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RESEARCH ON DESIGN METHOD OF HULL SURFACE BASED ON REVERSE ENGINEERING

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RESEARCH ON DESIGN METHOD OF HULL SURFACE BASED ON REVERSE ENGINEERING

Guan Guan*, Wenwen Gu, Xiaole Yang

Key words: hull surface, reverse engineering, surface reconstruction, design parameter extraction.

ABSTRACT

To shorten the development cycle of new ship form and improve the efficiency of ship design, this paper proposes a digital design method of hull surface based on reverse engineering. The point cloud information of the hull surface is obtained by a 3D laser scanner. The point cloud is aligned, denoised, and simplified by the improved ICP algorithm and chord height difference method. The hull surface is reconstructed in CATIA and the error analysis is performed. The smooth surface with considerable accuracy is obtained. The offsets of the reconstructed hull surface are obtained by the secondary development of CATIA. The lines plan is generated, which can be used in the subsequent redesign. This method provides a novel idea for the design of the new ship form.

I. INTRODUCTION

The traditional design process of the new ship is a forward design process. It is a sequential and repetitive process. Due to the complexity of the hull surface, it is difficult to express it with accurate mathematical expression in the preliminary design stage (Xu, 2005), which brings some difficulties to the designers. To overcome the inconvenience of the traditional ship design, a digital reverse design method based on ship physical model is proposed. The reverse design method can shorten the development cycle of the new ship form.

Due to the successful application of reverse engineering technology in other related fields, many scholars also applied reverse engineering technology to ship design and construction. Paoli and Razionale (2012) measured the side of a 59m yacht and reconstructed the 3D model by using the laser scanning method. However, the complex surface of the stern and bow was not measured. Roca-Pardinas et al. (2012) proposed a method to check the symmetry of the hull by using point cloud reconstruction. The point cloud data of the hull surface were obtained by the laser scanner and the surface was reconstructed. The symmetry of the hull was analyzed. Edessa and Bronsart (2015) proposed a method of hull surface reconstruction, which extracted sections and water lines directly from point cloud data to fit the hull surface, but it was difficult to extract the curves of the bow with large curvature. Tang et al. (2016) used the close-range photogrammetry to measure a tugboat. Zhang et al. (2016) applied 3D laser scanning technology and point cloud slicing technology to calculate ship displacement. Hübler et al. (2017) applied simulation technology and reverse engineering technology to ship reconstruction. The hull, rudder, and propeller were measured by the laser scanner, and the CAD models were reconstructed. Wang (2017) applied reverse engineering to the surface processing of ship structures. Zhang et al. (2017) proposed a method of hull line generation based on point cloud slicing. Njaastad et al. (2018) proposed a method of scanning the propeller, but only a single blade was measured.

Most of the above studies focus on the measurement and model reconstruction of the hull surface. This paper proposes a design method of the hull surface based on reverse engineering. The surface information of the ship model is measured by a 3D laser scanner, and the measured data are aligned, denoised and simplified to obtain the point cloud data which satisfied the requirements for the surface reconstruction. The surface of the ship model is reconstructed and the error is analyzed. Finally, the offsets of the reconstructed hull surface are extracted by the secondary development of CATIA, and the lines plan is generated. The specific process is shown in Figure 1.

II. POINT CLOUD DATA PROCESSING OF HULL SURFACE 3

Considering the advantages of the laser scanner, such as high speed, convenient measurement, and high accuracy, the laser scanner is used to measure the ship model.

2.1 Point cloud alignment

Multiple and multi-angle measurements are performed to digitize the product entirely. As a result, point clouds are measured

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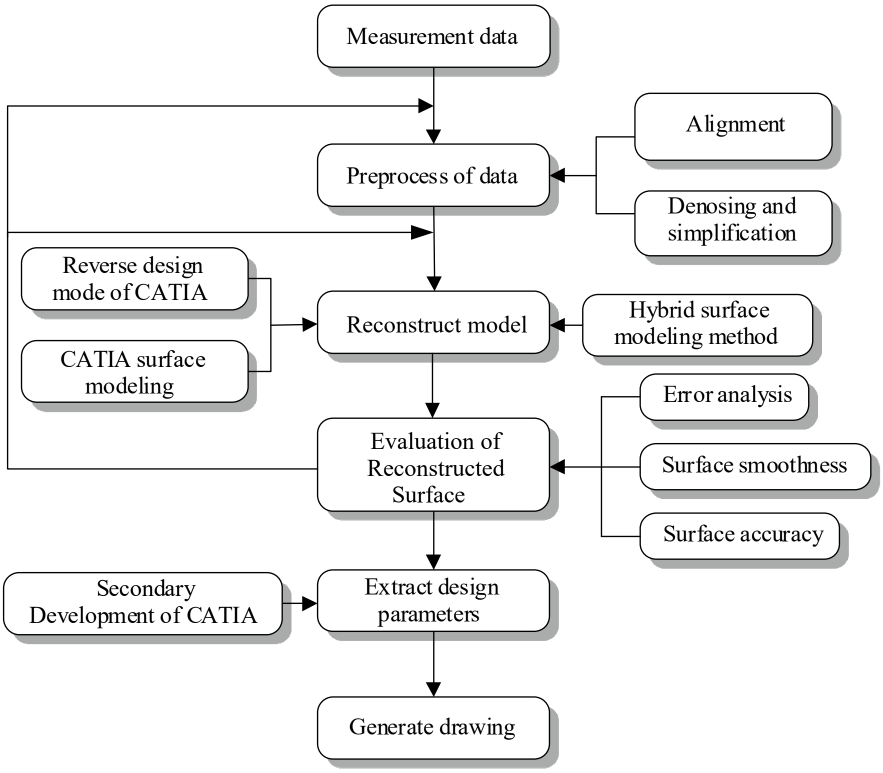


Fig. 1 Technology roadmap

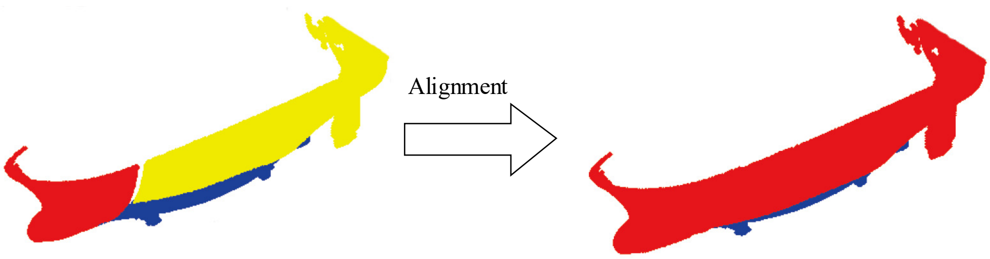


Fig. 2 Point cloud alignment of the hull surface

in different local coordinate systems. Hence, it is often necessary to locate and merge the different view measured cloud data in a global coordinate system. The improved ICP algorithm is used to align the hull surface point cloud (Gu, 2015). The basic steps are as follows:

(1) Determine the corresponding point set

Select point set $p=\{p_1, p_2, p_3, \ldots, p_m\} \in P$ in the target point cloud P. The k-d tree (Moore A, 1991) is used to search the corresponding point set in the reference point cloud Q, which requires the distance $\|q_i - p_i\|$ to be minimized.

(2) Compute the transformation matrix

The rotation matrix $\boldsymbol{R}$ and the translation vector $\boldsymbol{T}$ are solved to minimize the error function $f(\boldsymbol{R},\boldsymbol{T})$:

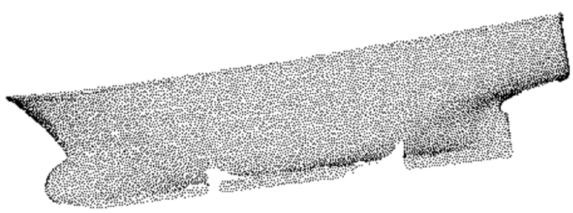


Fig. 3 Processed hull surface point cloud

$$f(\boldsymbol{R},\boldsymbol{T}) = \frac{1}{m}\sum_{i=1}^{m}\|q_i - (\boldsymbol{R}p_i + \boldsymbol{T})\|^2 = \min \quad (1)$$

(3) Align the point set

The rotation matrix $\boldsymbol{R}$ and the translation vector $\boldsymbol{T}$ are used to transform the point set p to a new point set p':

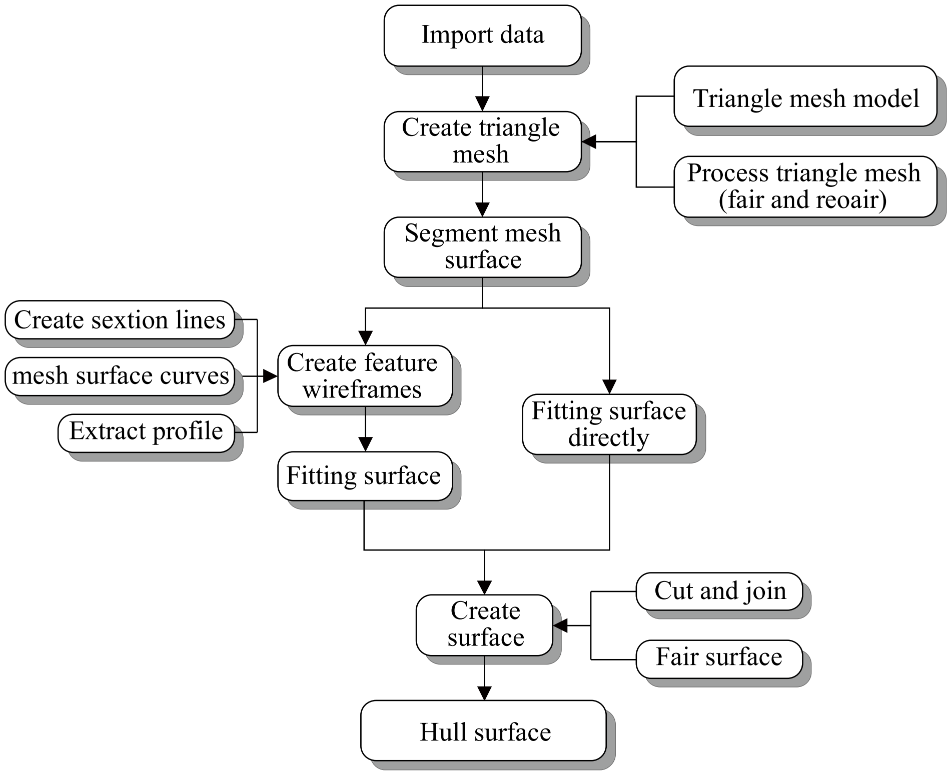


Fig. 4 Flow chart of hull surface reconstruction

$$p' = \left\{ p_i' = \boldsymbol{R}p_i + \boldsymbol{T}, p_i \in p \right\} \tag{2}$$

(4) Iterative calculation

The average distance from the new point set p' to the point set q is calculated. The target point cloud P will be transformed to align with the reference point cloud Q if the average distance d is less than the given threshold or the number of iterations exceeds the set value. Otherwise, return to step (2) until the convergence condition is satisfied. Then, the measured hull surface point cloud data are aligned as shown in Figure 2.

2.2 Point cloud denoising and simplification

Because of the measurement environment, noise points inevitably exist in the measured data. The noise points affect the alignment of the point cloud. In addition, due to the high density of point cloud data obtained from the laser scanner, point cloud data contain a great deal of redundant data which takes up a large amount of memory. Hence point cloud processing is required. First, unnecessary points from the background and fixed support are directly removed by interactive operation. Then, the chord height difference algorithm (Zhou, 2004) is applied to clean the remaining points. Figure 3 shows the final point cloud data of the ship model. During the laser scanning of the hull surface, two brackets are installed at the bottom of the hull for support. Points scanned from the brackets are removed after the processing, which results in the absence of points on two regions in Figure 3. The absent point cloud data will be filled in the subsequent reconstruction for the surface.

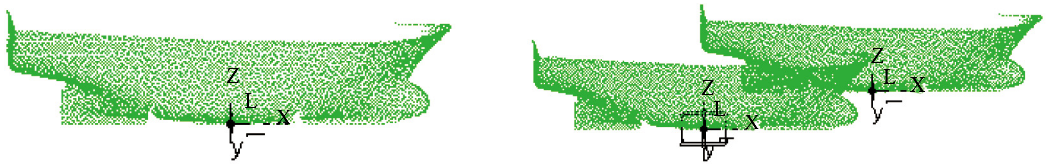
III. SURFACE RECONSTRUCTION

Surface reconstruction is the most critical and complex part of reverse engineering (Zhang. 2010). Non-Uniform Rational B-Spline (NURBS) is the most widely used surface modeling method. NURBS can represent free curve and surface, conic and regular surface, etc. (Guan et al, 2019). Therefore, NURBS is chosen to reconstruct the hull surface.

3.1 Hull surface reconstruction

Currently, surface reconstruction methods can be divided into traditional surface modeling and fast surface modeling (Yu. 2008). According to the characteristics of the complex hull surface, the hybrid surface modeling method, which combines the traditional surface modeling and the fast surface modeling, is used to reconstruct the hull surface. Firstly, the point cloud is polygonized by the fast surface modeling method. The boundary and characteristic curves of the point cloud are extracted by the function of extracting profile and section line in CATIA. Then, the surface patches are created by the traditional surface modeling method. The target surface is reconstructed by cutting and splicing the surface patches. The process of surface reconstruction is shown in Figure 4.

The specific steps of hull surface reconstruction are as follows:



(a) Define user coordinate system (b) Two coordinate systems

Fig. 5 Coordinate transformation

Fig. 6 Triangle mesh surface of the hull surface

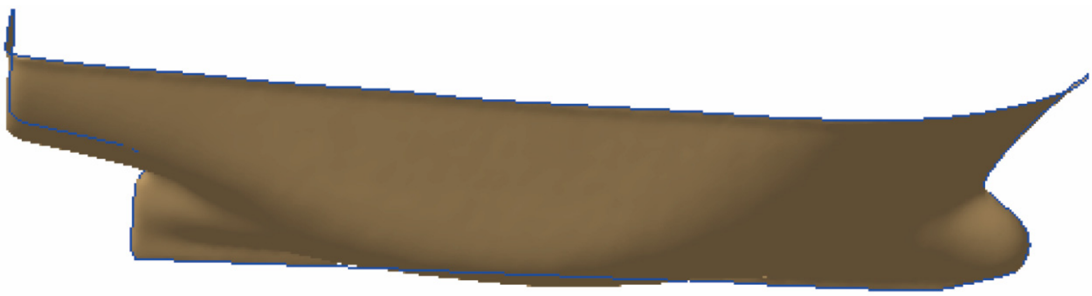


Fig. 7 The boundary of the hull surface

(1) Import point cloud data of the hull surface

The pre-processed hull surface point cloud data are imported into the DSE module of CATIA.

(2) Coordinate transformation

The imported hull surface data are asymmetrical to any plane of the world coordinate system. To facilitate the subsequent modeling, it is necessary to align the point cloud coordinate system with the world coordinate system. Firstly, the user coordinate system is defined, as shown in Figure 5 (a). The data of the hull surface are transformed from the local coordinate system to the world coordinate system by the function of the axis to axis position transformation, so that the two coordinate systems coincide, as shown in Figure 5 (b).

(3) Create mesh surface

The triangular mesh surface is created by using the 3D Mesher method. Sag value is set as 0, and the neighborhood value is the default value calculated by the system. Considering the requirement of fairing and accuracy of the hull surface reconstruction, the triangular mesh surface is faired properly without changing the characteristics and accuracy of the point cloud. The hole repair function is used to fill the missing point cloud data. In the process of the hole repair, the curvature continuous function is implemented. The curvature connection requires that the ends of the connection are coincident, the tangent direction and curvature of the connection are consistent. Then, the hole repair function will triangulate the holes and repair them with the triangular mesh surface. The faired triangular mesh of the hull surface is shown in Figure 6.

(4) Create boundary and characteristic curves

The boundary curve is the outer boundary of the maximum contour of the hull surface. The characteristic curves of the hull surface include section lines and waterlines. Firstly, the boundary of the hull surface is obtained by the free boundary extraction function, as shown in Figure 7. The Planar Section function is used to obtain the intersection curves of the transverse section and waterline section. Due to the complexity of the bow and stern surface, the number of body sections at the bow and stern is increased to meet the requirements of modeling accuracy. The characteristic wireframe of the hull surface is shown in Figure 8.

(5) Surface fitting

When creating the hull surface, if all surfaces are created by

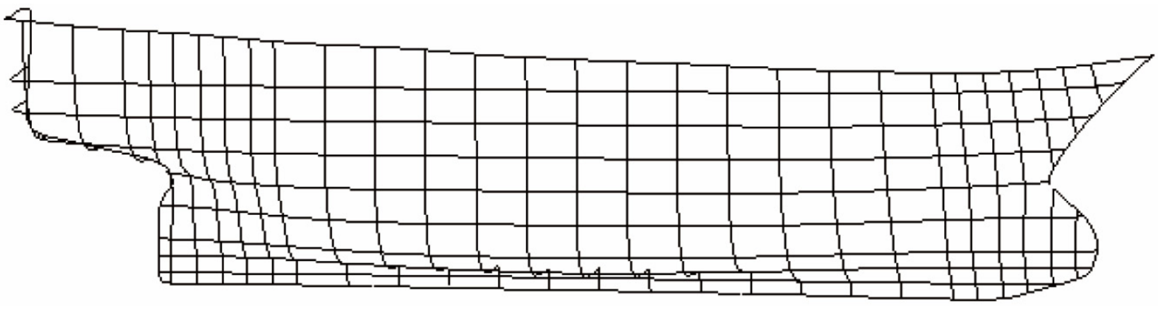


Fig. 8 Characteristic wireframe of the **hull surface**

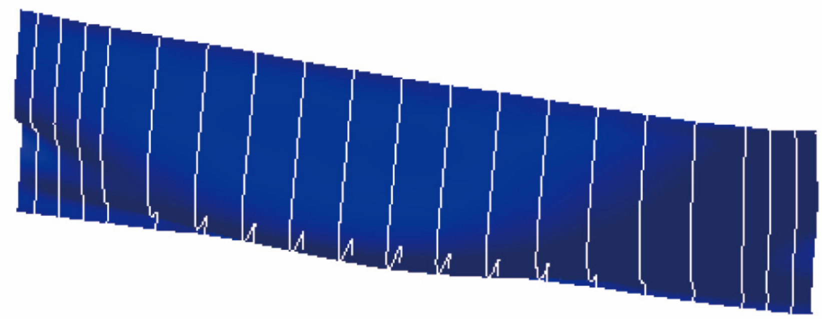


Fig. 9 Midship surface

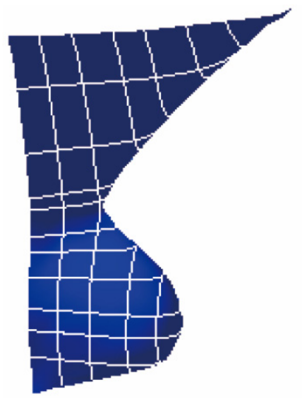


Fig. 10 Bow surface

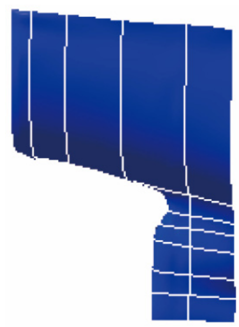


Fig. 11 Stern surface

lofting, the bow and stern parts will be not smooth, and the surface accuracy will be poor. Therefore, the whole hull surface is divided into three parts: bow, midship, and stern. Then, these three surfaces are trimmed and joined to obtain a complete hull surface.

The curvature of the midship surface does not change dramatically. The midship surface can be fitted by lofting the body sections, as shown in Figure 9.

For the bow surface, based on the section lines and waterlines, the method of combining mesh surface, lofting surface, and filling surface is used to fit the bow surface. To improve the accuracy of the bow surface, some auxiliary lines are added to complete the surface fitting. The auxiliary lines are a series of lines that are added to fit the surface with high precision. It is necessary to add more section lines and waterlines where the curvature changes greatly (Xu et al, 2017). The added auxiliary lines should be as close to the point cloud data as possible. The surface patches are trimmed and joined to obtain the bow surface as shown in Figure 10. Similarly, the stern surface is shown in Figure 11. Finally, the surfaces of the bow, midship, and stern are trimmed and joined to obtain a complete hull surface, as shown in Figure 12.

3.2 Error analysis of the reconstructed surface

The fairing of the reconstructed surface is evaluated by curve curvature analysis, Gaussian curvature analysis, and zebra line analysis. Figure 13 shows the curvature analysis of the curves of the hull surface. Figure 14 shows the zebra line

Fig. 12 Hull surface

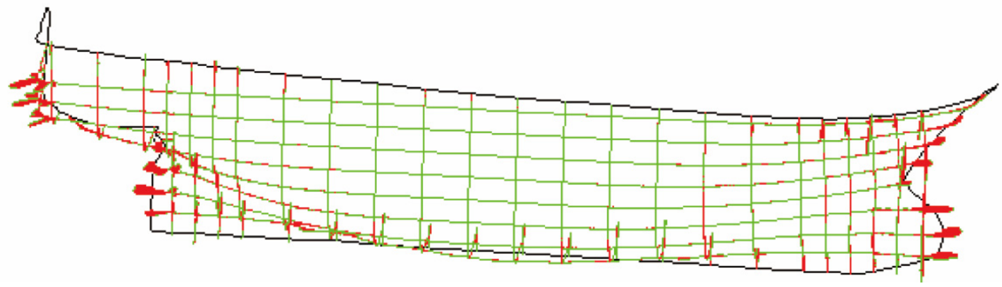


Fig. 13 Curvature analysis of curves

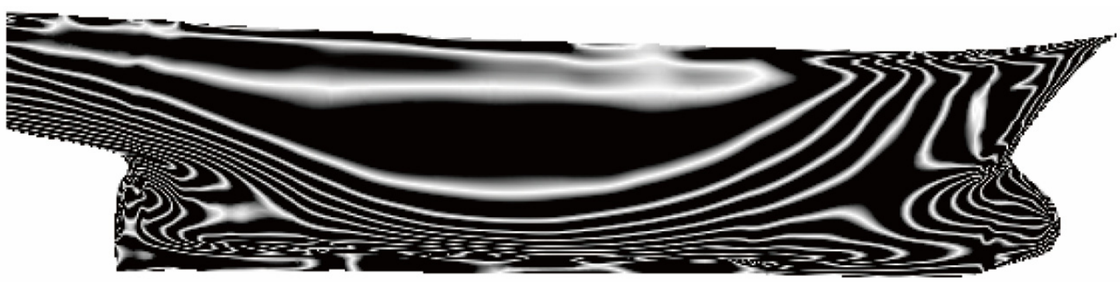


Fig. 14 Zebra line analysis

analysis of the hull surface. Figure 15 shows the Gauss curvature analysis of the hull surface.

The accuracy of the reconstructed surface is analyzed by the deviation analysis between the reconstructed hull surface and the point cloud data. As shown in Figure 16, it can be seen that the surface deviation of the bow and stern is slightly larger than the midship, which is related to the complexity of the surface. The number of points in different deviation ranges is expressed in percentage. According to the result of deviation, the deviation range of the reconstructed hull surface is 0~5mm. The distribution range of the deviation is shown in Figure 17. There are two main causes of the deviation: (1) Data processing. Although some errors caused by data measurement can be compensated by data preprocessing, some measurement point cloud errors of real characteristic information will also lead to data processing errors. (2) Surface reconstruction. In the process of surface reconstruction, the point cloud needs to be operated, including fitting polygon, creating characteristic lines, fitting surface patches, etc. These operations will cause surface reconstruction errors. It can be seen from Figure 17 that the deviation of 4.0-5.0mm only accounts for 0.06%, which is within the allowable error range. If the accuracy needs to be further improved, the local area (high error) can be adjusted manually to reduce the deviation between the digital model and the real object. Besides, the method of adding auxiliary lines can be used to make the digital model fit the real object better.

IV. DESIGN PARAMETER EXTRACTION FOR THE RECONSTRUCTED SURFACE

For the hull surface, the extraction of design parameters refers to obtaining offsets and generating lines plan. Lines plan is a very important ship general drawing. In this paper, the lines plan is obtained by extracting the intersection line between the plane and the hull surface. The offsets are obtained by extracting the intersection points of lines. It will take a lot of time if the offsets are obtained manually. Therefore, the

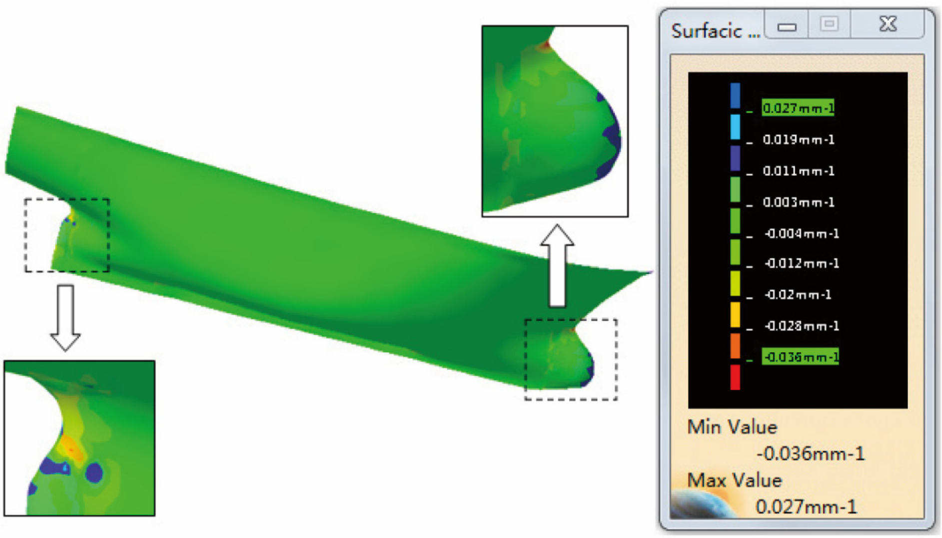


Fig. 15 Gauss curvature analysis

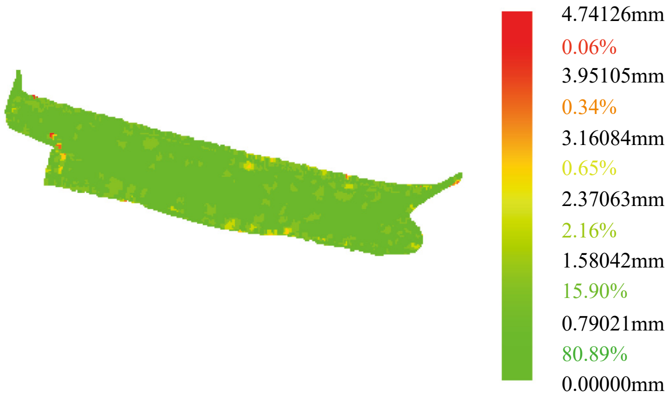


Fig. 16 Surface deviation analysis of the reconstructed hull surface

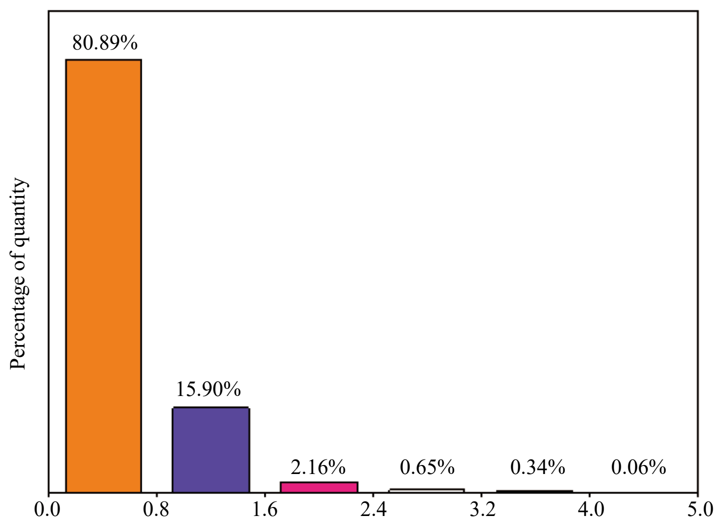


Fig. 17 Surface deviation distribution percentage of the reconstructed hull surface

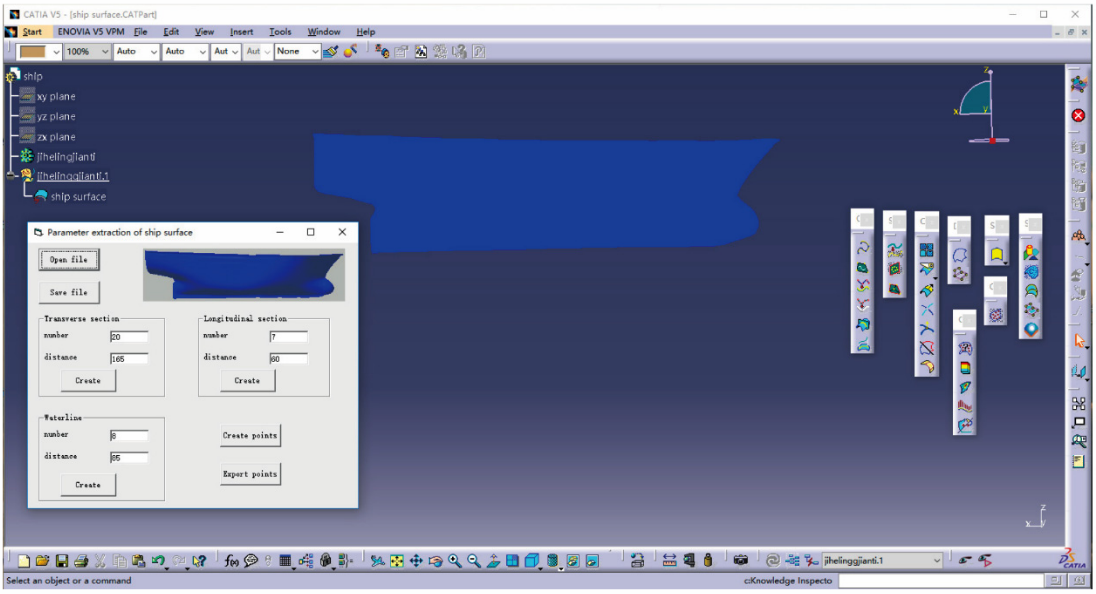


Fig. 18 Operating interface

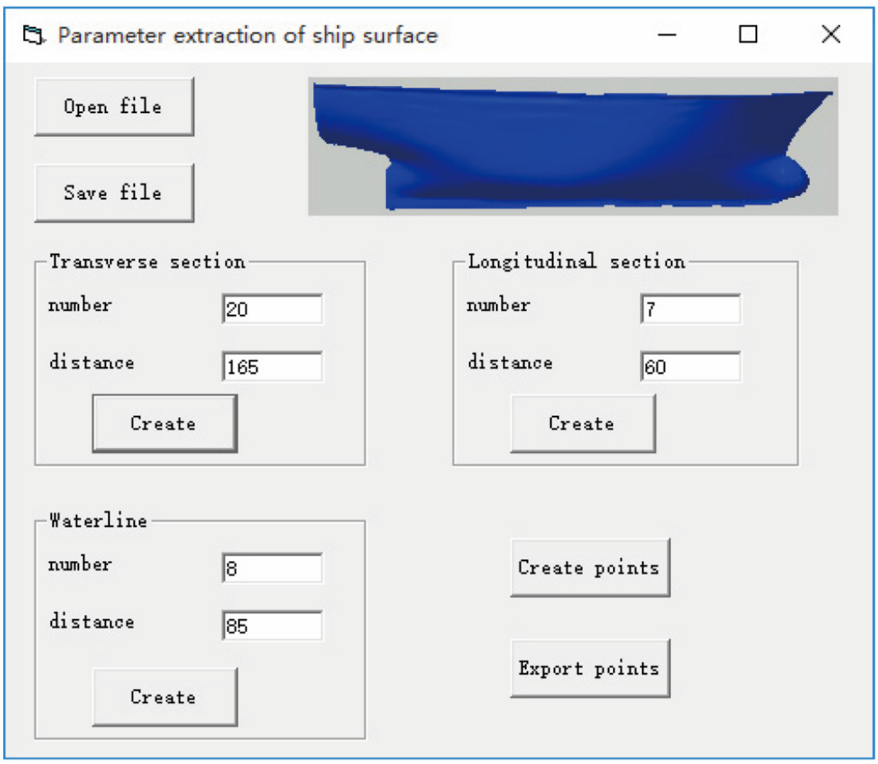


Fig. 19 Parameter Setting Interface

secondary development of CATIA with VB is utilized. The parameters of the surface are extracted. The program of automatic obtaining the offsets of the hull surface is written in VB. The method to extract the hull surface parameters is as follows:

(1) Preliminary

Firstly, all libraries of CATIA should be quoted in VB. CATIA files can be opened in VB. Define the "Top" function, so that the VB interface window is always on the top, as shown in Figure 18.

(2) Creation of Points

Table 1 Table of offsets

Station number	Height					Half-breadth				
	60LSL	120LSL	180LSL	240LSL	…	340water line	425water line	510water line	595water line	…
1	584.4	626.7	671.4	-	…	-	-	-	76.7	…
2	427.3	502.3	568.8	630	…	30	58.1	126.4	205.7	…
3	114.9	331.1	430.2	516.4	…	124.4	176.5	235.4	297.1	…
4	79.6	154.1	262.4	368.9	…	223.6	271.3	318.3	363.1	…
5	58.9	150.4	226.9	325.4	…	307.6	347	379.5	405.9	…
6	50.6	68	94.5	138.7	…	370	396.8	414.7	425.2	…
7	54.2	58.5	72.6	97.7	…	413.3	426.3	432.4	433.7	…
8	56.5	57.9	61.8	74.1	…	434.2	437.7	438.4	437.3	…
9	61.3	63.8	67.3	71.5	…	440.4	439.5	440.2	440.2	…
10	64.6	68.4	70.1	70.1	…	440	439.7	441.6	442.9	…
11	68.5	72.7	74.9	80.6	…	439.1	439.2	440.9	442.1	…
12	70	70.7	73.3	80.8	…	440.9	439.9	444.1	443.2	…
13	76.6	78.3	81	89	…	441.6	442	442.4	443.6	…
14	80	84	92.7	106.4	…	435.6	442.5	442.8	442.9	…
15	83.8	93.6	115.7	154.3	…	406.9	433.7	440.4	442.7	…
16	97.2	129.9	187.7	256.6	…	340.6	407.3	431.3	439.5	…
17	146.7	288	331.5	352.6	…	202.4	361.1	412.1	433.8	…
18	366.4	371.9	386.4	402.2	…	-	293.9	384.8	422.8	…
19	403.9	410.7	421.1	471.7	…	-	195.3	344.8	402.6	…
20	438.2	443.7	454.4	474.2	…	-	-	300	373.9	…

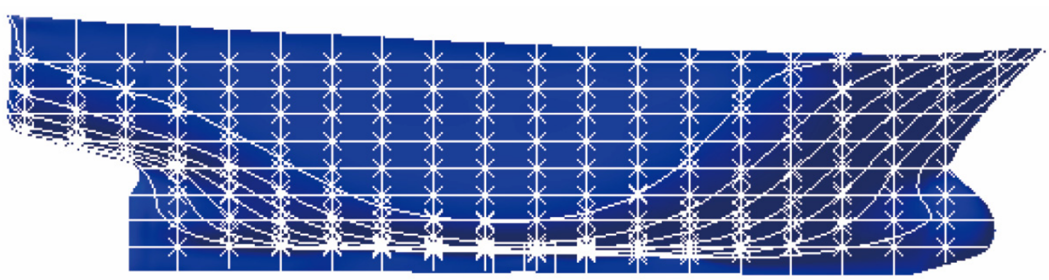


Fig. 20 Results of the program

To determine the initial and final position of the sections along with the surface size range, it is necessary to obtain the maximum and minimum values in a certain direction of the surface. The function AddNewExtremum is used to create the extremum of the current element. The grammar is AddNewExtremum (Reference iObject, HybridShapeDirection iDir, long iMinMax) As HybridShapeExtremum. Where iObject is the element that needs to calculate the extremum, i.e. the reconstructed surface, which can be obtained by defining the reference object; iDir represents the direction of the required extremum, which has three directions: x, y, and z, one of them is the main direction, and the other directions are the optional directions; iMinMax is used to determine whether the maximum or minimum value is needed in a certain direction.

(3) Creation of Planes

To obtain the intersection line, the surface is cut by planes. The position of the extreme point of the surface is the initial position of the section. Through the extreme point, a plane parallel to the coordinate plane is created. The plane is the reference plane of the subsequent offset sections. The other planes can be created by offset. The function AddNewPlaneOffsetPt is used to create the plane. The grammar is AddNewPlaneOffsetPt (Reference iPlane, Reference iPt). Where iPlane is the reference plane, the local coordinate system should be aligned with the world coordinate system of

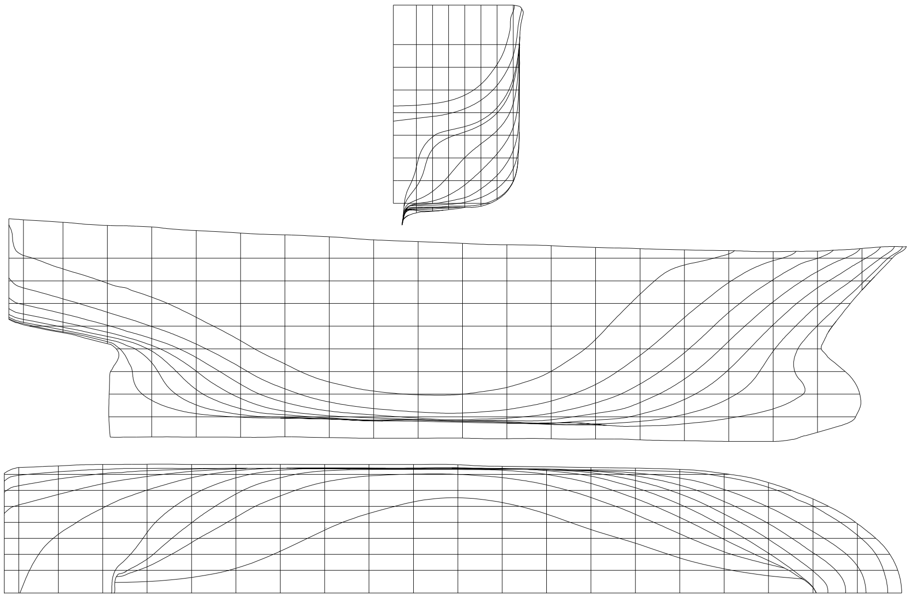


Fig. 21 Lines plan of the hull surface

CATIA. If no additional reference plane needs to be created, the plane of xoy, xoz, or yoz can be selected as the reference plane; iPt is the reference point.

In the program, we can get a series of sections by inputting the number and distance of the required sections. After the reference plane is created, the function AddNewPlaneOffset can be used to create the offset plane. The grammar is AddNewPlaneOffset (Reference iPlane, double iOffset, boolean iOrientation). Where iPlane is the reference plane; iOffset is the offset value, which can be determined by users; iOrientation is the direction of the offset.

(4) Get the intersection line

After the section is created, the intersection line between the section and the surface can be obtained. The function AddNewIntersection can be used to obtain the intersection line. The grammar is AddNewIntersection (Reference iObject1, Reference iObject2). Where iObject1 is the first reference element, i.e. the section; iObject2 is the second reference element, i.e. the reconstructed surface.

(5) Get the offsets

Similar to the method of getting the intersection line, the intersection point can be obtained by the function AddNewIntersection. We only need to change the surface element to the line element. According to the above method, the main program for obtaining the hull surface offsets is developed. The parameter setting interface is shown in Figure 19. In this interface, users can input the number of the transverse sections, the waterline sections and the longitudinal sections to be created, and the distance between them. After setting the relevant parameters, run the program, and the results are shown in Figure 20. The offsets are shown in Table 1, LSL represents the longitudinal section line.

In the engineering drawing module of CATIA, the three views of the hull surface can be obtained by using the projection view function, and the ship lines can be displayed in the three views. The three projections can be adjusted appropriately and saved as DWG format. The lines plan of the hull surface can be opened in CAD software for the later design. The exported lines plan is shown in Figure 21. The causes of the fluctuations and the sharp edges are related to the fairing of the scanned real hull surface model. Besides, if we want to deal with the sharp or discontinuous edges, the local area can be adjusted manually by adding or deleting interpolation points.

V. CONCLUSIONS

A hull surface design method based on reverse engineering is proposed. The point cloud data of the hull surface with high accuracy are obtained by a 3D laser scanner. By aligning, denoising, and simplifying the point cloud, it can be used to reconstruct the hull surface. The hull surface is reconstructed by combining the mixed surface modeling method and the surface modeling function of CATIA. The reconstructed surface model can make the basis of the subsequent design. The offsets and lines plan obtained by the secondary development of CATIA can be used to redesign. This method provides a novel idea for the design of the new ship form. The hull surface design method based on reverse engineering is very helpful to shorten the ship design cycle.

VI. ACKNOWLEDGMENTS

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