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RECONSTRUCTION OF PROPELLER AND COMPLEX SHIP HULL SURFACE BASED ON REVERSE ENGINEERING

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Key words: reverse engineering, ship surface; propeller, point cloud reconstruction, ICP algorithm.

ABSTRACT

To quickly obtain the digital model of ship surface for detection and redesign, a reconstruction method for propeller and ship surface is proposed. Three-dimensional point cloud data of ship hull was obtained by laser scanning technology and the cloud data was preprocessed by iterative closest point (ICP) algorithm and chord deviation method. Then the surface was reconstructed with traditional surface modeling method and fast surface modeling method. By comparing the reconstructed surface with the initial point cloud data, the error of the reconstructed model was obtained. The result shows that the reconstructed surface gains good smoothness and small error. With this method, ship surface can be reconstructed quickly and the reconstructed digital model is of good quality which can be used in detection and redesign.

I. INTRODUCTION

Reverse engineering is the general term of digitization technology, geometric model reconstruction technology, and product manufacturing technology, which converts a physical model into a digital model by computer-aided design. In recent years, with the rapid development of reverse engineering technology, more and more industries have made comprehensive innovations using reverse engineering technology. Reverse engineering has been studied and applied in many fields such as automobile manufacturing, aerospace engineering and medical field (Lulić et al., 2013; Fang et al., 2015; Nan et al., 2015; Gomez et al., 2017; Yun et al., 2019). In the field of ship construction, the process of new ship design and construction quality control needs a lot of manpower and time. Construction efficiency and quality can be significantly improved if reverse engineering technology is applied.

Many scholars have studied the application of reverse engineering in shipbuilding. Pérez (2008) used three-dimensional measurement and B-spline curves to extract the bow profiles. Ordóñez et al. (2009) used photography measurement to obtain the deck surface of a yacht. Paolia and Razinale (2012) proposed a new method for inspection of ships under construction by three-dimensional scanning technology. Edessa and Bronsart (2015) proposed a method for ship hull reconstruction that aligned the reverse engineering results into traditional hull form design procedures. Zhang et al. (2016) applied the technology of three-dimensional scanning and point cloud slicing to the calculation of ship displacement. Abbas et al. (2017) studied how to improve the accuracy of three-dimensional measurement and rapid modeling for yachts. Eirik et al. (2018) presented an approach for complete scanning of ship propeller blades. These studies have laid a foundation for the application of reverse engineering in shipbuilding.

Most of the above researches focus on the ship accuracy detection. There is little research on preprocessing of ship point cloud data and reconstruction of the complex surface. Due to the large scale of ships and the complexity of the surface, it takes numerous time on data processing and surface reconstruction, and more effective algorithms are needed to process data and reconstruct the surface. In our study, a modeling method based on reverse engineering is presented to reconstruct the complex ship surface. ICP (Iterative Closest Point) algorithm and chord deviation method are used for point cloud data processing. Traditional surface modeling method and fast surface modeling method are used to obtain a high-quality surface. The reconstructed digital model can be applied to the later detection and redesign process.

II. REVERSE RECONSTRUCTION OF SHIP SURFACE

Generally, reverse engineering mainly includes three parts: data measurement, data processing, and surface reconstruction. At present, three-dimensional measurement methods mainly

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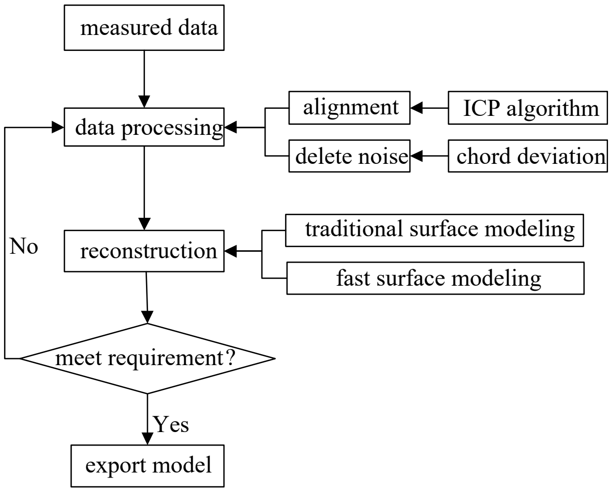
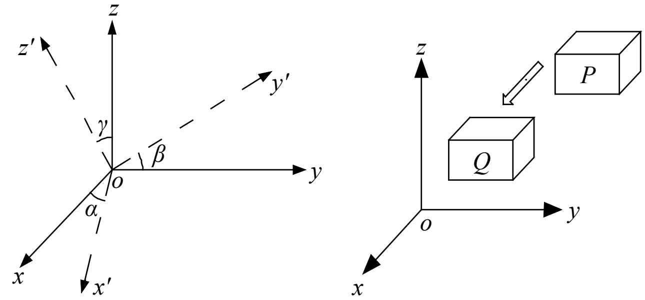


Fig. 1 Flow chart of ship surface reconstruction



(a) Rotation (b) Translation

Fig. 2 Rotation and translation transformation

include contact measurement and non-contact measurement. Because of the advantages of three-dimensional laser scanning, such as convenient measurement and better accuracy, three-dimensional laser scanning is selected to obtain point cloud data of ship surface. Data processing mainly includes data registration, data de-noising, and data extraction. In this paper, ICP algorithm is used to align the multi-view clouds, and chord deviation method is applied to delete noise data and extract data. Surface reconstruction is the most critical part in reverse engineering which fits the processed data into a surface. The surface is reconstructed by the traditional surface modeling method and the fast surface modeling method. The traditional modeling method follows the process of point, line and surface. The fast surface modeling method fits the surface after polygonization of the point cloud. Finally, the accuracy and smoothness of the reconstructed surface are analyzed by comparing the reconstructed surface with the point cloud. The specific flow chart is shown in Fig.1.

III. POINT CLOUD PROCESSING

In practical engineering, the scanner cannot get all the information of the object measured at one time due to the size of the object and the blind area of vision. It is necessary to divide the object into several sub-areas. Then point clouds from multiple perspectives are obtained, which are called multi-view point clouds. Because the local coordinate system is not consistent in each measurement, the local coordinate systems are unified to obtain the complete point cloud data of the measured object. The amount of data measured by three-dimensional scanner is huge, and the data contain noise points caused by light and measurement errors. It is very important for the efficiency and accuracy of later modeling to delete noise points and extract data reasonably (Wu et al., 2016).

1. Multi-view cloud registration

The point cloud alignment problem can be simplified to the motion of the three-dimensional rigid body. That is, two point clouds can be aligned by coordinate rotation and translation transformation according to the pre- calculated optimal registration algorithm. The rotation transformation is that the object rotates α, β, γ degree around the x-axis, y-axis, z-axis respectively, as shown in Fig.2 (a). The translation transformation is that the object only moves along the x-axis, y-axis and z-axis. As shown in Fig.2 (b), the point cloud P coincides with Q by moving forward, left and downward. The point pair p and p' in different coordinate systems can be transformed by the formula:

$$p' = \boldsymbol{R}p + \boldsymbol{T} \tag{1}$$

Where $\boldsymbol{R}$ is the rotation matrix and

$$\boldsymbol{R} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\alpha & \sin\alpha \\ 0 & -\sin\alpha & \cos\alpha \end{bmatrix} \begin{bmatrix} \cos\beta & 0 & -\sin\beta \\ 0 & 1 & 0 \\ \sin\beta & 0 & \cos\beta \end{bmatrix} \begin{bmatrix} \cos\gamma & \sin\gamma & 0 \\ -\sin\gamma & \cos\gamma & 0 \\ 0 & 0 & 1 \end{bmatrix}.$$

α, β, γ represent the rotation angles of the points around the x, y and z-axis respectively. $\boldsymbol{T}$ is the translation vector and $\boldsymbol{T} = \begin{bmatrix} t_x & t_y & t_z \end{bmatrix}^T$. t_x, t_y, t_z represent the translation distance along the x, y and z-axis respectively.

In this paper, ICP algorithm is chosen to align the point clouds (Yang et al., 2015). ICP algorithm was first proposed by Besl and Macay in 1992 (Besl and Macay, 1992). First, an initial pose is assumed and a certain number of points from one perspective are selected. Then the nearest point set corresponding to these points from another perspective is found. A transformation is obtained through the rigorous calculation to minimize the distance between the corresponding point sets. Finally, the convergence condition is met by iterative calculation. The steps of ICP algorithm are shown in Fig.3.

In the flow chart, singular value decomposition (SVD) is used to calculate the rotation matrix $\boldsymbol{R}$ and translation vector $\boldsymbol{t}$. The calculation steps are as follows:

(1) Compute the center of mass of the two point sets $p = \left\{ p_i \middle| p_i \in R^3, i = 1, 2, \cdots, n \right\}$ and

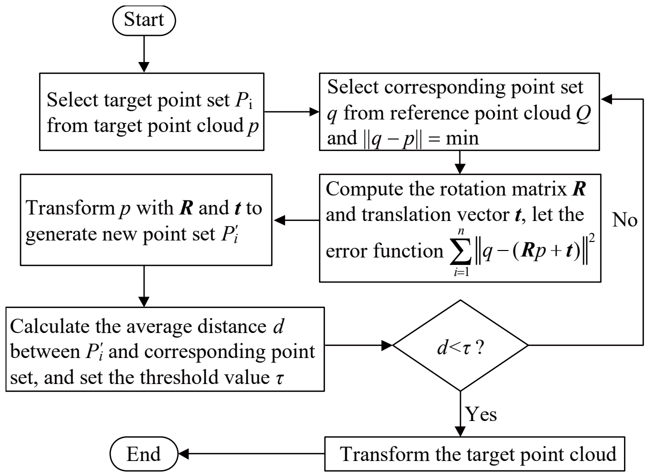


Fig. 3 Basic flow chart of ICP algorithm

$$q = \left\{ q_i \,\middle|\, q_i \in R^3, i = 1,2,\cdots,n \right\}: \quad \begin{cases} p_c = \dfrac{1}{n}\displaystyle\sum_{i=1}^{n} p_i \\ q_c = \dfrac{1}{n}\displaystyle\sum_{i=1}^{n} q_i \end{cases} \tag{2}$$

The point sets p and q are translated relative to the center of mass:

$$\begin{cases} p_i' = p_i - p_c \\ q_i' = q_i - q_c \end{cases} \tag{3}$$

(2) Calculate the matrix A:

$$\boldsymbol{A} = \sum_{i=1}^{n} p_i' q_i'^{T} \tag{4}$$

(3) The matrix A is dealt with SVD:

$$\boldsymbol{A} = \boldsymbol{U}\Delta\boldsymbol{V}^{\boldsymbol{T}} \tag{5}$$

$\boldsymbol{U}$ and $\boldsymbol{V}$ are orthogonal matrices.

(4) The rotation matrix R is obtained by the formula:

$$\boldsymbol{R} = \boldsymbol{V}\boldsymbol{U}^{\boldsymbol{T}} \tag{6}$$

(5) The translation vector is calculated by the formula:

$$\boldsymbol{t} = q - \boldsymbol{R}p \tag{7}$$

The point cloud data of ship surface measured by three-dimensional laser scanning are registered well through the ICP algorithm mentioned above.

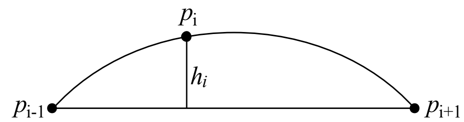


Fig. 4 Illustrative diagram of chord deviation algorithm

2. Point cloud de-noising and extraction

The general approach of deleting noise points is to interact with the system by users, and then the obvious error points are eliminated after visualization operation. Although the operation is simple, the workload is large and error-prone. In this paper, chord deviation method is chosen to delete noise and simplify point cloud. This method is simple and convenient, which is suitable for the occasions where the point cloud is distributed uniformly and densely, especially where the curvature changes greatly. The basic steps of chord deviation method are as follows:

(1) Take three consecutive points p_{i-1}, p_i, p_{i+1};

(2) The distance from p_i to the line connected by p_{i-1} and p_{i+1} in Fig. 4 is calculated by

$$h_i = \left| p_i - p_{i\text{-}1} - \frac{\left(p_i - p_{i\text{-}1}\right)\bullet\left(p_{i+1} - p_i\right)}{\left(p_{i+1} - p_i\right)^2}\left(p_{i+1} - p_i\right) \right|. \tag{8}$$

(3) Compare h_i with the allowable accuracy of the surface. If $h_i \geq [\varepsilon]$, p_i is considered to be a bad point and should be removed, otherwise turn to step (1).

When measuring ship surface, error data inevitably appear due to the measurement environment, equipment and so on. These noise points seriously affect the quality of later modeling. After point cloud alignment, the point cloud is de-noised and simplified by using the chord deviation method, then the processed data can be used for surface reconstruction in subsequent stages.

IV. SURFACE RECONSTRUCTION

Surface reconstruction is one of the core parts of reverse engineering, and it is also the basis of subsequent product redesign, manufacturing, and rapid prototyping. With a three-dimensional digital model, product redesign and engineering analysis can be carried out by using existing CAD/CAM/CAE technologies. Therefore, model reconstruction is the key and complex part of reverse engineering.

1. Mathematical models of curves and surfaces

The method of representing curves and surfaces as parametric functions was first proposed by Ferguson in 1963, which laid a foundation for surface modeling (Ferguson, 1963). Bezier (1971) proposed a new method to design curves by controlling polygons. Gordon and Riesenfeld (1974) proposed B-spline method and applied B-spline to shape descriptionVersprille (1974) proposed non-uniform rational B-spline (NURBS). Then, Piegl and Tiller (2008) improved NURBS curve method. NURBS curve method has been used by almost all commercial CAD software because of its good surface modeling quality.

In reverse modeling, this paper mainly uses B-Spline surface and NURBS surface to reconstruct the ship surface. B-Spline curve has the local control function with curve equation:

$$C(u)=\sum_{i=0}^{n}N_{i,p},(u)P_i \tag{9}$$

where $N_{i,p}(u)$ is the basis function of B-Spline, P_i is the control point, $n+1$ is the number of control points, $u$is the parameter value and p is the order number. The basis function of B-Spline is defined as:

$$\begin{aligned}&N_{i,0}(u)=\begin{cases}0 & u_i\le u\le u_{i+1}\\ 1 & \text{others}\end{cases}\\ &N_{i,p}(u)=\frac{u-u_i}{u_{i+p}-u_i}N_{i,p-1}(u)+\frac{u_{i+p+1}-u}{u_{i+p+1}-u_{i+1}}N_{i+1,p-1}(u)\end{aligned} \tag{10}$$

B-Spline surface has the same properties as B-Spline curve. The equation of B-Spline surfaces is as follows:

$$S(u,v)=\sum_{i=0}^{m}\sum_{j=0}^{n}N_{i,p}(u)N_{i,q}(v)P_{ij} \tag{11}$$

The equation of NURBS curve is described as follows:

$$\begin{aligned}&C(u)=\frac{\sum_{i=0}^{n}N_{i,p}(u)w_iP_i}{\sum_{i=0}^{n}N_{i,p}(u)w_i}=\sum_{i=0}^{n}R_{i,p}(u)P_i\\ &R_{i,p}(u)=\frac{N_{i,p}(u)w_i}{\sum_{i=0}^{n}N_{i,p}(u)w_i}\end{aligned} \tag{12}$$

where $N_{i,p}(u)$ is the basis function, P_i is the control point, w_i is the weighted value, u is the parameter value and p is the order number.

In geometry, two-dimensional space refers to one plane. Each point above can be represented by coordinates composed of two numbers. NURBS surface can be obtained by extending NURBS curves from one-dimensional space to two-dimensional space. The equation is described as:

$$\begin{aligned}&S(u,v)=\frac{\sum_{i=0}^{m}\sum_{j=0}^{n}N_{i,p}(u)N_{i,q}(v)w_{ij}P_{ij}}{\sum_{r=0}^{m}\sum_{s=0}^{n}N_{r,p}(u)N_{s,q}(v)w_{rs}}=\sum_{i=0}^{m}\sum_{j=0}^{n}R_{i,p;i,q}(u,v)P_{ij}\\ &R_{i,p;i,q}(u,v)=\frac{N_{i,p}(u)N_{i,q}(v)w_{ij}}{\sum_{r=0}^{m}\sum_{s=0}^{n}N_{r,p}(u)N_{s,q}(v)w_{rs}}\end{aligned} \tag{13}$$

where P_{ij} is the control point of the surface and $R_{i,p;i,q}(u,v)$ is the basis function of the NURBS surface.

2. Surface modeling method

According to the characteristics of surface reconstruction in current reverse modeling software, the methods of surface reconstruction can be divided into traditional modeling method and fast modeling method. Traditional surface modeling method generally has two modes: one is to directly fit surface patches by point clouds, and then generate model by these surface patches; the other is to fit feature lines according to point clouds, and then construct surface by feature lines. The traditional modeling method inherits the characteristics and processing skills of forwarding surface modeling and can realize the creation of high-quality surface. There are also two modes for fast surface modeling. One is to directly fit surface after polygonization of the point cloud, the other one is to divide point cloud into quadrangles after polygonization and fit the surface. The fast surface modeling method is easy to realize feature extraction and fast to reconstruct the surface.

According to the characteristics of ship surface, this paper reconstructs the ship complex surface by combining the two methods of surface modeling. Firstly, the point cloud is polygonized by using the fast surface modeling method. The triangular mesh model is used to extract the boundary and the characteristic curve of the point cloud. Then the surface is fitted by the traditional modeling method. The process of surface reconstruction is shown in Fig. 5.

V. EXAMPLE ANALYSIS

In this paper, the point cloud data of a propeller and a bow are measured by a three-dimensional scanner. Through these two examples, the modeling method of ship complex surface based on reverse engineering is introduced.

1. Propeller Surface Reconstruction

Data of propeller point clouds measured by a three-dimensional laser scanner are piecewise point clouds, which

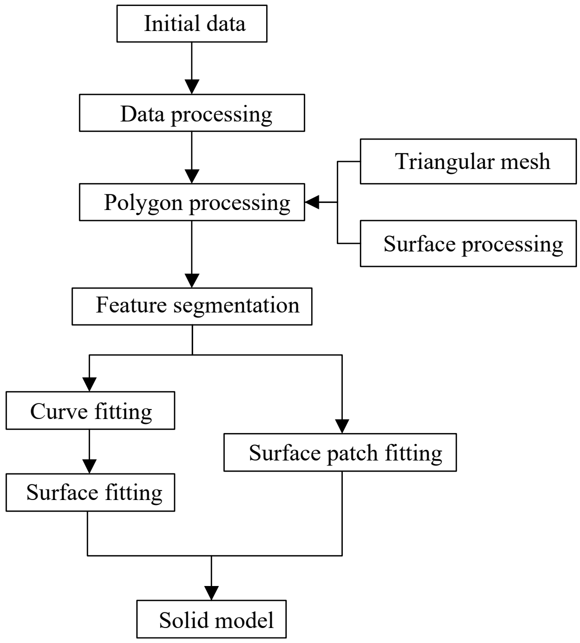


Fig. 5 Flow chart of surface reconstruction

(a) Initial data (b) Processed data

Fig. 6 Initial data and processed data

need to be processed as shown in Fig. 6(a). The propeller point clouds are processed by ICP algorithm and chord deviation method. The processed data are shown in Fig. 6(b).

The surface of propeller is reconstructed according to the above surface reconstruction process which combines the traditional surface modeling method and the fast surface modeling method. Because of the symmetry of the propeller, a quarter of the blade of the propeller is selected to explain the process of reconstruction. The point clouds are paved with triangular mesh, and then the triangular mesh surface is smoothed and repaired. The triangular mesh surface obtained from the initial data is irregular as shown in Fig. 7, which is not suitable for modeling. The triangular mesh surface obtained from the processed data is smooth as shown in Fig. 8. According to the characteristics of the propeller surface, the point cloud of the propeller is divided into blades and hub for surface fitting. The section curves of the blade are obtained from the triangular mesh surface as shown in Fig. 9. The blade surface is fitted according to the section curves. The hub part is fitted by using the triangular mesh directly. Finally, the whole surface is obtained by trimming and splicing the surfaces of the two parts. According to the same method, the surfaces of other blades can be obtained. The whole smoothed propeller surface is shown in Fig. 10.

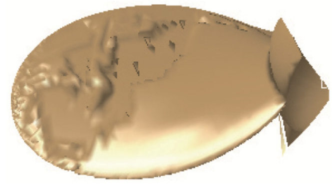


Fig. 7 Triangular mesh surface of the initial data

Fig. 8 Triangular mesh surface of the processed data

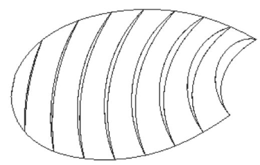


Fig. 9 Blade profile

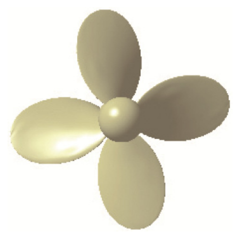


Fig. 10 The surface of the propeller

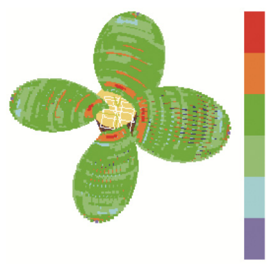
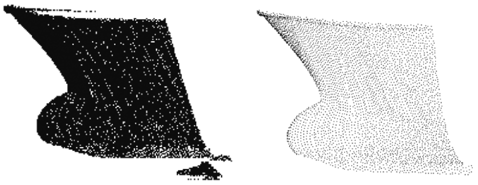


Fig. 11 Error analysis graph of the propeller

To judge the accuracy of the reconstructed propeller model, the reconstructed blade surface is compared with the point cloud data, and the error graph is shown in Fig. 11. It can be seen from Fig. 11 that the error between the reconstructed



(a) Initial data (b) Processed data

Fig .12 Initial data and processed data

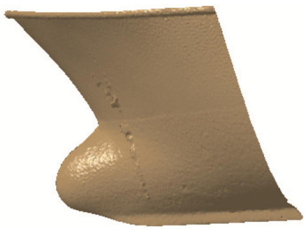


Fig. 13 Triangular mesh surface of the initial data

Fig. 14 Triangular mesh surface of the processed data

model and the point cloud data ranges -5 mm to 6 mm. The error mainly concentrates in the range of -0.5 mm to 0.4 mm. Hence the accuracy of the reconstructed model is satisfied with the requirement.

2. Bow surface reconstruction

The piecewise point cloud data of the bow are obtained by a three-dimensional laser scanner. Similar to the data processing steps of the propeller point cloud, the bow point cloud is aligned and de-noised by using ICP algorithm and chord deviation method. The initial data and processed point cloud data is shown in Fig. 12.

Firstly, all point clouds are paved with triangular mesh and smoothed. The triangular mesh surface obtained from the initial data is not smooth as shown in Fig. 13, which influences the quality of the model. The triangular mesh surface obtained from the processed data is very smooth as shown in Fig. 14. Fig. 15 shows the section curves of the bow extracted from the triangular mesh surface. According to the characteristics of the bow surface, the surface of the bulbous is directly fitted by the triangular mesh surface. The surface of the other parts is fitted according to the section curves. Finally, the surface of the two parts is merged to get the whole bow surface, as shown in Fig. 16.

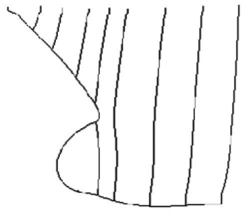


Fig. 15 Bow Profile

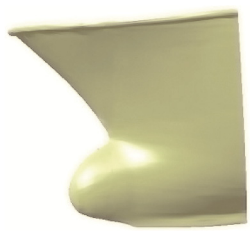


Fig. 16 The surface of the bow

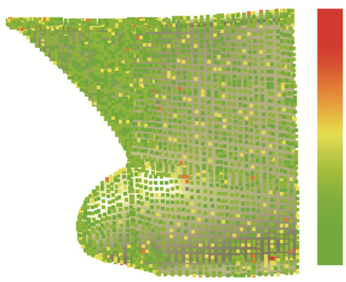


Fig. 17 Error analysis diagram of the bow

To judge the accuracy of the reconstructed bow surface, the reconstructed bow surface is compared with the point cloud data of the bow, and the error graph is shown in Fig. 17. According to Fig. 17, the error between the reconstructed bow surface and the point cloud data is within the range of 0 mm to 8 mm, the main error is within the range of 0 mm to 5 mm, and the accuracy of the reconstructed model is satisfied with the requirement.

In the above examples, when using ICP algorithm to align point clouds, better initial position and posture are needed. Because of the large number of point clouds，it takes lots of time to align the point clouds. Therefore, in the future research, we will improve ICP algorithm to shorten the registration time. Although the reconstructed model is of good quality, there are still some errors compared with the initial point cloud.

VI. CONCLUSION

In this paper, reverse engineering technology is applied to ship modeling and a method of rapid reconstruction of ship surface is proposed. The point cloud data of ship surface can be obtained quickly by measuring propeller and bow with a three-dimensional laser scanner. The point cloud is processed by ICP algorithm and chord deviation method. The processed data have great quality and satisfy the requirement of surface reconstruction in the later stage. The surface reconstruction method combining traditional surface modeling method with fast surface modeling method is used to obtain the surface. The accuracy of the reconstructed model obtained by this method is proved by two examples. The model reconstructed by this method can be applied in subsequent detection and modification design.

In our future research, the ICP algorithm will be improved and bilateral filtering algorithm will be used to improve the data processing accuracy. Thus the accuracy of the reconstructed surface will be improved.

The surface reconstruction method proposed in this paper can be used in actual ship detection and ship design. It reduces manpower and time in ship detection and improves the accuracy of the measurement. Also this method shortens the development cycle of new ship type and realizes the concurrent design and innovative design of ships.

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