads to a further decline in the competitiveness and attraction of ceramics [3–5].

In recent years, the application of computer-aided technology in product design has stimulated the collision of diversified design thinking, touched new design pain points and design ideas, and became a new pattern, which breaks the limitations of traditional design patterns and effectively discovers new design opportunities. However, in the field of ceramic product design, it still relies on traditional manual work, which is cumbersome and inefficient, and it has been difficult to meet customers’ aesthetic demand for ceramic ware shape and the development demand of large-scale personalized customization [6, 7]. Therefore, it is imperative to combine computer aesthetics with product design by applying 3D parametric technology in design and creation of
ceramic product. In this paper, Ru porcelain, an excellent porcelain in celadon series, is selected as the research object, and its shape design under the background of digital technology is studied.

2. Basis of Product Design of Ru Porcelain

Ru porcelain was attractive with its unique glaze color and flourished in the Song Dynasty. “Ru” refers to the geographical location of the Tang and Song dynasties as the “Ruzhou.” Ru porcelain is an excellent porcelain in celadon series, and its glaze color is just like “after a storm, the sky is clear and the clouds are broken,” where the glaze shows small pieces of cicada pattern [8, 9].

2.1. Artistic Features of Ru Porcelain

2.1.1. Shape Characteristics. The shape design of ceramics needs to meet its practical use needs. On this basis, the artistic elements of shape beauty and style are integrated into it, so that the function, form, and style form a unified whole. Seeking beauty from nature, an elegant and quiet aesthetic concept is shown through linear and three-dimensional structure. The shape of Ru kiln in Northern Song Dynasty has the regularity of formal beauty to a certain extent [10, 11]. Through various geometric structures, people in Song Dynasty advocated roundness at that time. This was because many objects that people saw in nature at that time were round, and they showed this emotion through ceramic shape, which is also the most practical in terms of firing process and use function. The most typical ceramic shape of Ru kiln is bottles, which is related to the culture and times at that time [12]. As shown in Figure 1, plum bottles and Yuhu spring bottles are porcelain used to hold wine. Because of different uses, there are great differences in design. The mouth of Yuhu spring bottle is curled outside, the neck is easy to grasp, and the center of gravity is below the abdomen after drinking, which is a kind of bottle that is convenient for scalding and drinking, while plum bottles have short mouth, abundant shoulders, and astringing abdomen.

Before the Tang and Song Dynasties, the overall design of shape was mainly based on demand of usage, followed by aesthetics. Since the Song Dynasty, aesthetic needs have been brought to the forefront of design. The literati sentiment and simple aesthetic style of the Song Dynasty led to the trend of the overall design, which pursues the flowing texture of lines.

2.1.2. Cultural Heritage. The celadon produced by Ru kiln not only meets the requirements of people’s life but also pursues aesthetics, which integrates the culture and customs of the Song Dynasty into creation of Ru porcelain. Different from the rough and majestic style of the Han Dynasty, the ornate and complicated decoration of the Tang Dynasty, the aesthetic style of the Song Dynasty pursued a simple and tranquil artistic style, whose aesthetic of purity and inaction had a profound influence on the aesthetic thought at that time [13, 14]. Song Huizong liked to drink tea and believe in Taoism, which also had a great influence on the aesthetic development of that time. Ru porcelain modeling is simple, in the process of high-temperature firing, the use of the different shrinkage coefficient between the glaze, the formation of cracks of different sizes on the glaze for natural decoration, as ice cracks in general, usually known as “ice cracks.” This kind of crack is naturally produced, and it is not intentional or intentional by craftsmen. This natural decoration perfectly fits the aesthetic concept of ancient China.

2.2. 3D Evolution Algorithm. One of the main forms of digital technology is image 3D reconstruction. Stereo vision performance by 3D evolution algorithm, the realization of
the stereo vision three-dimensional evolution process is stereo image matching and the label calibration process, each label corresponding to pixels of parallax in Markov random field is including three collections: network node set \( L \), neighboring relations system set \( N \), and collection of random variables \( F \). Among them, the set of sampling points is the set of network nodes, the set of connection relation between nodes is the set of adjacent relation system, and the set of possible values of a node element is the set of random variables.

Defining energy function is to transform matching problem into energy function problem. Therefore, stereo matching can be described as the energy function minimization problem. The matching algorithm can specify a label value for each pixel point. The operation is to find the appropriate label among all possible labels and quantify the label as an energy function. In the case of stereo matching, the label is parallax, reaching a set of parallax function values that minimize the energy function. The essence of stereo matching is to obtain the parallax value and parallax relation between pixels of different images. Therefore, the image segmentation stereo matching algorithm is divided into the following steps: composition — edge sorting — initialization — merging image regions — iterative output. Image segmentation through the above steps basically reflects the structure of the real scene, where the connection between images is a deep discontinuous area.

It is pointed out in the literature [15] that the integration of digital interactive technology into ceramic product design conforms to the requirements of The Times. Therefore, this paper proposes the modeling design of ceramic products based on 3D evolution algorithm of digital interactive image. The image based on this algorithm uses the implicit fitting Poisson 3D reconstruction algorithm, uses the indicator function to extract the isosurface and generate the triangulated surface prediction function, and uses the relationship between the constructed vector domain and the indicator function to realize the Poisson reconstruction, and completes the 3D modeling design of ceramic products through the above steps [16, 17].

According to the characteristics of ceramic products, the image modeling method is combined with solid design, and the design process is realized by data interaction and 3D evolution. Therefore, the Poisson reconstruction algorithm is proposed, which is a global solution. It adopts the sample points after the image segmentation in the previous section and does not need to be resegmented or fused. The reconstruction method limits the implicit function gradient at all spatial points with few errors [18]. The flow of the 3D evolution algorithm for Ru porcelain is shown in Figure 2.

Set the input data \( S \) as the set of sampling points \( s \). Any sampling point includes two properties: position \( s \). \( p \) and normal \( s \cdot N \). The sampling point is the point or approach point of the surface \( \partial M \) of the mold \( M \). The Poisson reconstruction is to extract the isosurface from the estimation model and present a closed triangulated surface prediction function by using the indicator function of the estimation model.

2.2.1. Construct the Integral Relation. Firstly, the integral relationship between the indicator function gradient and the construction vector domain is expressed, and the surface integral, that is, the gradient domain is summed and estimated by the point set. Then, the gradient domain is used to calculate the exponential function.

Set a ceramic with a surface estimated as \( \partial M \) surface, set \( \chi_M \) to represent the indicator function of \( M \), the inner surface normal is represented by \( \overline{N}_{\partial M} (p \rangle \), and the point \( p \in \partial M \), \( \bar{F}(q) \) represents the smooth filter. \( \bar{F}_p (q) = F(p \cdot q) \) represents the transformation of point \( p \), and the normal vector domain of the surface after the smoothing is equal to the surface after the slide; therefore,

\[
\nabla (\chi_M \cdot \bar{F})(q_0) = \int_{\partial M} \bar{F}_p(q_0) \overline{N}_{\partial M}(p) dp.
\]

Among them, \( \bar{F} \) represents a universal smoothing filter; \( q_0 \) represents the smoothed sampling point; and \( \bar{F}_p (q_0) \) is the transformation of smooth filter at the sampling point \( p \).

2.2.2. Estimate Surface Integral. According to the surface geometry information, the surface integrals are estimated by using point sets in the model. \( \partial M \) is segmented into the independent plane set \( \{ p \in \partial M \} \) by point set \( S \), and the integral on the independent plane \( p_i \) is predicted by the position \( s \). \( p \) of the sampling point set, and \( p_i \) region determines the sampling point set region; therefore,

\[
\nabla (\chi_M \cdot \bar{F})(q) = \sum_{s \in S} \int_{p_i} \bar{F}_p(q) \overline{N}_{\partial M}(p) dp = \sum_{s \in S} |p_i| \bar{F}_{xp}(q) s \cdot \overline{N} = \nabla (q).
\]

In formula (2), \( \bar{F}_{xp}(q) \) express \( \bar{F}(q) \) transform of sampling point position \( s \). \( p \) by smoothing filter; \( \nabla (\cdot) \) represents the vector field.

\( \bar{F}_{xp}(q) \) is the transform of \( \bar{F}(q) \) smooth filter at the sampling point \( s \). \( p \), and \( \nabla (\cdot) \) represents the vector domain of construction.

2.2.3. Define Vector Field. In order to solve the indicator function accurately, it is necessary to define the vector field, which can transform the sampling point into its

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**Figure 2:** The flow of the 3D evolution algorithm for Ru porcelain.
corresponding node center, and classify the sampling points on eight nearest neighboring nodes by using three-line interpolation, and then the indicator function gradient field can be described as

\[
\nabla (q) = \sum_{s \in S} \sum_{N_{\text{Ngbr}D(s)}} \alpha_{o,s} F_o(q)s \cdot N,
\]

(3)

where \(o\) represents the node corresponding to the sampling point; the node with the nearest depth \(D\) from the sampling point \(s\). \(P\) is represented by \(\text{Ngbr}D(s)\), and \(\alpha_{o,s}\) represents the trilinear interpolation weights. The underlying function of node \(o\) is expressed by \(F_o\).

2.2.4. Extract Isosurface. To obtain the reconstructed surface \(\partial M\), the isosurface is extracted by selecting the appropriate exponential function value, which should meet the requirement that the sampling point set is distributed near the isosurface as much as possible. The indicator function \(\lambda_M\) was estimated according to the sampling point set, and the mean value was used for isosurface extraction; therefore,

\[
\partial M = \{ q \in \mathbb{R}^3 | \chi(q) = \gamma \},
\]

\[
\gamma = \frac{1}{|S|} \sum_{s \in S} \chi (s,q),
\]

(4)

where \(\mathbb{R}\) represents the set of functions of sampling point set acquired by scaling or transformation; \(\chi(q)\) is the indicator function of sample point \(q\). \(\gamma\) represents constant; \(\chi(s,q)\) indicates the location of sampling points.

Assuming that the sampling point set is distributed on the surface of the model, the vector domain is constructed, expressed by the function in space, and then the surface estimation of the isosurface is obtained from the generated indicator function, and the 3D modeling design of ceramic products is realized by the above digital interactive 3D evolution algorithm.

3. Collaborative Product Design of Ru Porcelain

In this paper, the Yuhu spring bottle is designed as the representative, which is a shape with curled mouth, thin neck, drooping belly and round feet, and a soft curve as the contour line. Its basic shape is composed of two symmetrical S-shaped curves on the left and right, with graceful and soft lines with a kind of oriental feminine softness, reflecting the oriental aesthetic of porcelain [19]. In this paper, the generation of 3D Yuhu spring bottle model is shown in Figure 3. The feature information of product sketch pixel was extracted, the model components were constructed by parametric pixel method, and the model was constructed by geometric rotation stitching. To generate the model, global shape and local shape of products are converted into parameter requirements, and graphic element shape changes accordingly. At the same time, the linear model of 3D model is manually adjusted to realize rapid shape and collaborative change of the 3D ceramic model.

3.1. Simulation of 2D Image. Parameterized design means that when the dimension parameters of a certain part of the graphic element are changed or the defined part parameters are modified, the system automatically completes the change of the graphic related parts to realize the graphic driving [20]. It connects the shapes, features, and functions of products through constraints, which constrains the size and geometric structure of graphic elements, and combines them into design drawings. The parameterized design methods include parameterized pel and parameterized modification engine [21]. Parameterized pel controls the geometry and features of the underlying controls of the model through input data, and parameterized modification engine controls the correlation between each module. With the help of parameterization, the sketch is divided into \(n\) components, which are defined as \(\{P_i\}\), and the parameter information of basic geometric primitives is extracted and given different descriptions, which is shown in Figure 4.

Pels are the basic elements of 3D entities. All pels can be decomposed into four basic elements: point, line, arc, and circle [22], as shown in Figure 5.

The parametric curve \(S_p = \{S_p, L\}\) consists of a series of three-dimensional curve control points \(S_p = \{S_p_i\}\) and discrete line segment control points \(L = \{L_p\}\). A set of spatial closed plane domains \(G = \{A_r, C, P_o, R_o\}\) is defined. The closed plane domain includes a circle \(C = \{C_p_o, C_p_1\}\) controlled by the center and a point on the circumference, and an ellipse \(A_r = \{A_p_0, A_p_1\}\) controlled by the corner points on the center and the surrounding rectangle.

\(D\) is defined as position stitching constraint, \(D = \{D_i | i = 0, 1, \cdots, 3(n - 1)\}\), \(n\) is the number of parts in the sketch, and \(D\) realizes position stitching between parts. \(H\) is the hollow-out constraint, \(a\) is the hollow-out rate, \(M\) is the collision stitching constraint, \(M = \{(p,M_p) | p = 1, 2\),
,⋯,n"}, p is the component identification, and \((p,M_c)\) defines the type of stitching between component \(p\) and the stitching body as \(M_c\). According to the above description, the parameterized expression of ceramic products is

\[
Z = ([P_i \mid i = 0, 1, \cdots, n], D, M, \alpha) \ P_i = (G, Sp, T, H). \tag{5}
\]

### 3.2. Assembly Simulation of Each Component

The construction of 3D model makes the effect of product design closer to reality and displays it in the most intuitive way. The complete 3D entity has a complex structure, which can be divided into several components, modeled separately and then spliced and merged. As shown in Figure 6, ceramic products are divided into multiple components, and each product component is generated in three dimensions, and a complete 3D model is generated by geometric splicing and merging of components and modeling adjustment.

The splicing of product shall be carried out within the same size to show that they are the main body, and the splicing display parts shall perform uniform size operation. The distance formula \(\text{dis}(p_1, p_2)\) and the scale factor \(d\) are defined as follows:

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**Figure 4:** Parametric simulation of 2D image.

**Figure 5:** Definition of primitive parameters: (a) parametric circle \(C\); (b) parametric ellipse \(A\).

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\[
\begin{align*}
\text{CP0} & \quad \text{CP1} \\
\text{AP1} & \quad \text{AP0}
\end{align*}
\]

(a) parametric circle \(C\); (b) parametric ellipse \(A\).
\[ \text{dis}(p_1, p_2) = \sqrt{(p_1 \cdot x - p_2 \cdot x)^2 + (p_1 \cdot y - p_2 \cdot y)^2 + (p_1 \cdot z - p_2 \cdot z)^2}. \]  

(6)

\[ d = \frac{h_2}{h_1} = \frac{\text{dis}(D_{11}, D_{12})}{\text{dis}(D_{21}, D_{22})}. \]  

(7)

As shown in Figure 6, the identification of feature points is transformed in the 2D image, where \( D_0 \) is the coordinate of the center point of the nozzle section in the sketch, and \( D_1, D_2 \) are the coordinate of the characteristic point at the joint of two parts in the sketch; in the entity to be spliced, \( D_{01}, D_{11}, \) and \( D_{21} \) are the feature points corresponding to the sketch in the entity part; in the entity of body part, \( D_{02} \) is the corresponding position of the center to be splice, and \( D_{12}, D_{22} \) are the corresponding feature point in the body entity of bottle.

By defining the connection and inclusion relationship between components, the components are spliced and merged to generate the 3D entity. The stitching of ceramic parts contains the constraints of position stitching, when the modeling of different parts is merged into the same entity, it needs to be transformed into the same modeling space in position, and the transformation process involves the size change, position conversion, and rotation operation of parts. The stitch of pot is taken as an example to give the operation process, as shown in Figure 7.

In order to realize the stitch of entity, coordinate \( D_{02} \) needs to be solved according to two-position image information, and the solving process is as follows:

\[ g_1 = \frac{\text{dis}(D_{12}, D_{22})}{\text{dis}(D_{11}, D_{21})}. \]  

(8)

\[ D_{02} = D_{12} - g_1 \times (D_1 - D_0). \]  

(9)

Given three points \( D_{01}, D_{11}, D_{21} \) and corresponding coordinate points \( D_{02}, D_{12}, D_{22} \) after transformation, \( R, T \)
can be solved, and then the transformation matrix of pot is
\[
R_{p} = \begin{bmatrix} R & T \\
0 & 1 \end{bmatrix}.
\]
Assuming that the corresponding three points after the transformation of \( R \) are \( 3 \times 3 \) matrix \( T \) are \( 3 \times 1 \) matrix sequence, \( B = R \times A + T \). The transformation matrix can be obtained by solving
\[
\begin{align*}
\mu_A & = \frac{1}{N} \sum_{i=1}^{N} D_{A_i} \\
\mu_B & = \frac{1}{N} \sum_{i=1}^{N} D_{B_i} \\
A_i & = \{ D_{A_i} - \mu_A \} \\
B_i & = \{ D_{B_i} - \mu_B \} \\
H & = \sum_{i=1}^{N} A_i B_i^T = \sum_{i=1}^{N} (D_{A_i} - \mu_A)(D_{B_i} - \mu_B)^T
\end{align*}
\]
\([U, S, V] = SVD(H)\)
\[R = VU^T\]
\[T = -R \times \mu_A + \mu_B.\]

According to equation (10), the transformation matrix
\[
\begin{bmatrix} R & T \\
0 & 1 \end{bmatrix}
\]
is obtained to realize position stitching.

3.3. Assembly Optimization of Ceramic Parts. The position constraint realizes the seamless stitching between ceramic parts, and the Boolean operation between parts completes the processing of the overlap area between parts in the stitching process. To perform Boolean operations on product parts, two parts need to intersect, and there is a common area. \( M \in \{M_0, M_1\} \), where \( M_0 \) represents adjacency and merge and \( M_0 \) removes the intersection and merge. Using Boolean operation, adjacency merges two parts of geometry space, removing the intersection and merge means remove two common parts and then execute operation of merge. Meanwhile, for a single component, \( H \in \{0,1\} \) can be defined to perform the hollow operation of the component entity, where \( \alpha \) is the hollow coefficient. The optimization process is calculated by the following formulas:
\[
S = \begin{cases} S & H = 0 \\
S \times (1 - \alpha) & H = 1 \end{cases}
\]
\[
S_i = \begin{cases} S & M = M_0 \\
S \cup S_{i+1} & M = M_1 \\
S_{i+1} \cup (S_i - S_i \cap S_{i+1}) & M = M_1 \end{cases}
\]

where \( S_i \) controls position adjustment, allowing the model components to rotate as required. The scale adjustment is shown in formula (13), and the global variable \( m = (m_x, m_y, m_z) \) is defined as the size variable constraint, and \( m_x, m_y, m_z \) are the scaling proportion of components in \( X, Y, \) and \( Z \) axes. Users perform global adjustments to each component or entity, including scaling and positioning. Proportional adjustment supports horizontal, vertical, and all-round size of the product proportional transformation, only changes the size of the shape without changing the shape of the shape.

3.4. Process of Collaborative Design. Based on the user experience, collaborative design aims to design products that meet the user’s needs, which are convenient and efficient to use. It allows users to learn better, complete tasks faster, and satisfy the unique experience of them in the process of experience. In addition, users are no longer inclined to the invariable design of ceramic products aesthetic, but more
inclined to diversified, special-shaped product design. Parametric 3D model generation, which can quickly generate 3D model with input of feature point, is suitable for mass production but not for personalized customization by users. Therefore, the shape design method of collaborative ceramic product is introduced to personalize the products in fixed mode, so as to realize the interaction between people and products with convenient operation and excellent real-time effect [23]. The collaborative design in Ru porcelain makes it difficult to adjust the shape of the generated 3D models. Therefore, this paper draws a 3D linear model to describe the outline information and cross section feature information of the model. According to the user’s own requirements, manually stretch and drag the position of each feature point on each line and section of the linear model to realize the change of sketch outline and section shape, and constrain the corresponding primitives in the 3D model entity to realize the 3D model reconstruction. According to the change effect, users can further adjust to realize real-time collaborative design of products. The shape of the generated 3D model can be further adjusted, where online space mouse manually changes the position of contour curve and the size of primitive, and realizes the shape change of Ru porcelain.

4. Analysis of Simulation Results

The effective application of digital technology improves the level of product design. In order to verify the feasibility of the algorithm in this paper, the following simulation experiments are carried out. Based on the image feature of Ru porcelain as the basis of 3D product design, the shape design of ceramic products is carried out by using the Poisson reconstruction algorithm and subdivision surface reconstruction algorithm. Four groups of image feature data of Ru porcelain are shown in Figure 8.

Compare the design time and effect differences of each group among Ru porcelain products. The specific data are shown in Tables 1 and 2.

Table 1 shows the statistical data of shape design of ceramic products using the Poisson reconstruction algorithm, and Table 2 adopts the subdivision surface reconstruction algorithm. From the perspective of shape design time in Table 1, the subdivision surface reconstruction algorithm takes more than 60 minutes for shape design of Ru porcelain, and the maximum time has reached 80 minutes, which shows that the design efficiency by this algorithm is low. However, the algorithm in this paper takes less time for shape design of Ru porcelain, which is basically around 16 min, indicating that the algorithm in this paper is efficient. Moreover, from the output effect of Ru porcelain, the clarity of shape output in this paper is over 95%, while that of subdivision surface reconstruction algorithm is less than 50%. Therefore, comparing the two algorithms, the performance of the algorithm in this paper is better.

The method has real-time interactivity and adjustability of the model, which meets the personalized design requirements, allows users to quickly complete the 3D model construction of ceramic products under a fixed model, simultaneously meets the user’s requirements for the change of the width-height ratio and the shape of each component, and greatly improves the efficiency and convenience of design. In addition, it has practical significance for professional and nonprofessional people to design the appearance of Ru porcelain, which provides great convenience and portability for ceramic product design.

5. Conclusion

By applying 3D parametric technology to the design and creation of ceramic, the combination of computer aesthetics and product design is helpful to stimulate the collision of diversified design ideas and trigger a brand-new design mode of ceramic. In this paper, Ru porcelain, an excellent porcelain in celadon series, is selected as the research object. According to its artistic characteristics and cultural heritage, innovative collaborative design based on 3D evolution was carried out for its shape. The simulation results show that the clarity of Ru porcelain designed by the algorithm in this paper is more than 95%, and the design time is less than 20 min, which greatly improves the efficiency and
convenience of design, and is of practical significance to professional and nonprofessional shape design, thus providing great convenience and portability for design of Ru porcelain.

Data Availability
The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest
The authors declare that there are no conflicts of interest.

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