Application of Reverse Engineering on Spacecraft Assembly Process Simulation

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Abstract. This paper proposes a new process that assembly simulation with 3-D model which obtained from product to improve the reliability of spacecraft assembly. 3-D model of the satellite camera which obtained by reverse engineering was used in DELMIA virtual assembly simulation. The point cloud date of the model was scanned by laser radar, and the scanning accuracy is 0.3mm. To get more accurate model data, firstly it’s necessary to remove noise data by the method of HCI and curve inspect; then, min-distance method was used to streamline the point data, and repair the data by complementary surface; finally, reconstruct the model by the triangular Bezier surface. Because the model obtained by RE is more exact than the ordinary model, the virtual assembly simulation is more useful. During the period of installing the camera, as the simulation, the risk was avoided and the process was successful.

1. Introduction

Spacecraft products are featured by high functional density, high sensitivity, and complex shape. In order to avoid product interference during assembly, to ensure product safety and ensure the perfect completion of assembly, it is required to identify the risks in assembly in advance during the stage of process design and preventive measures should be developed accordingly.

Virtual assembly simulation is an effective way to identify the risks in complex assembly processes, and the validity of the simulation results depends largely on the accuracy of the product model. In a real case, the outer surface of some product may be a complex free-form surface, which is difficult to be described by a strict and unified mathematical language. The design model of a product often cannot accurately reflect the appearance parameters of the real product. For example, the details such as instrument angle and electrical connectors and flexible entities such as thermal control multilayers cannot be fully described in the design model. Therefore, the real assembly process cannot be accurately simulated using existing design models.

The physical 3D model reconstructed by reverse engineering can more accurately reflect the complex surfaces and flexible entities that cannot be accurately described in the traditional 3D model, and the reconstructed model has a high similarity with the real one. The assembly simulation using the accurate 3D model obtained by reverse engineering can effectively verify the feasibility of assembly and detect the interference points and risks in advance.

This research focuses on the virtual assembly simulation of a certain type of camera on a satellite. The reverse engineering technology is used to reconstruct the camera model. The reconstructed model is used to simulate the assembly process. The risks and challenges in the assembly process are
successfully identified, and the countermeasures are given. Finally, this type of camera is successfully assembled, showing the great potentials of the application of reverse engineering to the assembly process design of spacecraft.

2. Overall design

The overall process of virtual assembly simulation is shown in Figure 1. The data scanning is to obtain the point cloud data of the measured object by means of measurement. The model reconstruction in reverse engineering is to extract the points, lines and surfaces required for the reconstruction through the measurement and analysis of the object, and to construct the 3D model by surface reconstruction technique [1]. Digital measurement technology is the basis of reverse engineering and the main means of digitizing the surface of the object. Choosing the right measuring instruments and testing methods to obtain the high-precision features of the object surface is the basis and key to achieving the reverse modeling. In this research, laser radar is used to perform 3D scanning on the physical object to obtain its point cloud data.

The point cloud data obtained by 3D scanning cannot be directly used for model reconstruction due to the great noise, massive amount of data, and “holes” in scanning process. Therefore, it is necessary to perform data preprocessing, to remove the noise, streamline the data, and repair the “holes” before model reconstruction. The inverse reconstruction is to reconstruct the object surface using the processed point cloud data, and finally generate a 3D model of the object. The accuracy of the reconstructed model is closely related to the techniques used in data preprocessing and surface reconstruction.

After obtaining the accurate 3D model of the object, we can start to simulate the virtual assembly process, analyze and verify the assembly path, the feasibility of the assembly, identify the operation risks, and develop the countermeasures, thereby improving the reliability of assembly process.

![Figure 1. Overall process of virtual assembly simulation](image)

In this paper, a camera of a certain type is used as the research object. The camera has a complex outline, a large number of protrusions, and a large area of the camera surface is covered with thermal control multilayers. Thus, the design model cannot truly reflect the physical shape. The camera is installed in a relatively small and enclosed cabin. Therefore, the safety distance between the camera and the cabin is small, which makes it prone to have bump or interference. As a result, it is necessary to pre-identify the assembly risks through virtual assembly simulation.

The cabin where the camera is mounted has a rigid structure. After the 3D scanning on the cabin, the result shows that the scanned model is the same as the design model, and can completely reflect the actual state of the cabin to be assembled. The camera model for assembly simulation is obtained through reverse engineering. The cabin to be assembled adopts the existing design model.

3. 3D scanning

Data measurement in reverse engineering refers to measure the outline information of an object through a measuring device. The measurement methods include contact measurement and non-contact measurement [2]. In this research, the outer surface of the camera is covered with multi-layer thermal insulation components, and the component surface is made of a flexible material. Therefore, non-contact measurement is adopted in this research.
Laser radar is used for 3D scanning. The virtual vision scanning mode of the laser radar can collect a large amount of data during the process of scanning a certain surface. The laser radar model is MV330, with scanning precision of 0.3 mm in the virtual vision mode, scanning speed of 1000 points per second. The steps for performing laser radar-based 3D scanning are described in the following subsections.

3.1 Divide the scanning area and determine the reference points
As the camera surface coated with the multi-layer thermal insulation components is a free-form surface, the data is collected according to the surface features and the flow direction in order to collect the effective data. The measurement area is usually divided into several sub-areas according to the distribution of the surface features, and the division generally follows the following principles [3]:

a). Scan the entire surface as much as possible. If the surface cannot be scanned with one time, minimize the number of sub-areas as much as possible.

b). The division of the measurement area should avoid the boundary line from crossing or intersecting the feature line. It is better to divide the transition area into one measurement sub-area to ensure the integrity of the feature data.

c). The direction of the feature lines in the measurement area should be as uniform as possible.

d). To ensure the integrity of the data, there should be some overlap in the measurement area.

According to the principle of surface division and the surface features of the camera, the scanning area is divided into five sub-areas, and the 3D scanning is performed on the five sub-areas. In order to establish the relative coordinate relationship of each sub-area, 14 balls are used as the reference points on the camera to establish reference point coordinate system that covers different angles of view.

3.2 Setting of sampling density
In the process of 3D scanning, different sampling densities can be set for the surfaces of different features, in order to improve the scanning efficiency with accuracy maintained. After analyzing the surface features of the camera, in order to more realistically reconstruct the contour, a small scanning density of $0.3 \text{ mm} \times 0.3 \text{ mm}$ is set for the irregular surface covered with multi-layer thermal insulation components and the mounting surface between the camera and the cabin. By contrast, for a more regular surface, the scanning density can be appropriately enlarged to $0.5 \text{ mm} \times 1.0 \text{ mm}$ without involving the feature boundary and the critical dimension. During the scanning process, the scanning density of some boundary areas will be higher than the actual scanning density due to the overlap of scanning area.

3.3 Data measurement in virtual vision mode
When using the virtual vision scanning mode of the laser radar for reverse engineering, the first step is to determine the boundary of the scanning area according to the divided scanning sub-areas. The contour points (i.e. the boundary points of scanning area) are measured in the SAMVx software. A certain number of contour points are scanned according to the spatial order and area features, and then these points are connected to form an enclosed curve as the scanning area of the current scan.

After the contour setting of each scanning area, the laser radar can automatically perform data scanning and acquisition in the area. There is a need to ensure that the data of each scan is in the same coordinate system. So, after the coordinate system is established in the first scan, the reference points of balls are first transferred before each scan. In order to reduce the error caused by the transfer, at least 6 points are selected for measurement at the time of the transfer. Then the uncertainty analysis is performed to remove the points with large error, and the error of the transfer is finally controlled within 0.01 mm. The data scanned at different angles is displayed in one coordinate, as shown in Figure 2.
Data preprocessing is an important step of reverse engineering as it determines whether the subsequent reconstruction process can be carried out in a convenient and accurate manner. In order to better complete the model reconstruction, the raw measurement data must be preprocessed.

1) Removal of noise

The existence of great noise directly leads to a large difference between the reconstructed model and the physical object. Thus, it is necessary to identify and remove the noise in the measurement data. In addition, in order to improve the modeling speed of the subsequent reverse model, the redundant data should be removed as much as possible while ensuring the accuracy of the measured surface. Commonly-used noise filtering methods include human-computer interaction method, curve inspection method and string height difference method [2].

In this paper, the human-computer interaction method and the curve inspection method are combined to remove the noise of the curved point cloud of the camera. Firstly, the human-computer interaction method is used to remove the obvious useless points in the point cloud image. Then, the curve check method is used to discriminate the point cloud by the fitted data curve, and the noise is identified and removed.

2) Streamlining of data

In the reverse operation process, too much point cloud data not only reduces the processing efficiency, but also has a serious impact on the smoothness of the surface. Therefore, it is necessary to streamline the measured massive data. Commonly-used methods for data streaming include: minimum distance method, angle deviation method, uniform network method and adaptive minimum distance method [1]. The adaptive minimum distance method calculates the scanning curvature based on the minimum distance method, and sets different angle thresholds according to the curvature change, thereby ensuring that the scanning line data retains considerable quantity of points in the place where the curvature changes greatly, and retains relatively few points in the place where the curvature changes gently. So, we can keep the micro-features of sudden-change places while streamlining the data, which is a good method in terms of accuracy, simplicity and speed [4]. The algorithm of curvature-based sampling in the surface reconstruction module Pro/SCANTOOLS of Pro/E software adopts this algorithm. This paper uses this module to streamline the point cloud data.

3) Repair of data points

Currently, the widely-used methods in reverse engineering include modeling design method, curves and physical filling method, and surface interpolation method, etc. [5] In order to obtain a complete 3D model that is basically consistent with the physical contour, the supplementary measurements are performed on the undetectable areas with obvious surface features to ensure the integrity of the data. As for the small holes still exist in the later stage, they are mainly repaired by the surface interpolation method. In the filling and repairing process, the curvature of the circled points is calculated, and the segment of point data is filled based on the curvature calculation result. Therefore, we can ensure the surface features in the filling area, and ensure that the repaired small holes are as close as possible to the real object. Hole repair is achieved by the tool in Pro/E, and the data to be repaired is repaired after estimating the curvature of the circled points. Figure 3 shows the point cloud data after preprocessing.
5. Reverse reconstruction of the model
Surface reconstruction can be achieved by two methods. One is to represent the model using NURBS surface, where the parameters are automatically segmented according to the specified surface range, and then the control points of the NURBS surface are calculated using the point cloud data. The other is to represent the model using triangular Bezier surface, and the specific steps are as follows. Firstly, any three points of the point cloud data that form a number of facets are interpolated and reconstructed using the triangular Bezier surface. As the calculation of NURBS surface consumes large resources, and the noise of data as well as the effect of parameter segmentation has great influence on the accuracy and smoothness of the reconstructed surface [2], this paper chooses the method of triangular Bezier surface.

The triangular Bezier surface method is most suitable for representing the objects with irregular complex surfaces. Firstly, the measured point cloud data is divided into several triangular planes, and then the divided triangular mesh is fitted into a Bezier surface. In the Pro/E facet module, the point cloud data is enveloped into a number of small triangular planes by the facet envelope process. After the coarse and fine adjustment of the small triangle planes, the surface patches are defined, and the system will make the small surfaces be reasonably distributed on the surface of the model according to the curvature and composition features of the model. The surface is automatically generated by the command “Create Surface” in the Pro/E menu. After the preliminary surface is created, the curve shape can be adjusted by modifying the mathematical properties and control points of the surface. Finally, through the reconstruction of the surface, such as deleting the small surfaces, reconstructing the boundary lines, etc., the surface is reconstructed, and finally a 3D solid model is generated, with its local view shown in Figure 4.

6. Virtual assembly simulation
Assembly simulation is an effective means to verify the detachability/assemblability of a product. The movement pattern and spatial relationship of the components during the assembly process are visualized by relevant visualization methods and interference inspection tools. Besides, assembly path and scheme can also be provided by the visualization. The other aspect is process simulation. The
assembly environment is constructed using virtual reality technology, to verify the feasibility of the assembly process, and visually simulate the assembly process in a way close to real assembly [6]. Through three-digit simulation verification, it is possible to find possible challenges and risks from the virtual assembly operation, thereby improving the assembly process and giving corresponding countermeasures [7, 8]. In this paper, DELMIA software is used to realize virtual assembly simulation. The virtual assembly technology based on DELMIA introduces ergonomics factors, which can not only simulate the real assembly process, but also deeply analyze the operability, visibility and accessibility [9].

The satellite model and the camera model reconstructed by reverse engineering are introduced into DELMIA for virtual assembly simulation. The interference detection and collision check in the assembly process are carried out through the collision detection software in DELMIA. The assembly simulation is shown in Figure 5. The risks and challenges identified during assembly simulation shown in Table 1 are consistent with the counterparts found in the real assembly process. The simulated assembly process and the effects of using it in the real assembly process are also shown in Table 1. The developed process effectively avoids the risks in the real assembly, reduces the assembly difficulty, and ensures the smooth completion of the assembly process.

![Figure 5. Schematic diagram of the assembly simulation process](image)

| Table 1. Comparative analysis of simulation result |
|--------------------------------------------------|
| **Risks and challenges identified in simulation** | **Formulated process measures** | **Analysis of real assembly** |
| 1 The camera has a small waveguide spacing on the -Y vertical baffle, which is easy to bump waveguide. | Wrap about 30 mm-thick antistatic foam to the waveguide of the vertical baffle before assembly to prevent damage to the waveguide. | Anti-static foam effectively prevents the camera from colliding with the waveguide and protects the waveguide on the vertical baffle. |
| 2 No tightening and force measurement space for the fasteners between the camera and the bottom frame. | Design a torque adapter rod that meets the current condition, and calibrate the rod in advance. | The newly-developed torque adapter rod successfully solves the force measurement problem under this working condition. |
| 3 The pin on the -Z+Y side is less visible and difficult to align and mount. | Insert the long screw ahead of time near the pin position where fasteners are installed, assist the pin to align, and provide special lighting tools for better lighting. | The equipped lighting tool effectively enhances the visibility at the position of the pin, and the auxiliary screw effectively assists the pin to smoothly align. |
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