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The Study and Development of Personal 3D Modeling Generator Based on Parametric Design

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Abstract. This study introduces a system called "Personal 3D Modeling Generator", which was created through the parametric software Grasshopper. This system collects, analyzes, and transforms gesture trajectory data into 3D model outputs. By leveraging visual features such as the path, outline, and size of gesture trajectories, this system generates unique 3D artworks for each individual gesture trajectory data. The multi-sensory interpretation of this data art provides users with the ability to create personalized artworks by crafting their own "gesture trajectory signatures", enabling a multitude of interactive experiences.

Keywords. Parametric Design, Gesture Trajectory，Personalization, 3D Modeling.

1. Introduction

We are in an era of the Maker Era, and digitally-manufactured tools are pretty common in daily life, such as laser cutting machines, 3D printers, etc. The process of using these devices to manufacture and assemble objects through computer numerical control is generally referred to as "digital fabrication" of these devices [1]. The standardization of cross-industry data approaches will be a crucial driving factor in this autonomy, accelerating the adoption of 3D product models in areas such as analysis, machine learning, and the Internet of Things (IoT). The evolution of the geometric shape and key characteristics of products will also be able to be modeled in real-time [2]. The public can easily use these digital tools and open sources on the Internet to design, make, and improve the convenience of self-made. However, due to the convenience of obtaining the design files of other designers from open source, the design outcomes are very similar and lack the characteristics of personalized design.

Parametric Design is a 3D modeling method that uses visual programming software and parametric correlation to generate a series of continuous designs with 3D model transformation through digital tools and scripts [3]. Digital self-manufacturing brings new ways of thinking and creating objects. It sparks our interest in "parametric design" and research motivation.

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This study uses a parametric product design and personalized manufacturing method and develops a “personalized 3D modeling generator” system. “Personalized 3D modeling generation algorithm” was created through the parametric software Grasshopper. Specifically, the user's gesture trajectory obtained by free drawing in three-dimensional space is used as the input source, a personalized 3D digital file is generated through an algorithm and then output through a 3D printer, thereby obtaining a unique hand-painted trajectory sculpture. This research combines scientific research, computer graphics, mathematics, and digital manufacturing to explore new paradigms in product design and manufacturing. The research is not about designing objects themselves, but about making computing systems to get countless different creations and discover new ways of human-machine symbiosis.

2. Related Work

2.1. 3D Modeling Techniques

The traditional 3D modeling algorithms are based on polygon mesh modeling and NURBS modeling, and the interaction is mainly through mouse and screen. According to Xi-Dao LUAN et al, traditional 3D modeling methods can assist designers in interactive modeling [4], but these methods are time-consuming and require designers to have a basic understanding of relevant 3D modeling software techniques.

In 2011, Jonathan Mirtschin pointed out that Rhino, the 3D modeling software, through parametric design and the use of the Grasshopper plugin, allows users to create complex geometric shapes and designs through visual programming [5]. In 2018, E. Haines stated that real-time rendering and interactivity in modeling software have gradually increased, enabling designers to intuitively edit and view models [6]. The core of parametric design is transforming all related design elements into variables of functions, and changing the function parameters to adjust and alter the overall design scheme. However, Grasshopper, being a Visual Programming Language, has a higher learning curve compared to traditional 3D modeling techniques. In 2020, Paul Henderson introduced a new generation process for 3D meshes, where he learned from a collection of 2D images without any 3D information, resulting in the formation of 3D samples [7]. This approach moves away from the traditional mouse and screen interaction of 3D modeling techniques.

2.2. Application of Gesture Trajectory in 3D Modeling

Leap Motion is a device for micro-motion detection. It is applied to micro-joint motion capture. It can help developers achieve self-defined development and design by sensing and collecting data such as object gestures, making somatosensory interaction simpler and faster [8].

Holz and Wilson proposed Data miming as an approach towards descriptive shape modeling wherein voxel representation of a user’s hand motion is used to deduce the shape which the user is describing [9]. Prieto et al. presented a system for creating 3D frames for structural design [10]. These proposals only allow wireframes creation, which could be difficult to understand for complex geometries. Vinayak et al. (2013) defined 3D modeling activities, such as shape creation, modification, and manipulation, using a depth-sensing camera (Kinect) [11]. In 2015, they further explored the potential of a depth-sensing camera (Leap Motion) in a pottery-inspired application, which demonstrated how users use their hands to express their intent for deformation during the pot shaping process [12]. While gesture theory primarily focuses on gestures performed in conjunction with speech, most gesture-based interfaces are supported by other modes of interaction. It was further found that the nature and appropriateness of gestures used was not a primary factor in gesture elicitation when designing gesture based systems, and that ease of technology implementation often took precedence.

In this study, we enable users to freely draw in a three-dimensional space and capture their trajectories using Leap Motion. The trace of gesture mapping will serve as the input data source for our developed 3D generator. Through a generator-driven design, we interpret the user's data and transform it into an interactive storytelling scene, enhancing the ease of communication between the audience and machine technology.

2.3. Parametric Design and Personalization

In the doctoral dissertation, Ivan Sutherland, the pioneer of computer-aided design in the 1960s, took the concept of parameterization as the core of his Sketchpad system. The parameter values were modified through the inter-face to obtain different design elements [13]. Parametricism originated in architecture, breaking the geometric construction method of nonlinear association of traditional modeling methods. This computer-based design approach treats the geometric properties of the design as variables. Dimensions, angles, and geometric properties such as curvature remain malleable as the design progresses.

With the continuous advancement of parametric design research, this design method is gradually used in product design. In 2007, Gernot Oberfell of the German design firm Wertel Oberfell constructed a coffee table using a mathematical algorithm (Fractal-T) [14], and in 2014 Dutch designer Joris Laarman designed an Adaptation Chair through parametric design [15]. NERVOUS Studio not only uses a parametric design method to develop products but also released online design applications based on the Nervous System that enables customers to co-create products to make the design more accessible [16]. These tools allow for endless design variation and customization.

At present, the maturity of parametric design in dealing with a single object is not as good as that of traditional modeling methods. Still, traditional modeling is far less convenient than parametric design when dealing with many logics of the same steps simultaneously [17]. The personalization of NERVOUS Studio is based on a limited input source. Users can personalize and fine-tune parameters in the interface system, and the interaction form only lies in the mouse and the interface system. This study believes that the designer's role should be to help the public to create forms cooperatively, or to make them interact with the creation, and let the user interact with the work as one of the ways of creation.

2.4. Conclusion

Current research primarily focuses on the application of gestures in 3D modeling and the field of Parametric Design and Personalization, with limited exploration of the integration between parametric design and free gestures. This study aims to combine 3D modeling technology, the dynamic system characteristics in parametric design, and gesture trajectory capture to explore the potential application of the “personalized 3D modeling generator” system in artistic creation.

Based on the rapid development of 3D modeling and research in parametric design, this paper presents the development of a “personalized 3D modeling automatic generator” system. This research offers three key advancements. Firstly, from a designer's perspective, the system combines computer and digital tools to establish a new design thinking process, liberating designers from traditional 2D methods and enabling them to create personalized works. Secondly, from a consumer's standpoint, the system meets the public's desire for unique and personalized products, offering consumers the opportunity to make choices beyond purchasing pre-made products. Lastly, from the application of parametric design, the system integrates the user's movement trajectory into the design process, generating personalized products and artworks based on the user's finger movements. With this system, multiple unique product design and application methods can be created, providing innovative directions for the development and application of parametric design.

3. Construction Method of Personalized 3D Modeling Generator System

The human body motion capture device is used to capture and record the movements of various external behaviors of the human body, from large movements such as limbs and hands to subtle movements of facial expressions. This research is based on technologies such as gesture recognition as the input of the "personalized 3D modeling generator" system. At the same time, gesture recognition technology enables viewers to become co-creators directly, experiment with various creative possibilities of the works, and explore the diversity of creative works.

3.1. Research Design and Experimental Apparatus

This research explores the design of personalized works from the perspective of digital makers, develops a set of “personalized 3D modeling automatic generator” systems based on “parametric design”, and creates examples for further illustration and discussion of the research method. First, Leap Motion (now called Ultra-leap) [8] device allows users to draw freely in the air to form a trajectory motion file. Then, through the algorithm developed in this study, a computerized method generates a 3D model with trajectories of individual gestures. Then, through the algorithms developed in this study, the automated process generates 3D models featuring individual gesture trajectories. This research uses the Grasshopper (GH) visual programming language to construct an automatic method of the parametric algorithm, allowing users to adjust parameters in the system to generate 3D creative models related to air gesture trajectories. We will use geometric mathematics to ex-plain the research method of this paper. (Note: The diagram of the hand-drawn trajectory in Figures 3-5 is just a schematic illustration of a representative trajectory)

Figure 1 explains how the “Personalized 3D Modeling Generator” system uses the entire flowchart of Grasshopper. The whole system is divided into four modules (algorithms). Respectively, A (hand-drawn curve) module, B (3D shape) module, C (folds) module, and D (cut surface) module, E (distortion) module. The purpose of this flow chart is that anyone can capture hand-drawn line traces through Leap Motion and the algorithm automatically transform them into 3D models. Users can continue processing the 3D sculpture models with different artistic qualities (folds, cuts, distortions). Finally, an artistic 3D object is printed through a 3D printer. In short, this system hopes everyone can draw freely, and eventually generate artistic sculptures so everyone can create artworks.

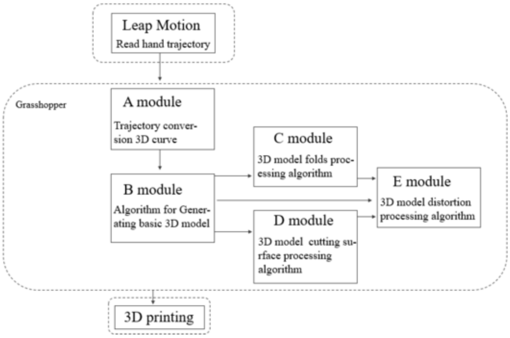

Figure 1. The Flow Chart of "Personalized 3D Modeling Generator" System.

3.2. Experimental Steps

"Personalized 3D Modeling Generator" System Algorithm contains 5 modules, as follows:

Module A: It is a 3D curve trajectory conversion algorithm that converts the user's hand-drawn motion trajectory into 3D curves.

Module B: The B module is mainly a 3D basic generation algorithm. The primary purpose is to allow users to draw and draw data after analysis freely and finally process and generate 3D molding. Module B includes four sub-algorithms (B1~B4): generating extended plane, generating sampling point & generating interpolation curve, filtering scale, generating 3D molding, and other algorithms. The relationship between the four sub-algorithms is serial. It is a basic 3D model generation algorithm. By finding the sampling points of the 3D curve to generate an interpolation curve, etc, the final loft is generated as a 3D shape.

Module C: The C module is mainly based on the 3D shape from the A module, using the interpolation points in A to sample the curve as the n points needed to form the fold surface. Step 2 divides the n points into odd-numbered points and even-numbered points. In Step 3, two kinds of points are moved to the inner and outer directions respectively and linked to form a fold line. In Step 4, loft the fold line of each layer of the extended plane to finally form a folded surface. The larger the value of n, the more fold lines will be. The larger the m is, the greater the degree of fold curvature is. It is a 3D model wrinkle processing algorithm that can add the artistic effect of folds to the 3D form generated by module B.

Module D: The D module is mainly based on the A module's 3D shape, using the A module's interpolation point curve to sample the points needed to form the cutting surface. Points sampled in each layer are connected in three directions to form a triangular mesh and, finally, generate cutting surfaces from grid lines of triangle mesh. The n in modules C and D have the same meaning, and both are adjustable parameters. We chose different values to differentiate generated effects. It is the 3D model dicing surface processing algorithm. It can add the artistic effect of the cutting surface to the 3D form generated by module B.

Module E: The E module contains the following three steps, mainly to reprocess the three modules B, C, and D. Use the A module to generate a 3D shape to find the central axis of this shape. Use the central axis as the central control axis of the distortion to form a distorted visual effect. The length of the central axis is controlled by r times the z-axis direction, $0<r<1$. Each interpolation curve rotates clockwise by w°, $-180° < w < 180°$. The r and w values are used to control the distortion of the 3D shape .It is a 3D model distortion algorithm that adds distorted artistic effect after module B, C, or D is processed.

3.3. The Core Module: Generating Basic 3D Shape

The B module is the core key of the "Personalized 3D Modeling Generator" system, which processes the original data of gesture trajectories into basic 3D models.

B-1 module: Generate extended planes. Create a tangent cuboid frame for the hand-drawn curve in three-dimensional space. Intersect the upper and lower sections of the cuboid (i.e., the top surface and the bottom surface) and locate the center points of these two surfaces. Connect the center points with a straight line. Divide this straight line with t horizontal planes, where t represents the number of planes. Each plane is referred to as an “extended plane”. Remove the top and bottom planes, leaving only t minus 2 planes.

B-2 Module: Generate sampling points and generate interpolation curve. This module aims to intercept the intersections between each horizontal extension plane and the hand-drawn curve, and then generate sampling points and interpolate a curve based on those intersections. There are three cases to address for optimal processing:

Case 1: Identify points on the extended plane that have only one intersection with the curve. These points should be deleted and marked in green (refer to Figure 2).

Case 2: Locate the point where the extended plane intersects the curve in exactly two points (refer to Figure 2), and denote these two points as a1and a2. (1) Calculate the distance between a1 and a2, referred to as l. The center point between these two points should be vertically aligned. Find a point, a3, that lies one-quarter of the distance l away from the line connecting a1 and a2. (2) Draw an interpolation curve through the intersections of a1, a2, and a3 on the extended plane, ensuring that the curve passes through each intersection point in a clockwise direction (refer to Figure 3).

Case 3: Find out the points where the extended plane has more than two intersection points (>2) (Figure 2); for each intersection point on the extended plane >2, find out intersection points with the smallest x-coordinate, the largest x-coordinate, and the smallest y-coordinate and the maximum y coordinate. (1) When there are four intersections, draw an interpolation point curve and pass each intersection clockwise; (2) When there are actually only three points (two points overlap), use an interpolation point curve and pass clockwise along each intersection (Figure 4); (3) When there are actually only two points (two points overlap), execute Case 2.

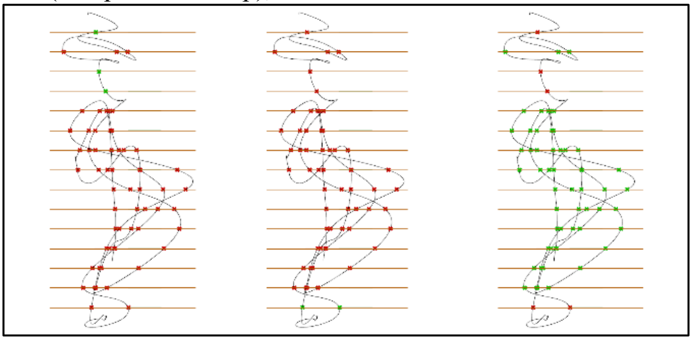

Figure 2. Gesture trajectory.

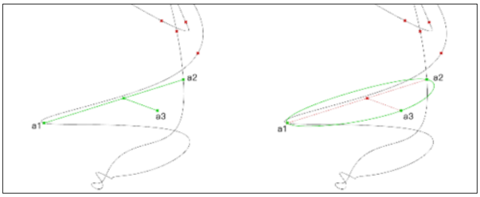

Figure 3. Gesture trajectory of cases 2.

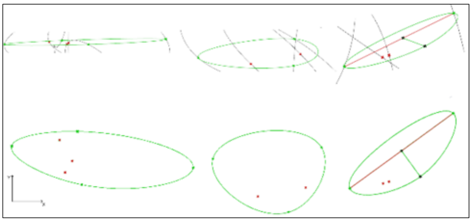

Figure 4. Gesture trajectory of cases 3.

The B-3 module only contains one step, which is mainly to judge a series of screening ratios, eliminating the maximum and minimum values with extreme values, in order to ensure the overall fluency of the interpolation point curve and also to ensure that the 3D model generated is printable via 3D printer. The screening ratio here is a parameter that can be adjusted.

The B-4 module generate 3D shape are mainly to avoid generating interlaced surfaces, internal and external reversed surfaces, etc., which are the situations that would occur in 3D software modeling. Ensure that the generated 3D shape is printable.

4. Implement and Discussion

In this paper, we developed a system called the “Personalized 3D Modeling Generator” and carried out several works based on this system. The procedure is as follows: Firstly, the user’s finger’s free movement is captured using the Leap Motion technology and converted into a line file within Rhino software (Figure 5). The blue dot depicted in the figure simulates the hand gesture on the computer and indicates the index finger, while the red line represents the motion trajectory of the hand. Subsequently, a 3D model is generated through the “Personalized 3D Modeling Generator” by adjusting the relevant parameters. The resulting 3D model file is then exported to the software of a 3D printer for slicing and subsequently printed. This process enables users to create their personalized 3D artworks known as “gesture track signatures”.

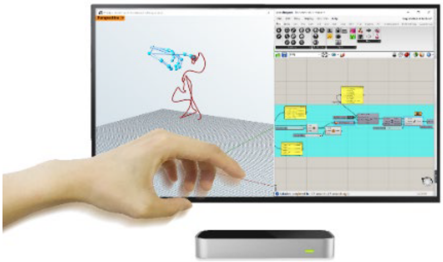

Figure 5. Leap Motion reads gesture trajectories. (Left)

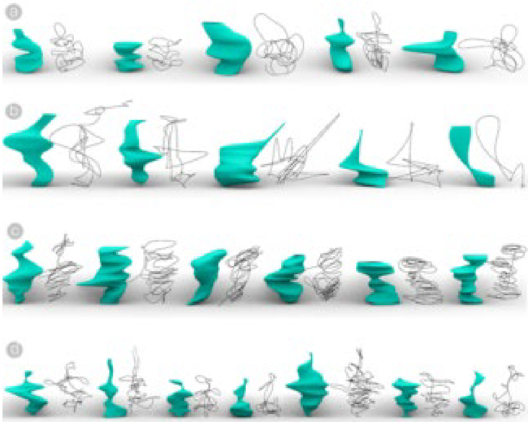

Figure 6. Hand-drawn trajectories and 3D sculptures of four user.(Right)

We also invited various users to utilize the “Personalized 3D Modeling Generator” system developed by our team at an art exhibition. Figure 6 illustrates the hand-drawn trajectories and 3D simulations of the generation process for four users, highlighting their distinct artistic styles. The 3D shapes are exclusively generated by leveraging their hand-drawn trajectories.

4.1. Artwork Generated

Figure 7 shows the 3D model generated by a “personalized 3D modeling generator” based on a “hand-drawn line trajectory”. The five works, a, b, c, d, e, correspond to the generated results of the five modules. The upper part of the “hand-drawn line trajectory” is only slightly horizontal, so the appearance of the shape is similar to a tightened bottleneck. The lines in the lower part show the dynamics and contour curves. The proportions in the process are well balanced, and the whole shape presents a dynamic beauty, like a female figure with a dynamic sense of dancing. The result of this attempt is astonishing. The interpretation of the algorithm captures the trajectory of artificial actions, showing the original intention expressed in this research, and also generates a sense of beauty. This is an ingenious fusion of rational algorithms and sensual consciousness. In Figures 7 and 8 (a) and (d), the artistic style shown here is similar to the artistic sculpture form of French artist Hans Arp's “Demeter”. They all present a smooth and rounded biological form, with a feminine sense of dynamic and beauty. This is a testament to our wrinkling algorithm's ability to create fluidity and the beauty of wrinkling on the form.

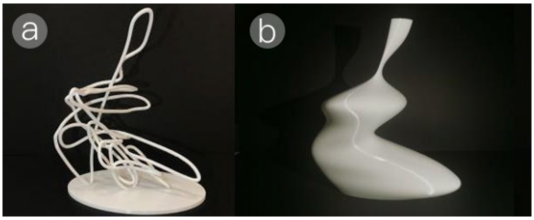

Figure 7. (a) shows 3D printed generated lines 228mm x 204mm x177mm (l x w x h). Material: PLA; (b) shows the whole 3D shape generated and 3D printed from front view and side view 165mm x 106mm x192mm (l x w x h). Material: PLA.

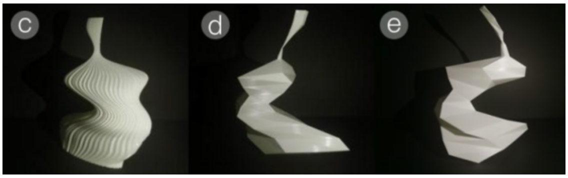

Figure 8. (c) shows 3D printed "olds" 165mm x 106mm x 192mm (l x w x h). Material: PLA; (d) shows 3D printed "cutting surfaces"165mm x 106mm x 192mm (l x w x h). Material: PLA; (e) shows 3D printed "folded cutting surfaces"165mm x 106mm x 192mm (l x w x h). Material: PLA.

4.2. Implement Potential

Artists and sculptors can employ the free gesture conversion technology presented in this research to capture their creative movements and transform the gesture into digital models, thereby crafting distinctive 3D sculptural artworks. This innovation offers a more intuitive and personalized approach to creative expression in the field of visual arts. In a virtual reality context, the free gesture conversion technology can be leveraged to create immersive digital art exhibitions. Audiences can interact with the digital pieces through gestures, providing a fresh and engaging artistic encounter. In the realm of customized industrial design, manufacturers can collaborate with clients using the free gesture conversion technology to intuitively grasp their requirements and preferences, facilitating the creation of personalized products.

Furthermore, in the field of sign language expression creation, this research offers the ability to convert movement trajectories that convey gesture meanings into 3D files. These 3D files can then be printed, delivering visually appealing representations of sign language expressions for the deaf community and sign language professionals.

These examples merely scratch the surface, as the technology to convert free gestures into 3D sculptures holds potential applications in numerous other fields, particularly those that demand intuitive interaction and creative expression.

5. Conclusions and Future Works

5.1. Key findings and conclusions

This research mainly develops the "personalized 3D modeling generator" system. This system uses a parametric visual programming tool (geometric function algorithm) combined with Leap Motion, allowing the public to draw freely and generate personalized three-dimensional sculptures from gesture trajectories, instead of relying on open sources on the Internet to make similarities. This research hopes to allow designers to break away from the traditional thinking frame through timely data capture and analysis and then transfer key parameters to the "personalized 3D modeling generator" system. In short, this system hopes to allow everyone to draw freely, resulting in artistic and personal sculptures, allowing everyone to create works of art. Moreover, this research presents a new opportunity in interpreting gesture data (free gestures), and creating a novel measurement approach by crafting their own "gesture track signature". The system can trigger new modes of interaction between art and science.

5.2. Limitations and Future Work

Due to the real-time nature of inputting hand-drawn trajectory data into Grasshopper (GH), the overall computational data volume becomes excessive. Therefore, in the design of the "Personalized 3D Modeling Generator" system, a switch has been implemented in GH, which only commands the computer to start calculating the corresponding 3D model once all hand gesture trajectories have been completed. In the future, a predefined set of gestures could be established to denote the start and end points, enabling smoother system operation and fully harnessing the real-time computing advantages of this system. Furthermore, the "filtering ratio" in Module B-2 enables the removal of extreme values from the hand gesture trajectories. This setting is implemented to mitigate the risk of accidental errors, albeit potentially leading to a lower similarity between the resulting 3D model and the freely hand-drawn lines. Given the multitude of unpredictable factors in hand-drawn lines, these challenges are need to be addressed in future research and development.

Therefore, in light of these points, this research holds the following prospects:

Firstly, offering users the freedom to customize parameters. The "Personalized 3D Modeling Generator" system empowers users to adjust parameters according to their personal preferences and aesthetic perspectives, potentially leading to the creation of real-time interactive installations.

Secondly, the mobile phone online system and app are supposed to be developed. With the advancing functionalities of mobile devices, the system can be transformed into an online platform and seamlessly incorporated into a dedicated app. Such advancements would liberate the output shapes from the constraints of being exclusively columnar.

Our system allows users' touch-less drawing tracks to combine computers and digital tools to establish new design thinking and generate new human-machine symbiosis creations. In the future, we expect to create more applications of human-computer symbiosis, as well as the infinite possibilities of a self-created digital future. The development potential of personalized works is expected.

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