Reverse Design and Manufacturing of a Double Wolf Head Model Based on 3D Printing and Five-Axis Machining

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Abstract. The design and machining technology of curved and irregular surfaces has always been an important subject in the field of engineering. In the product design process, sequential design and reverse design approaches each have their own characteristics in the field of modeling. This paper puts forward a sequential/reverse hybrid modeling method based on combined Geomagic Wrap, Geomagic Design X and UG in order to improve the efficiency of modeling. The method takes into consideration the characteristics of both sequential and reverse designs and brings out their advantages. With the “double wolf head” model of complex structures as the object of study, the “double wolf head” is re-developed and remanufactured based on 3D printing and five-axis machining combined with reverse design, and data from the model are collected using a three-dimensional scanner and Geomagic Wrap. Reverse engineering to parametric modeling is generated using Geomagic Design X; this solid model is then imported to the 3D printing and slicing software Cura and the multi-axis programming software hyperMILL, respectively, before machining, and the 3D printing model and the five-axis machining model are obtained. This method explores a new approach to part modeling, which vastly improves the machining precision and accuracy of model data, accurately perceives the real size of an object and is of great significance to shorten product development cycle times.

1. Introduction
In traditional industrial and product design, product components are conceived in tune with the needs of customers or the market, and then each component is designed, manufactured, inspected, and tested. This is the sequential design process. On an integrated 3D CAD/CAM platform, sequential design software capitalizes on wireframe modeling, solid modeling or parametric modeling methods to create 3D digital models that involve complex components. Sequential design is a process which develops a high-level conceptual design into a solid model [1-3]. Using the sequential design modeling method, the designed components can be parametrically edited, modified and redesigned, so they have a powerful subsequent machining advantage. However, in the process of product development, design and manufacturing, many times the product is not represented using a 3D CAD model [4, 5]; it is presented to the designer and manufacturer as a solid model, and sometimes there are even no drawing or instruction references. In order to meet the design and manufacturing requirements, it is necessary to convert the existing solid model into a 3D digital model at this time [6-8]. This approach of obtaining
model data from solid products and developing the same or similar products can also quickly manufacture the designed products. This is the value of the practical application of reverse engineering.

Relying solely on the sequential design process will lead to a long product design cycle without introducing advanced manufacturing and production technologies. However, relying solely on the reverse design process will lead to difficulties in data positioning and excessive data volume during the measurement process. Using reverse data processing software is difficult to achieve parametric and structured design. It only replicates the product and is not conducive to innovation [9, 10]. In view of the above characteristics of sequential and reverse designs, this paper proposes a hybrid design process that combines both sequential and reverse engineering [11].

Taking the “double wolf head” model that involves complex structures as the object of study, this paper uses reverse engineering to create a parametric model of the “double wolf head”. Through 3D printing software, the components are segmented and printed. It is expected that the result provides a theoretical basis for the development of complex curved surface design and machining technology, plays a positive role in the integrative development of reverse engineering and five-axis numerical control technology, and can promote the process of Made in China 2025.

2. Materials and Methods

2.1. Test materials
To make the research typical, this paper takes the “double wolf head” handicraft model of complex structures as the object of the study. The instruments and equipment used are Win3D scanner, Geomagic Wrap for point cloud parameter processing and surface encapsulation, Geomagic Design X for 3D solid modeling, FDM desktop 3D printer, among others.
2.2. Test method

2.2.1. Calibration of scanning systems. The basic principle of scanning systems is to use advanced heterodyne grating phase-shift measurement technology. First, the grating fringes are projected onto the surface of the workpiece to be scanned. The amplitude and phase of the grating fringes are modulated, and the modulated fringes are collected by 3D scanning systems and sent to a computer, thereby obtaining the 3D coordinates of the workpiece. The measuring equipment is a Win3D scanner, with the scanning range of 700 mm, the single scanning time of less than 3s, the scanning point-to-point distance of 0.2~1.5 mm, the scanning ball space error of 0.005+L/15 000, the sphericity error of 0.005+L/40 000, and the flatness error of 0.005+L/25 000, where L is the length of the diagonal of a single scan. The working status and related parameters of the Win3D scanner is adjusted (Figure 1). According to the accuracy requirements of the model, the acquisition error of the 3D scanner is set to be 0.02 mm; the “double wolf head” model (Figure 2) is sprayed with a developer and the calibration points are labeled. The calibration points should be pasted on the plane surface of the workpiece or the curved surface with a curvature as small as possible, and a little farther away from the boundary of the workpiece; the calibration points should not be pasted on a straight line, and should be pasted asymmetrically as much as possible; the number is generally 5-7. The pasted calibration points should ensure the smooth implementation of the scanning strategy, and the calibration points should be reasonably distributed in the length, width, and height directions.

2.2.2. Parametric modelling. Model data collection: Put the calibrated “double wolf head” model on the calibration plate at the bottom of the scanner. Collect the point cloud data of the “double wolf head” model through a 3D scanner, and use Geomagic Wrap to parameterize the point cloud data. The commands often used at this stage consist of in-vitro isolated points, noise reduction, and unified sampling. The method of least squares is used to reduce point cloud noise, as shown in Formula (1). Finally, it is encapsulated into a polygon “double wolf head” model. Commonly used commands in the polygon stage are hole filling, defecture, mesh doctor, fix boundary, simplifying, relax/abrasion. The processed polygon model is saved as a *.stl file. The *.stl file is imported into Geomagic Design X for reverse parametric solid modeling, and finally into the sequential modeling software. The base is redesigned, and the new model as shown in Figure 3 is obtained. The new model is sequentially output as a *.stl file and a *.stp file for 3D printing and five-axis programming, respectively.

Figure 3. “Double wolf head” parametric model
\[ \begin{aligned}
\hat{a} &= \bar{y} - \hat{b} \bar{x} \\
\hat{b} &= \frac{\sum_{i=1}^{n} x_i y_i - n \bar{x} \bar{y}}{\sum_{i=1}^{n} x_i^2 - n \bar{x}^2}
\end{aligned} \] (1)

2.3. Machining and manufacturing

2.3.1. 3D printing. The “double wolf head” parametric solid model in *.stl files is imported into Cura for slicing application. When slicing, the slicing direction and the slicing thickness will affect the mechanical properties and accuracy requirements after printing, and should be selected reasonably according to the structural characteristics of the model. For the suction nozzle structure designed in this paper, if horizontal layering is used, deposition will occur on the upper surface during printing, which will cause large volume errors and affect printing accuracy, so vertical layering is adopted. For the layer thickness, in order to meet the surface performance requirements, uniform-thickness layer is used to reduce the staircase phenomenon to minimize the influence of the volume error, thereby improving the printing accuracy and overall performance. After the slicing is completed, a G-Code is generated from the model and imported to an FDM desktop 3D printer.

![Figure 4. “Double wolf head” 3D printing model](image)

2.3.2. Five-axis machining. This paper uses Mikron HEM 500U five-axis CNC machining center to complete the machining test. The “double wolf head” model file in *.stp files is imported into hyperMILL for CNC programming. The model has a complex structure and can be processed in three processes, namely roughing, semi-finishing and finishing. Roughing (Figure 5a) adopts fixed-axis machining in high speed, which is four-axis machining. It does not rotate along the B-axis, and completes basic contour rough machining using an end mill reserving a machining allowance of 0.15 mm. Semi-finishing (Figure 5b) also adopts fixed-axis machining in high speed. The semi-finishing of each curved surface is completed using a ball cutter, reserving a machining allowance of 0.15 mm. During finishing (Figure 5c), five-axis work together. With high-speed cutting of small surfaces (at high speed with small feed), machining of the “double wolf head” model is finished. After the program corresponding to each process is checked, the corresponding hyperMILL program is post-processed,
and the machine tool processing program code is generated to prepare for the actual processing of the machine tool.

On June 20, 2019, the CNC machining center training base at the Shaanxi Institute of Technology conducted a “double wolf head” machining test and the machining results are shown in Figure 6. After the machining was completed, CONTURA G2 three-coordinate measuring machine was used to detect the shape and size errors of the “double head wolf” machining model and the reverse test model, and the maximum error was less than 0.06 mm. TR200 surface roughness measuring tester was used to detect the surface quality, and the roughness reached Ra3.2, which can meet the requirements of dimensional accuracy and surface quality in engineering.

3. Results and Discussion

3.1. Reverse modeling analysis

Reverse modeling is to create a digital model of an existing object using parametric modeling. By comparing Figure 2 and Figure 3, it can be found that the reverse modeling method can perfectly replicate the complex model, so it can be used for secondary innovative design in Geomagic Design X. Since this process is to collect model point cloud data using a 3D scanner, it has much higher efficiency and accuracy than traditional three-coordinate measurement methods. The reverse design method is the main direction of the innovative design of complex models in the future.
3.2. Reverse modeling and 3D processing analysis

A parametric model of the “double wolf head” model is established through reverse modeling, and the model is processed using 3D printing and five-axis machining. The integration of reverse engineering, sequential engineering, 3D printing and five-axis machining can achieve innovative product design in high quality and shorten product production cycle times, which is of great significance for promoting my country's industrialization process.

4. Conclusion

In order to study the design and machining technology of complex curved surfaces, this paper takes the “double wolf head” model as the object and carries out reverse modeling, 3D printing and five-axis machining. The idea of development and remanufacturing organically links emerging development technologies with emerging manufacturing methods. While improving development efficiency, it can not only reduce process difficulty and processing costs, but also promote product innovation and improvement. With impressive advancements in reverse engineering combined with 3D printing technology, the development model based on the combination of 3D printing and reverse engineering will embark on intelligence, popularization, and diversification journeys, thus providing ground-breaking ideas and methods for the development and molding of complex components in the future manufacturing industry.

Acknowledgments

This work was financially supported by Shaanxi higher education teaching reform research project fund-Research and Practice on the training of numerical control technology talents for intelligent manufacturing(17GY014), The 13th five year plan of Educational Science in Shaanxi Province in 2020 fund(SGH20Y1567) and the national treasury of digital manufacturing (CAM) curriculum resources of China (1211911).

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