

A Haptics-guided Hole-filling System Based on Triangular Mesh

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ABSTRACT

Defects of primitive models such as holes are not uncommon in the process of reconstructing a physical object model through an optical scanner. Most hole-filling methods are focused on repairing model automatically. However automatic technologies cannot give satisfactory results when dealing with complex holes because points on the hole boundaries are error prone and must be pre-processed before any automatic methods be applied. In order to provide a more intuitive and efficient tool for model reconstruction in reverse engineering (RE) a novel hole-filling system with haptic characteristic based on triangular mesh is implemented compared with traditional unnatural mouse-based computer interfaces that can not be used to edit point clouds intuitively. Smoothing and stitching operations based on haptics are proposed to modify error-prone hole boundaries and simplify complex holes. A sculpting operation based on loop subdivision is developed to allow a user to deform the surface in the multi-sided and multi-level polygonal domains. By employing both automatic and interactive methods for hole filling, this system is more efficient and robust. A primitive prototype system has been implemented and several examples are presented to demonstrate the effectiveness of this system.

Keywords: Hole filling, Haptics, Model reconstruction.

1. INTRODUCTION

Data acquisition is a crucial part of reverse engineering. Optical methods of data acquisition are probably the most popular because of relatively fast acquisition rates. However, there are many factors affecting the optical scanners' accuracies such as accessibility, occlusion, video resolution, distance from the measured surface, laser power and surface properties of artifact etc [17]. Accessibility is the issue of scanning data that is not easily acquired due to the configuration or topology of the part. Occlusion is the blocking of the scanning medium due to shadowing or obstruction. Incomplete data of model such as holes, gaps is primarily raised by inaccessibility and occlusion. Noises on the boundaries of holes or gaps and sharp edges are not uncommon due to those factors mentioned above. Therefore, after triangulation modifying these defects such as holes in the model is a necessary step in RE.

Many studies on hole-filling methods are focused on automatic model modification [2, 3, 5, 9, 13, 16, 18]. Due to complexity of region where holes are generated, the automatic model modification methods may not give satisfactory results in dealing with holes. Fig.1(a) and Fig.1(c) show two models repaired incorrectly by means of automatic hole-filling methods adopted by FreeForm® Modeling Plus™ system of SensAble technologies compared with repaired models in Fig.1(b) and Fig.1(d) by means of our haptics-guided method. In our belief, a user should take the initiative in the hole modification process to get satisfactory models.

However, three-dimensional (3D) interactive editing and modeling remains a problem of current CAD systems, since the screen and the desktop for manipulation of mouse are only two-dimensional (2D). It is difficult to handle these 3D points, lines, polygons and etc. with the traditional CAD interfaces. Recently many 3D editing and modeling interfaces have been proposed using virtual reality (VR). These methods include shadow widgets[8], semi-transparent moving cursor plane[10], a tracked stylus[14], a head mounted display[1] and etc. A novel haptics-based interface and sculpting system for physics-based geometric design was proposed by Dachille [4]. Haptics refers to the modality of touch and the sensation of shape and texture a user feels when exploring a virtual object, such as a 3D model of a tool, instrument, or art object [12]. It provides users a hand-based mechanism for intuitive, manual interactions with virtual environments towards realistic tactile exploration and manipulation. Using force-feedback controls, designers, artists, as well as non-expert users can feel the model representation and modify the object directly as in as real setting, thus enhancing the understanding of object properties and the overall design.

In this paper, a novel hole-filling system which is based on haptics is proposed for reverse engineering and a prototype system has been implemented based on a Phantom device from Sensible Technologies as shown in Fig.2. This system provides a user with a more intuitive and effective tool to modify the model than traditional CAD systems in RE. The remainder of this paper is organized as follows. Section 2 presents related work on hole-filling methods. Section 3 elaborates on hole-filling algorithm proposed in this paper. An experiment system is described and several examples are given in section 4, followed by conclusions in the last section.

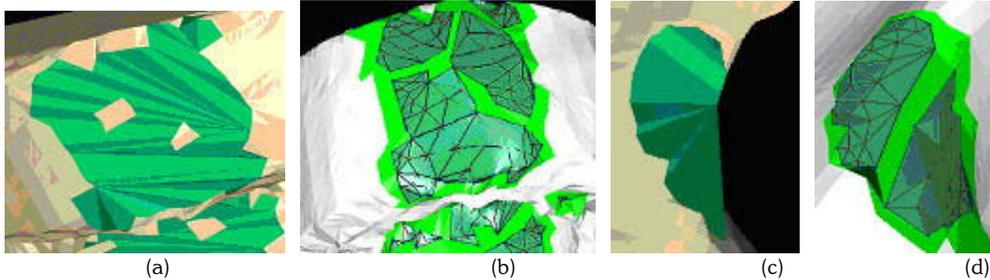


Fig. 1. Comparison between the automatic and our haptic-guided hole-filling methods. (a) holes are filled but some data left “floating” on the green mesh; (b) holes are stitched and filled by our method; (c) the hole is filled but the ridge is not reconstructed; (d) the ridge are recovered by our method.

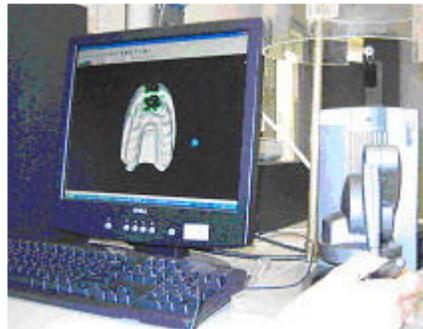


Fig. 2. The hole-filling system configuration.

2. RELATED WORK

Hole filling is an important step in RE to get watertight 3D models. Many studies on hole filling can be categorized into two methods, namely automatic and manual one. Most of the automatic hole-filling methods are based on the following techniques: multisided patch, trimmed B-spline surface, surface reconstruction, subdivision and volumetric diffusion.

DeRose and Loop [6] developed surface representations over generalized n -sided domains. However this formulation applied only to regular polygons. Chui and Lai [2] used energy minimization method to fill polygonal holes by C^1 cubic triangular spline patches based on Clough-Tocher’s refinement method. Rayevskaya and Schumaker [13] used C^r macro-element spaces consisted of polynomial super-splines defined on triangulations to fill n -sided holes. Yau et al. [18] proposed a method that could stitch and repair STL models globally and automatically by means of surface reconstruction algorithm. Wang and Oliveira [16] proposed an algorithm for identifying and filling holes on locally smooth surface by means of surface reconstruction based on moving least squares solution. But this algorithm cannot deal with complex holes, which have unclosed boundaries or are not locally smooth. Curless and Levoy [3] employed a mesh-based method to integrate hole filling into surface reconstruction. This method converted each mesh to a signed distance function and extracted zero set to produce the watertight surface. But it required the knowledge of scanner lines of sight. Davis et al. [5] used volumetric diffusion process to fill geometrically or topologically complex holes. The method can produce watertight, manifold and non-interpenetrating surfaces. But it contains a lot of free parameters difficult to be determined and needs additional knowledge of line-of-sight to eliminate appropriate bridges resulting from hole filling. When dealing with a large model this algorithm is of time and memory consuming. Ulrich [15] proposed a new method for the fair filling of holes in CAD models with trimmed tensor product B-spline surfaces.

A more straightforward hole-filling method was proposed by Jun [9]. He proposed a piecewise hole-filling method that could incrementally split a complex hole into several simple holes, which could be filled automatically by planar triangulation method.

All these algorithms for hole filling mentioned above mainly focus on automatic methods for hole filling. The automatic method of course has some merits such as better efficiency over manual one. However, in view of the complexity of hole, the automatic one may not work correctly when encountering the complex hole. Most of the information in hole is missing but it is important for getting a satisfactory model. So this paper tries to combine manual and automatic methods to improve current hole-filling methods. As for the manual method, this paper applies haptic tool to hole filling since it provides a user a good manipulator to feel and modify the model according to the original artifact when the automatic one does not work.

3. HAPTIC HOLE-FILLING ALGORITHM

3.1 Hole-filling Process

Our hole-filling process consists of six parts: hole identification, boundary smoothing, stitching operation, polygon triangulation, triangle subdivision and mesh deformation as shown in Fig.3.

A user can import a scanned model and the system will establish the relationships between triangles automatically thereby identifying the holes. Then the system will re-generate the hole boundary edges automatically and require the user to modify the positions of boundaries manually. After the smoothing operation, the user can decompose those complex holes into simpler holes by means of stitching operation. Then an automatic polygon triangulation for hole boundaries is applied to generate triangular meshes in each of the simpler hole regions. If the user is not satisfied with the result, he/she can sculpt the hole meshes. In the last a watertight model is exported.

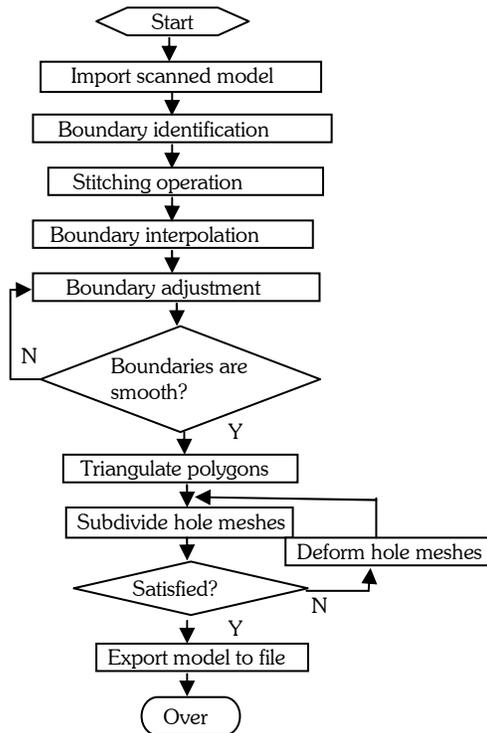


Fig. 3. Flow chart of haptic hole filling.

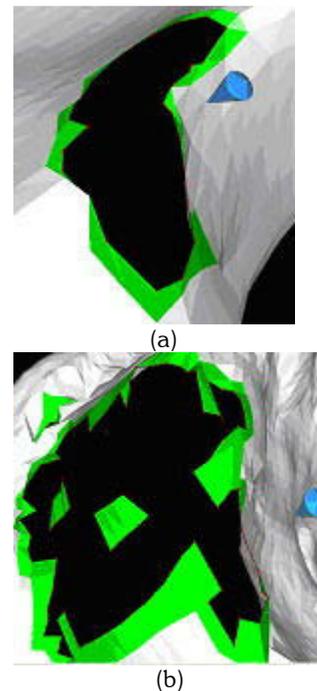


Fig. 4. Hole boundary. (a). hole boundary marked in green color; (b) “islands and peninsulas” in a complex hole.

3.2 Hole Identification

We first identify the mesh by boundary and inner meshes. Boundary meshes are composed of triangles which share boundary vertices. A boundary vertex can be found through inspecting boundary edges which are shared by only one triangle. Fig. 4 shows two examples of hole boundary meshes identified in this system. For complicated models, missing data from 3D scanner are commonplace. Boundaries with long and narrow even isolated triangles like islands

may appear such as shown in Fig. 4(b). Some superimposed vertices and invalid triangles can also be found due to noises and limitation of triangulation algorithms adopted by some scanner software. So it is necessary to check all these possibilities and correct them at the beginning.

3.3 Smoothing Operation

3.3.1. Boundary Interpolation and Adjustment

Points in boundaries are prone to be unreliable since these boundaries always appear in the fringe of concave regions of model and light of scanner reflected from model is feeble. The lengths of boundary edges differ from each other significantly, which goes against the following steps such as triangulation and sculpting. Further more the topologies in boundaries sometimes are incorrect such as intersection and unnecessary triangulation. Therefore, before the hole filling a smoothing operation should be applied to make boundary meshes smooth and rectify all these incorrect topologies in boundaries.

The boundary edges will greatly affect the results of the following steps such as triangulation and sculpting. Hence, it is necessary to make sure that the sharp changes of edge positions and uneven distribution of edge points should be avoided. A cubic spline interpolation based on the chord length parameterization is applied for automatic smoothing operation. After this automatic interpolation, the boundary edges are re-generated and the points on this boundary are nearly evenly distributed. However, this automatic method cannot guarantee smooth boundaries and correct topologies sometimes. So the user may check and modify them manually through pulling those points to desired positions. Resorting to haptic tool, picking and pulling 3D points become an easy task. When pulling a point, a user can feel the force provided by PHANToM[®] according to spring model, and when picking a point, the user can not only see the point highlight, but also feel the contact.

3.3.2. Point and Triangle Selection

In the proposed system a haptic device called Phantom Desktop[®] is developed for selecting 3D points and triangles in an easy way. When selecting a point or triangle facet using the haptic device, all points and surfaces are touchable and deformable but are not penetrable. In the process of pushing or pulling a point, a user can feel the force provided by the PHANToM[®] device according to a mass-spring model. In boundary regions incorrect triangulations should also be corrected. A user can delete and re-triangulate a region with the aid of the haptic tool, which make the process easier than that picking a point in three-dimensions with the traditional mouse-based interfaces. When a user manipulates the haptic stylus to poke a triangle, the haptic rendering is done by means of the proxy method. The proxy (also known as the “god-object”) is a point which closely follows the position of the haptic stylus. The position of the proxy is constrained to the outside of the surfaces of all touchable triangles. The force sent to the haptic device is calculated by stretching a virtual spring-damper between the haptic stylus position and the proxy position as shown in Fig. 5(a).

$$\mathbf{F} = k(\mathbf{SCP} - \mathbf{X}) - \zeta \mathbf{V} \quad (1)$$

where k is the stiffness constant, \mathbf{X} is the end-effector position, \mathbf{SCP} is surface contact point, ζ is the damping constant and \mathbf{V} is the velocity of end-effector. When the user touches a triangle and the button of the haptic stylus is pressed the corresponding triangle will be selected and deleted. A user can also select three points in the counter-clockwise direction to form a new triangle facet. To select a 3D point in a triangle with the haptic stylus, a user can touch the triangle first and then slide the stylus towards that point and press the button when the haptic stylus is attached to the point as shown in Fig. 5(b) in a similar way as in “snap to grid”. An attraction magnetic force is applied to each point in order to facilitate point selection. A point has a force influence radius δ . When a user moves the haptic stylus to a position less than the radius δ , a magnetic force is sent to the haptic stylus thereby attracting it to that point and a dialog box will pop up to the user asking if this point should be selected. If yes, the point will be selected, otherwise, the force is released and the stylus can be used for other operations.

3.4 Stitching Operation

If a hole contains some missing information such as ridges or valleys, no automatic methods can give you satisfactory results. In these cases, manual stitching that provides some topologic clues is necessary. When dealing with complex holes, a user can manually separate a complex hole into several simple holes with the haptic stitching operation. Fig. 6 shows two examples of stitching operation. After this operation, a long and narrow hole can be decomposed into two simple holes and a ridge is formed as shown in Fig. 6 (b) and (c). The stitching operation is useful when dealing with complex holes. A user can take advantage of this operation to eliminate islands and peninsulas to shape simpler holes as shown in Fig. 6 (d) and (e). A spring model is made to simulate stitching so that a user can feel the force as if he or

she is pulling a thread. The magnitude of the force is proportional to the distance between the two vertices to be stitched as shown in Fig. 6(a).

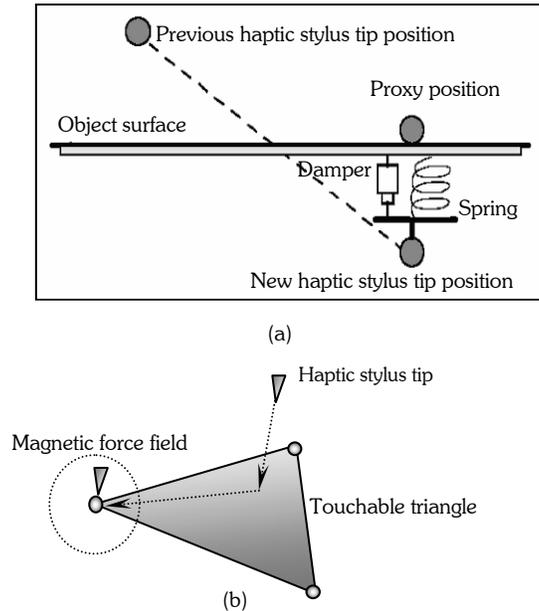


Fig. 5. The “god object” and point selecting method.

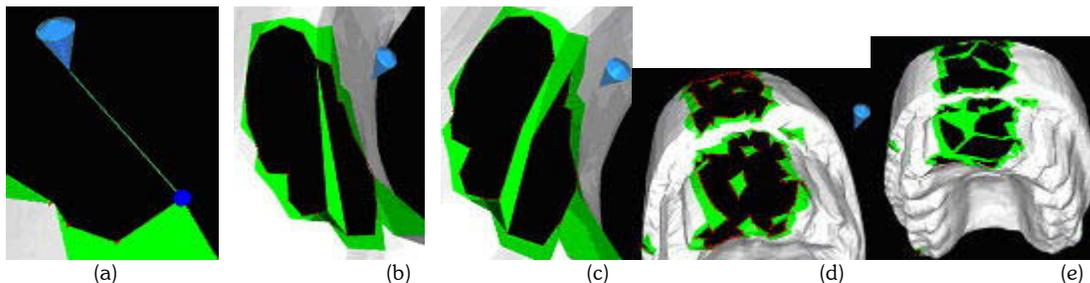


Fig. 6. The stitching operation. (a) a stitching thread; (b) stitching a irregular hole; (c) a ridge created by stitching and split operation; (d) a jawbone model with complex holes; (e) simpler holes after stitching.

3.5. Polygon Triangulation Method

An optimal polygon triangulation method based on classic ear-cutting algorithm for complex polygon triangulation in 3D is developed in this hole filling system in order to provide a more robust method. The basic ideas of this algorithm are: First, find the optimal ear of a polygon then cut it off from the polygon. This process can be run recursively until only three vertices are left and then finish the triangulation. The optimal ear is selected from all the ears of polygon based on constraints such as minimal distance, even angles, minimal normal variation. Although the time complexity of this algorithm is $O(n^2)$, the edge number of polygon in our case is always small (complex holes are simplified by stitching operations) and the calculation time and memory space requirement are reduced due to the prior stitching process.

3.6. Triangle Subdivision Method

After hole triangulation, the density of triangles in boundary regions are always much bigger than that of inner regions and slim or narrow triangles may be formed at the boundaries. Therefore subdivision technique is applied to these triangles so that subsequent deformation process can be done easier. A subdivision surface is a polygonal mesh that

has been subdivided and smoothed. Every polygon of the mesh is sliced into two or more polygons, and each vertex is moved to a calculated position. The subdivision method used in this system is based on a modified Loop subdivision [11] surfaces. The calculations of edge points and vertices are based on Eqn. (2) and (3).

$$V_j^{i+1} = \frac{3}{8}(V_j^i + V_{j+1}^i) + \frac{1}{8}(V_{j+2}^i + V_{j+3}^i) \tag{2}$$

$$V_k^{i+1} = (1 - N\alpha)V_k^i + \alpha \sum_{j=0}^{N-1} V_j^i \tag{3}$$

$$\alpha = \frac{1}{N} \left[\frac{5}{8} - \left(\frac{3}{8} + \frac{1}{4} \cos \frac{2\pi}{N} \right)^2 \right]$$

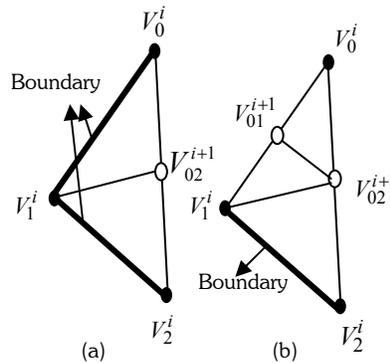


Fig. 7. Boundary triangle subdivision.

The edges on the boundary cannot be interpolated with points in view of topology consistency. The subdivision method picks up a triangle and checks whether its edges are on the boundary. If not, then it calculates with Loop edge vertices Eqn. (2) to interpolate edge point. As to update of old vertices, the system also check whether old vertex is on the boundary. If so, this vertex should be copied for next loop. Otherwise, it could be updated with Loop vertex update calculation Eqn. (3). Take a triangle $\Delta V_0^i V_1^i V_2^i$ for example as shown in Fig. 7. If the triangle has two boundary edges $\overline{V_0^i V_1^i}$ and $\overline{V_1^i V_2^i}$, then it only calculates the edge point V_{02}^{i+1} on edge $\overline{V_0^i V_2^i}$. Because all three vertices of this triangle are on the boundary, these vertices are copied to V_0^{i+1} , V_1^{i+1} and V_2^{i+1} respectively. Hence, this triangle could be divided into two triangles $\Delta V_0^{i+1} V_1^{i+1} V_{02}^{i+1}$ and $\Delta V_{02}^{i+1} V_1^{i+1} V_2^{i+1}$ as shown in Fig. 7(a). If it has only one boundary edge $\overline{V_1^i V_2^i}$, then it calculates V_{01}^{i+1} , V_{02}^{i+1} and copies V_1^i, V_2^i to V_1^{i+1}, V_2^{i+1} respectively. And it updates the vertex V_0^i with Eqn. (2) to get V_0^{i+1} . Comparing the length d_1 of edge $\overline{V_1^{i+1} V_{02}^{i+1}}$ with the length d_2 of edge $\overline{V_2^{i+1} V_{01}^{i+1}}$, if $d_1 < d_2$, then this triangle is divided into three triangles $\Delta V_0^{i+1} V_{01}^{i+1} V_{02}^{i+1}$, $\Delta V_{01}^{i+1} V_{02}^{i+1} V_1^{i+1}$ and $\Delta V_{02}^{i+1} V_2^{i+1} V_1^{i+1}$ as shown in Fig. 7 (b).

3.7 Sculpting Operation

Because the automatic triangulation and Loop subdivision [11] methods bring much artificial geometry into boundary regions, there is much distinction between the physical object and the model to be modified in the hole regions. Hence, a user should sculpt surfaces in hole regions with a haptic tool. Surfaces generated by subdivision methods mentioned above can be easily deformed by editing internal vertices of the net at some level of the subdivision. Small scale deformations can be done by moving internal vertices in an advanced iteration of subdivision, while large scale deformation corresponds to moving vertices in one of the first subdivision iterations as shown in Fig. 8. Thus, this

approach allows free-form multi-resolution editing, which is natural to subdivision schemes. Corresponding force \bar{F} sent to the haptic stylus is calculated by means of spring model.

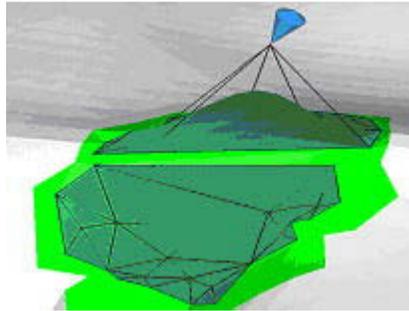


Fig. 8. The deformation operation.

4. EXPERIMENTAL STUDIES

A prototype hole-filling system based on the proposed methods has been implemented. In our implementation, the haptic and visual rendering machine is a desktop PC with dual 2.2 GHz CPU and 1.0 GB RAM. The haptic device in this system is a PHANTOM[®] Desktop with 6 degrees of freedom (DOF) of position sensing and 3 DOF of force feedback. The software is written in VC++, OpenGL and 3D Touch™ GHOST[®] API for graphic and haptic rendering. Using the proposed system, several scanned models with typical complex holes have been repaired successfully. An example for spine model reconstruction is shown in Fig. 9. A user can feel force feedback if he/she touches the surface of the model as manifested by the blue cone cursor. Force feedback makes the smoothing, stitching and sculpting operations easier than traditional mouse manipulations. Fig. 10, Fig. 11 and Fig. 12 show the other three examples of hole-filling results.

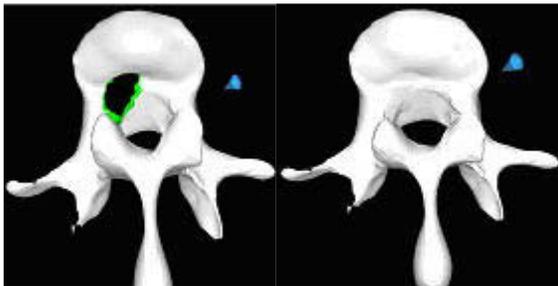


Fig. 9. A spine model hole filling.

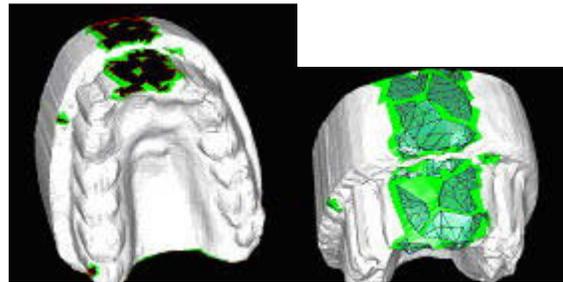


Fig. 10. A jawbone hole filling.

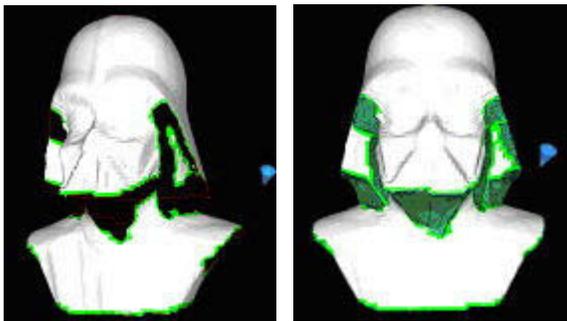


Fig. 11. A fighter model hole filling.

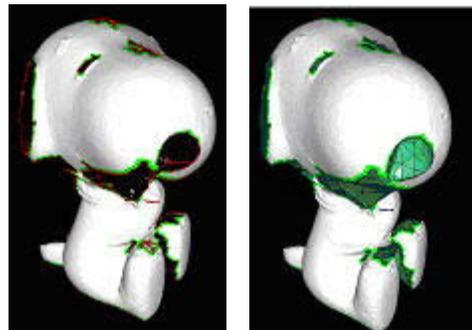


Fig. 12. A snoopy model hole filling.

5. CONCLUSIONS

In this paper, a haptics-guided hole-filling system based on triangular mesh is proposed for reverse engineering and a prototype system has been implemented. By means of introducing haptic techniques into this system, a user can more intuitively manipulate points, triangles in 3D to modify and repair models with complex holes. Before filling a complex or compound hole, a boundary edge smoothing method based on haptics is proposed. A user can use stitching operation with a haptic tool to decompose a complex hole into several simple holes. Each simple hole is then automatically triangulated. Combining automatic and manual hole-filling methods the system is more flexible, robust and effective. A sculpting operation based on Loop subdivision is developed in order to compensate defects of automatic methods. Several examples have verified the effectiveness and user friendliness of this system.

6. ACKNOWLEDGEMENT

This research is supported by a grant from Hong Kong Research Grants Council under the code HKU 7116/05E.

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