USER-GUIDED FEATURE SENSITIVE HOLE FILLING
FOR 3D MESHES

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Abstract: Most hole filling approaches use techniques to fill up a hole first and then to smooth it. Very few tries rebuild features on the filled surface of the original 3D model. We propose an efficient hole-filling methodology which preserves sharp features of the geometry of the original model. The main idea is that we reconstruct feature curves in the missing parts of the given mesh before filling the hole with smoothing surface. The feature curves in the missing part are reconstructed by extending salient features of the existing parts. The hole is partitioned into several smaller and more planar sub-holes divided by the feature curves and then the hole-filling step follows. User intervention is available to design the features to be desired shape to guide feature curve reconstruction wherever ambiguity exists or results are unsatisfactory. Our hole filling techniques is different from other existing techniques as features are taken as the first subject to reconstruct, which eventually drive the feature-definite surface filling process. It is also very efficient as a user is interfering only with features and the actual hole-filling step is dealing with only planar holes.

1 INTRODUCTION

3D computer models of real life objects can be obtained by several ways such as 3D scanning devices, or computer-aided design software (Autodesk Maya, 3DS Max, etc.). A common scenario, especially when dealing with 3D shapes obtained from 3D scanning, is to have incomplete surfaces. These appear in areas where the object geometry occludes the scanning device, notable examples when scanning human bodies include the area under the chin, armpits or between the fingers, hence limiting the information obtained. Because of these issues, many post processing techniques are needed to be applied onto the raw models before being able to use them as the input of design or animation applications. The repair of incomplete polygon meshes is a fundamental problem in the reconstruction of 3D models in the field of computer graphics.

One of key aspects of reconstruction of 3D models is hole-filling. This is to complete the shape of the 3D object where surface information is missing. This is essential for a wide range of applications such as computer animation, pattern recognition, or character design. Hole-filling

techniques aim to keep the filled surface continuously and smoothly fitted at the boundary of the hole to conform to the shape of the original model. Although there is a large body of research on hole filling, very little attention has been devoted to the problem of recovering fine features of the 3D object, for instance the sharpness of the edge geometry. Most research focuses on automatic methods that require performing complex optimization processes (Chui and Lai, 2000; Attene et al., 2003; Liepa, 2003; Jun, 2005; Podolak and Rusinkiewicz, 2005; Zhao et al., 2007; Chen and Cheng, 2008). In many cases, although the models obtained are hole-free, interpolation algorithms fail to preserve fine details, ignoring sharp edges and corner shapes.

Due to the complexity of the regions where holes are generated, automatic model modification methods may not give satisfactory results in dealing with holes. Complex optimization frameworks are computationally expensive. In addition, processing large and complicated models is a time consuming task. Despite of the great computational overhead, fine features in models are not recovered. Since there are potentially several possible results for the surface recovery process, the user should have the

ability to influence the quality of the output surface. Furthermore, although there are ways to set the constraints for automatic methods to resolve ambiguous topology problem, there will always be the cases that require high-level knowledge to disambiguate or have multiple answers, where the selection depends on user's preference. We believe a program interface that allows user intervention efficiently helps to reduce the implementation effort, to give better visually plausible results and to enhance the versatility of the system since the user would have the ability to choose the desired feature-topology and the shape of the filled mesh.

We are motivated by the need of a hole filling system that is able to plausibly recover the fine geometry features of the 3D models, especially the sharp features, with some possible simple guidance by users at the hole locations using a real time Graphics User Interface (GUI). Our goal is to develop a system that can repair the holes of the 3D models and, at the same time, aesthetically preserve the sharpness of the model at the hole locations with the aid from user intervention.

Our main contributions are two-fold: (i) salient features of the mesh geometry are taken as the first subject to reconstruct, which eventually drive the feature-definite surface filling process; (ii) the user is allowed to influence the hole filling process at feature designing level while the rest is taken care by the automatic functions. Our results show missing hole features are recovered with high quality while supporting flexibility.

2 RELATED WORKS

Many researches on hole filling topic have been done up to now. However, there are only few hole-filling approaches attempting to preserve and to recover the sharp features of the 3D model. In this section we focus our discussion on feature sensitive recovering methods for 3D meshes as they are of our special interest.

Barequet and Kumar (Barequet and Kumar, 1997) proposed a method that allows users to inspect the automatic results of the first iteration and also to mark the areas to be corrected. The second iteration produces the final results. The approach can produce "intuitively-correct" filling of the holes with the aid of the user.

In (Ohtake and Belyaev, 2003), to preserve the shape of sharp edges and corners at the hole locations, a multilevel piecewise surface fitting method is employed to represent a mesh model that

has fine structures. Local approximation for fitting edges and corners are based on the piecewise quadric surface fitting method. It consists of a number of tests (edge tests and corner tests) in order to determine the type of approximation surface or shape function that should be used. Edges and corners are automatically recognized by clustering the normals of the mesh vertices.

In (Sharf et al., 2004), a context-based completion method is proposed to recover the missing fine details in a repaired hole. The method employs the idea of texture synthesis, by replicating portions of regions from adequate examples. Based on this idea, the fine structure of the 3D model is recovered by finding a piece in the original model or in the template models that is similar in shape to replace the initial repaired hole. Hence, this method is particularly efficient for repairing holes in textured mesh model.

Attene et al. (Attene et al., 2003) proposed a method to recover the sharp features of 3D mesh model which are lost by reverse engineering or by remeshing processes that use a non-adaptive sampling of the original surface. The algorithm starts by identifying the smooth edges in the mesh model then applying the filters to get the chamfer edges. Each chamfer edge and its incident triangles are subdivided by inserting new vertices. These vertices are calculated so that they lie on intersections of planes that locally approximate the smooth surfaces that meet at the sharp features.

In (Chen et al., 2005), holes are filled and sharpness is recovered by applying a sharpness-dependent filter. The filter operates based on the distribution of the sharpness values of triangle faces in the vicinity of a hole boundary. In this context, the vicinity of a hole boundary is defined as its two-ring neighborhood. For any triangle face, its sharpness value is computed as the variance of the angles between its normal and each of the normals of the neighboring faces.

In (He and Chen, 2006), both automatic and interactive methods are employed for hole-filling. A novel hole-filling system that makes use of a haptic device is proposed. After the hole identification phase, the hole boundaries are smoothed in the interpolation step. This step is to correct boundary topologies and to adjust the boundary edge lengths in order to avoid the uneven distribution of points at the hole boundary. Then the user can decompose those complex holes into simpler ones in stitching process. Sub-holes are then automatically triangulated using regular triangulation methods. The user can repeat the intervention process until

obtaining satisfactory results. The authors proposed an interesting idea about using haptic for 3D user intervention. However, the limitation of this method is the lack of an automatic method to detect the fine features of the mesh to serve as the guidance for the user.

In (Zhao et al., 2006), holes are detected then triangulated using the modified minimum-weight triangulation technique. Sharp features are recovered by crest line fairing. The system makes use of the crest line detection technique in (Yoshizawa et al., 2005) to detect the feature lines in the original mesh. Crest lines are the salient surface features defined via the first- and the second-order curvature derivatives. Detected crest lines are then used in region growing and fairing processes to recover the sharp features at the hole areas. The users are also able to connect some crest lines before the region growing step.

Chen and Cheng (Chen and Cheng, 2008) presented a sharpness-based method for filling holes. The whole algorithm performs in two steps: an interpolation step for filling the hole which produces the first approximation of the final model, and a post-processing step which modifies the approximation model to match the original. The patch for the hole is interpolated using the radial basis function to create a smooth implicit surface to fill the holes. The implicit surface is triangulated using a regularized matching tetrahedral algorithm. Then the triangulated surface patch is stitched to the hole boundary to obtain the repaired model. In the post-processing step, a sharpness-dependent filter is applied to the repaired model to recover its sharp features. In this paper, the sharpness-dependent filter is an improvement of the one presented in (Chen et al., 2005). Although the algorithm works quite effectively in repairing the models, the system is difficult to implement.

Although an automatic system is always desirable, dealing with fine features at the hole areas is a challenging task. In spite of a complicated hole-filling optimization engine to get the results automatically as in (Zhao et al., 2007), the fine features are not adequately recovered in many cases. Most of the systems require user intervention (Barequet and Kuma, 1997; He and Chen, 2006; Zhao et al., 2006) to obtain the best guess of fine features at the hole areas and to correct the automatic results.

Our hole-filling system provides both fully automatic and semi-automatic capabilities where semi-automatic allows user to be comfortable dealing with only several feature elements. If there is

no ambiguity in pairing the feature points and no inaccurate crest lines detected at the hole vicinities, our system can fully automatically produce aesthetical results. Furthermore, while most hole filling algorithms provide only automatic function and manual hole filling takes a lot of user's time and effort as it is at surface mesh level with numerous points to touch and requires expert knowledge about the objects and about how to manipulate on the 3D mesh, our hole filling method, in the more complex cases, need a very limited user intervention at the feature level to support the hole filling procedure.

3 USER-GUIDED FEATURE SENSITIVE HOLE FILLING

Our hole filling algorithm can completely fill the holes of a model and aesthetically recover the sharpness of the model at the hole areas, if any. It includes the solution for efficient preservation of sharpness properties of 3D mesh models during the hole filling procedure; the solution for implementation of a user-friendly interface to support user intervention in real-time.

3.1 Algorithm Overview

Figure 1 shows a high level view of our user-guided feature sensitive hole filling system. The input model information is loaded into our designed data structure for further usage in two modules: Crest
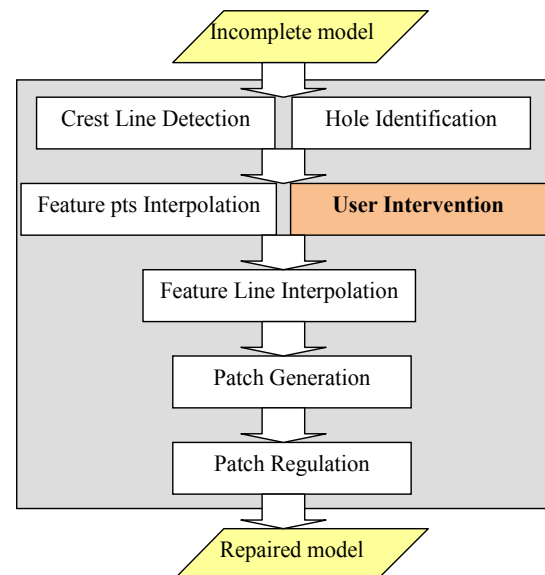

Figure 1: The framework of our system.

Line Detection and Hole Identification. Crest line information helps to find feature points in the holes and their vicinities, which are used later for sharp feature interpolation. Here, the user can interfere the crest point positions and design the shape of the patch mesh. Using this corrected information, our system performs a feature line interpolation procedure over the holes. This process defines the expected fine features of the hole geometries and also divides large complex holes into smaller and more planar ones. For each of these simpler holes, patch is generated by projecting the hole on its projection plane, performing triangulation and then mapping the triangulated topology back to 3D space. The 3D patch is then stitched into the 3D model, and it is regularized to make the patch consistent with the original mesh, in order to produce the final repaired mesh model.

3.2 Crest Line Detection

Defined in (Yoshizawa et al., 2005), the crest lines are the salient surface features defined via the first- and the second-order curvature derivatives. Crest line detection has a significant role in our system since it guides the user to pair the feature points on the hole boundaries and to correctly interpolate the feature lines over the holes. In our implementation, we employed the crest line detection approach proposed in (Yoshizawa et al., 2005).

Consider an oriented surface S and denote k_{max} and k_{min} its maximal and minimal principal curvatures. Denote by t_{max} and t_{min} the corresponding principal directions. Denote c_{max} and c_{min} the derivatives of the principal curvatures along their corresponding curvature directions. The *convex crest lines,* also called *ridges*, are given by

$$c_{max} = 0, \ \delta c_{max}/\delta t_{max} < 0, \quad (1)$$
$$k_{max} > |k_{min}|$$

while the *concave crest lines*, also called *ravines*, are characterized by

$$c_{min} = 0, \ \delta c_{min}/\delta t_{min} > 0, \quad (2)$$
$$k_{min} < -|k_{min}|$$

It also turns out that in our cases, the mesh models are usually with holes, the crest lines that suppose to pass over the holes areas are missing after the crest line detection phase and need to be recovered by some way. Furthermore, since there is no surface information at the hole areas the detected crest lines in the hole vicinity are usually go incorrectly comparing to the case when the mesh model is complete. In our algorithm, the detected crest line information is used to interpolate the

missing parts. Hence, in order to have the accurate interpolation results it is necessary to correct the crest information at the hole vicinities first before the interpolation is proceeded. We believe user intervention to correct the crest line information is the most efficient way and it is chosen in our method. An example of inaccurately detected crest lines at the hole's vicinity and the corrected ones by user through our GUI is showed in Figure 2.
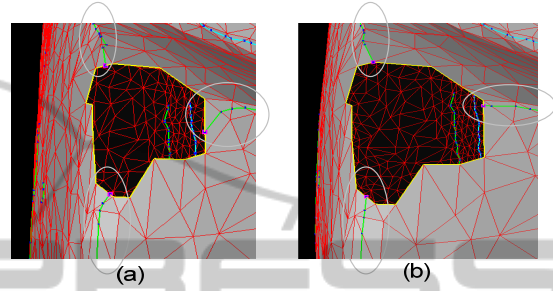

Figure 2: (a) An example of inaccurate crest line detection at the hole area: detected crest lines and crest points are colored in green and blue correspondingly; (b) Crest lines are corrected by user intervention.

3.3 Hole Identification

In the loading phase, all of the 1-ring neighbourhood and connected component information of vertices, edges and triangles of the input mesh model are calculated and stored in our designed data structures to facilitate further processing. Hence, at this step, all boundary edges can be easily identified by checking the numbers of their adjacent triangles, i.e. for an edge, if the number of its adjacent triangles is equal to one then that edge is a boundary edge. Its two end vertices are the boundary vertices and its adjacent triangle is the boundary triangle. Once the boundary edge is detected, its two end vertices are used as seeds to trace along the connected boundary edges and vertices. If all identified points form a closed loop they make up a hole.

3.4 Feature Line Interpolation

At this step, before doing the filling work, we attempt to recover the sharp features, i.e. the feature lines that suppose to pass over the hole areas. After the feature lines are interpolated, the holes are also subdivided by these feature lines into the smaller and more planar ones. This indeed facilitates the later hole filling procedure.

3.4.1 Basic Concepts

In our system convention, *feature points* are defined

as the crest points, either *detected* or *interpolated,* that lie on the feature line segment passing over a hole. *Detected feature point* is defined as the intersection point between the crest line, either ridge or ravine, with the hole boundary (see Figure 3). Intersection point are the detected crest point, either ridge- or ravine- point, that lies on hole edge, also called boundary edge. *Interpolated feature point* is the feature point obtained during the feature line interpolation process. Figure 3 provides illustration of these concepts.
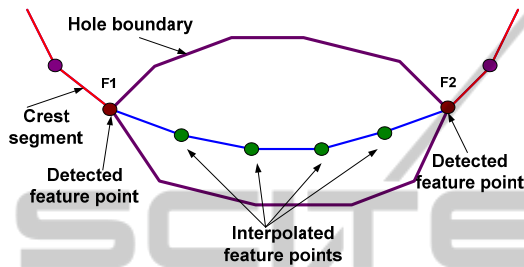
Figure 3: An example of interpolating the feature lines over a hole using spline interpolation: the interpolated feature line is colored in blue, the interpolated feature points are colored in green.

In the same way with Jun (Jun, 2005), we consider two types of holes: *simple hole* and *complex hole*. Simple holes are those that can be filled with planar triangulations, which is the case when all boundary edges can be projected into a plane, without self-intersection (as illustrated in Figure 4(a)). It is not adequate to fill the complex hole with planar triangulations since there are usually self-intersections when projecting the complex hole boundaries into a plane (Figure 4(b)). Thus, in our perspective, we attempt to properly subdivide the complex holes into simple ones in order to fill the holes by planar triangulation (see Section 3.4.4).
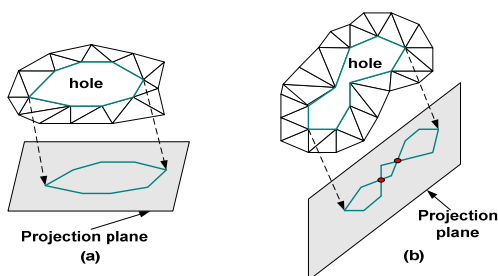

Figure 4: Example of projecting holes onto planes: (a) Simple hole makes no self-intersections; (b) Complex hole creates self-intersections (colored in red) on the projection plane.

3.4.2 User Intervention

Once feature points are detected in the previous step, some limited user intervention at feature level is needed

- To pair the detected feature points to avoid ambiguity for the case there are multiple feature lines passing over the hole;
- To adjust the inaccurately detected crest points to enhance the accuracy and the quality of the final result; and to specify the hole at the corner of the object model by specifying the triple of detected feature points lying on the hole boundary at the corner area.

3.4.3 Feature Line Interpolation

To interpolate the missing feature lines passing over the holes, the following issue should be addressed: since we try to make use of the crest line information which is automatically detected by the system, the interpolated feature lines passing over the hole should be interpolated by the available crest lines and crest points.

We choose spline interpolation for interpolating the feature lines at the hole areas. A spline is a mathematical representation of a curve. It consists of a series of points, called control points, at certain intervals along the curve, and a function that allows defining additional points within an interval.

Two requirements for the spline interpolation in our case are
i. The curve should pass through all the control points, as they define feature line, and its segments act as the edges in the polygonal mesh model;
ii. It is necessary to be able to calculate the exact positions of missing control points of the spline based on the available ones.

There are various functions available for approximating a curve and Catmull-Rom spline is the one that satisfy the above requirements.
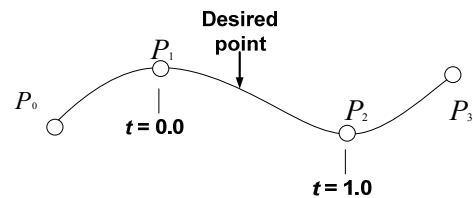

Figure 5: The Catmull-Rom spline passes through all of its control points.

Recall the properties of Catmull-Rom spline interpolation, a new point can be found between two control points. This point is specified by a value t

that represents a proportion of the distance from one control point to the next one, as shown in Figure 5. Given the control points P_0, P_1, P_2, P_3 and parameter t, $0 \le t \le 1.0$, we can compute the new point location q using the following equation:

$$q(t) = 0.5 * (1.0, t, t^2, t^3) * \begin{pmatrix} 0 & 2 & 0 & 0 \\ -1 & 0 & 1 & 0 \\ 2 & -5 & 4 & -1 \\ -1 & 3 & -3 & 1 \end{pmatrix} * \begin{pmatrix} P_0 \\ P_1 \\ P_2 \\ P_3 \end{pmatrix} \quad (3)$$

Figure 3 illustrates our method to interpolate a feature line passing over a hole using the detected crest line information. In our implementation, to interpolate a feature line passing over a hole, the pair of feature points on the hole boundary and their adjacent crest points make four initial control points for the Catmull-Rom interpolation equation (3). Since we attempt to interpolate a feature line that has the point density as consistent as possible to the original mesh, the value t that appears in equation (3) is approximated in our implementation as follow: Given a hole that has n edges on its boundary. Denote $length(e_i)$ the length of boundary edge e_i; denote a the average edge length of the hole boundary. We have

$$a = \frac{\sum_{i=1}^{n} length(e_i)}{n} \quad (4)$$

Denote d the Euclidean distance between the feature points F_1 and F_2 then we have

$$t = \frac{d}{a} \quad (5)$$

3.4.4 Hole Partitioning

Once all the feature lines at the holes are interpolated, a hole tracing procedure is executed. For each hole, the procedure starts with a vertex on the hole boundary, then it does the tracing along the connected boundary edges and its corresponding feature lines. If all identified points form a closed loop they make up a hole. By involving feature lines in the hole identification process at this step, the original complex holes are indeed subdivided into smaller, more planar and simpler sub-holes right at the feature line locations.

In (Jun, 2005), the author discusses the self-intersection problem when projecting a complex hole onto a plane. This means some edges on the hole boundary may overlap each other in the

projection plane. In our system, since the holes are split at the salient feature curves, the sub-holes obtained are already quite planar. In addition, by using of the tangent plane of the hole boundary as its projection plane our approach avoids efficiently the self-intersection of the hole boundary.

3.5 Hole Filling

After all the polygonal holes in the original mesh model are identified, for each hole its boundary edges are then projected onto a projection plane for further triangulation.

3.5.1 Projection Plane Calculation

For each hole or sub-hole identified in the input mesh, we need to calculate the plane to project its boundary onto. The requirement for such a plane is that the projection of the boundary edges of a polygonal hole on it is a bounded domain and it should limit the possibility of creating the problem of self-intersecting of the projected boundary as much as possible.

We use the method to calculate the projection plane that is based on the maximum area vector method. The direction of the plane is derived from the normalized sum of the normals of the boundary triangles. The illustration of a hole and the direction of its projection plane are shown in Figure 6. The formula for computing the normal N of the projection plane P for a hole is as follow:

$$N = \sum_{i=1}^{v} n_i \quad (6)$$

where v is the number of the boundary triangles of the hole, n_i is the normal of the ith boundary triangle of the hole.
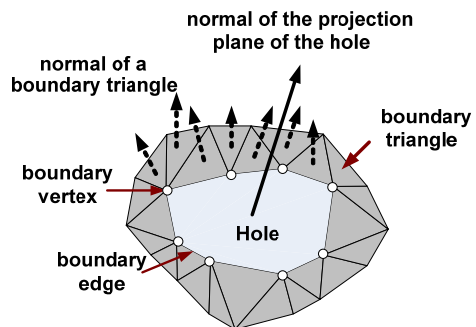

Figure 6: An example of a hole and the direction of its projection plane.

3.5.2 Filling Holes through Planar Triangulation

In our system, for each hole, once its boundary in the original mesh model are projected onto its corresponding projection plane, the projected boundary vertices are used as the input for the constrained Delaunay triangulation to get the patch mesh for the hole in 2D. The procedure of mapping back to 3D space of the patch mesh is done by applying the topological structure of the constructed 2D triangulation to the original 3D boundary.

4 RESULTS AND VALIDATION

The visualization system Hole3D was developed as the implementation to demonstrate our user-guided feature sensitive hole filling system presented in this paper. The visualization and user interface were implemented in MS Visual Studio 2005 Development Environment with Coin3D (a high-level 3D graphics toolkit for developing cross-platform real-time 3D visualization and visual simulation software), VTK (the Visualization Toolkit) and MFC (Microsoft® Foundation Classes). The programming language used is C++.
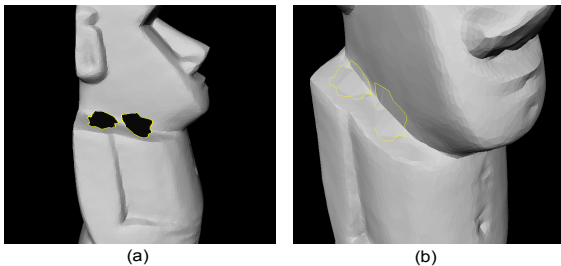

(a)　(b)

Figure 7: Applied our algorithm: (a) The input moai model with two holes and concave sharp edges; (b) Hole filling result obtained in our system with user intervention to pair the feature points.

We demonstrate how the proposed algorithm can be used to reconstruct hole regions. Basically, the test cases are processed in two mesh models, the moai model and the stripped fandisk model. Many possible cases of hole are created and filled by our system to verify its effectiveness.

Figure 7 shows the input moai model with two holes and concave sharp edges at the neck area. The sharp features are recovered properly using our method. The patches stitched to the hole areas are marked with the yellow boundary. Although we do not implement mesh refinement and fairing techniques in our system, the patch is adequate to complete the model in expected way. Figure 12 shows the result of filling a fandisk model with a concave corner hole (Figure 12(a)). The final mesh model after applying our feature sensitive hole filling algorithm are displayed in Figure 12(b)(c).

As shown in Figure 9, with the hole at the convex sharp edge, our system can achieve the proper results. Figure 9(b) shows the hole filling result obtained automatically by our system without a user correcting the detected crest lines. Better result can be obtained with user interaction to correct the detected crest lines before interpolating feature lines passing over the hole as shown in Figure 9(c).

We demonstrate the robustness of our system by comparing our experiment results with the results presented in papers (Chen et al., 2005; Zhao et al., 2006). As shown in Figure 10, there are three holes in fandisk mesh model, which has one, two and three ridges passed through them (Figure 10(a)). As presented in (Zhao et al., 2006), the method in (Liepa, 2003) can only close the holes (Figure 10(b)), the method in (Zhao et al., 2006) produces better result but the geometry at the corner hole is not recovered properly (Figure 10(c)). Figure 11 demonstrates the hole filling results for convex and concave corner holes obtained after applying the *sharpness dependent filter* hole filling method in (Chen et al., 2005).
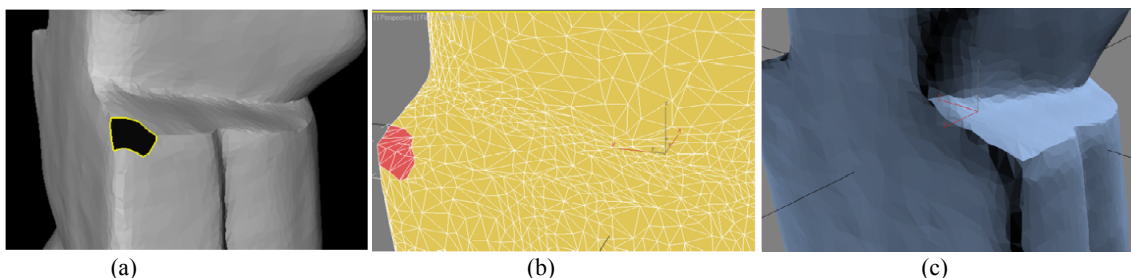

(a)　(b)　(c)

Figure 8: Applied our algorithm: (a) The input moai model with a convex corner hole; (b) Our final hole filling result with polygonal presentation, the hole patch is colored in red; (c) Flat shaded render of the final result.
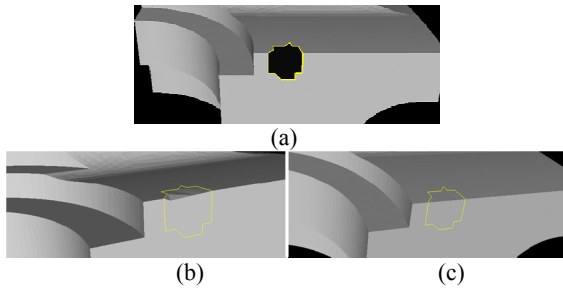
Figure 9: Applied our algorithm: (a) The input stripped fan disk model with a hole on the convex sharp edge; (b) Our hole filling result without the user intervention to correct the detected crest points at the hole area; (c) Our hole filling result where the detected crest points are corrected at the hole area.

To have a visual comparison with the aforementioned algorithms, as shown in Figure 13, we applied our hole filling method to the fandisk model with holes at the same locations as in the input mesh model in Figure 10 that reproduced from (Zhao et al., 2006). Indeed, the modified mesh model shows three typical kinds of holes that have sharp features need to be recovered: one hole with one feature line passing over, one hole with two feature lines passing over and one hole at the corner. The results of our hole filling technique are shown in Figure 13: the sharp edges are recovered aesthetically; the corner shape is reconstructed consistently with the original shape. Figure 13(b) shows the final hole filling result with the hole highlighted in green. Figure 13(c) shows the hole filling result obtained by our system, the patches are stitched to the input mesh as the hole areas to get the final mesh model. The sharp features at the concave corner hole in Figure 12 are recovered nicely using our method comparing to the result shown in Figure 11(b).
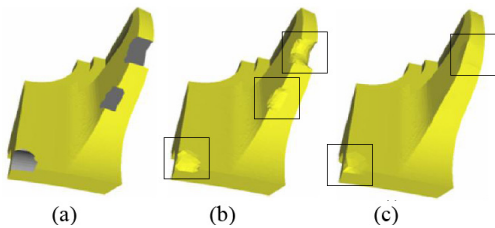

Figure 10: Applied the algorithms in (Liepa, 2003) and (Zhao et al., 2006): (a) The input mesh model with 3 holes; (b) The result obtained by using method in (Liepa, 2003); (c) The result obtained by using method in (Zhao et al., 2006) (reproduced from (Zhao et al., 2006)).
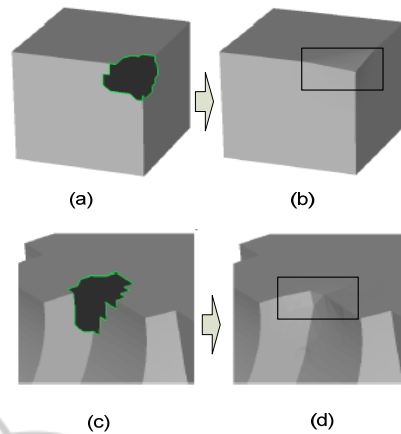

Figure 11: Applied the hole filling algorithm in (Chen et al., 2005) to the holes at the corners: (a) A original mesh model with a convex corner hole; (b) The result after filling the hole in the model in (a); (c) A original mesh model with a concave corner hole; (d) The result after filling the hole in the model in (c) (reproduced from (Chen et al., 2005)).

The experiments show that our method can produce excellent results for filling the holes at the corners. The mesh quality of the patches could be improved to make them more consistent with the original mesh quality by applying mesh refinement techniques.

5 DISCUSSION

Certainly, fully automated methods for hole filling have several advantages over a method that requires user intervention. However, from the point of view of the complexity of the hole, a fully automated method may not work correctly for holes with complex geometries. Our research aims to combine manual and automatic methods to improve current hole-filling methods, making this process more versatile, robust and effective.

Most of the feature sensitive hole-filling methods rely significantly on the normals of the vertices around the hole areas to decide whether or not there exist fine features. This makes those methods sensitive to the mesh quality, e.g. the point density, the shapes of triangles and the point distribution. In our algorithm, since the feature curves are interpolated from the salient information detected in the mesh model, user intervention allows to correct the detected crest line information. This enables the whole algorithm to produce the final results quite independently from the quality of the input mesh
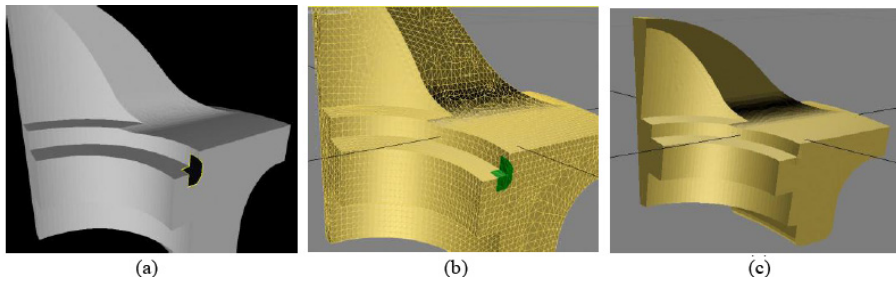
Figure 12: Our algorithm results: (a) The input stripped fandisk model with a concave corner hole; (b) Our final hole filling result with polygonal presentation, the hole patch is colored in green; (d) Flat shaded render of the final result model.
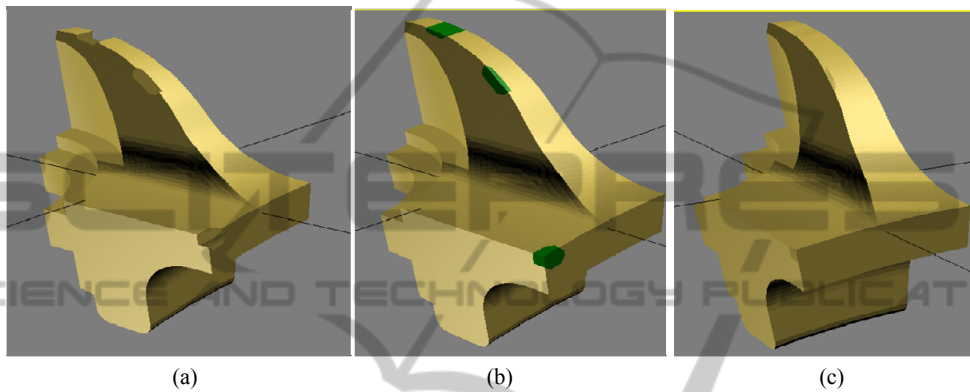

Figure 13: Applied our algorithm to a moai model with 3 types of holes: (a) The original mesh model with 3 kinds of holes; (b) The final result obtained by our system with the highlighted patches; (c) Flat shaded render of the final mesh result.

model.

The core idea of our algorithm using the salient information to recover the sharp feature is simple but effective. Among the existing techniques that have attempted to reconstruct fine features of the original mesh at the hole areas, our hole filling techniques is different since the fine features are taken as the first subjects to reconstruct, which eventually drive the feature-definite surface filling process. Our results show the effectiveness of our method in filling the hole and preserving aesthetically the sharp edges.

The accuracy of our method depends to a great extent on the accuracy of the crest line detection method. We expect that improvements in crest line detection will produce a higher quality results from a fully automatic procedure based on our approach. In our implementation, all of the salient and polygonal-based information of the input mesh model are extracted and stored in our designed data structures in the loading phase then further computation is limited to areas near holes. This makes the algorithm efficient to run on large models.

Our system improves the visual quality of the results with respect to previous approaches and provides real-time user interaction. On the other hand, it strongly relies on crest line detection, and therefore it is very sensitive to changes in this geometrical feature. Our system is able to recover efficiently the sharp features, especially when the feature curves or the profile of the sharp edges are close to the cubic splines. However, if the profile of the sharp edges in the input mesh is more complex than cubic splines, the results may not be necessarily accurate and may even be far from the real geometry.

Further mesh refinement and fairing methods may be used to improve the quality of the generated patch meshes. By doing this, the point density and triangle shape in the patch mesh will be consistent with the input mesh.

6 CONCLUSIONS

We have presented a novel technique for filling holes in 3D triangulated mesh models which is able to recover efficiently the sharp features of the original geometry, producing plausible results which are consistent with the geometry of the original mesh models. For each input mesh, our system identifies its hole and crest line information. Then it

uses this information to geometrically segment complex holes into simple approximately planar holes, called sub-holes. The patch meshes that are used to fill those sub-holes are generated by using planar triangulation algorithm for the point set at the hole boundaries. Then these patch meshes are mapped back to the 3D space and stitched to the original model at the hole areas to achieve the final result. The user is able to interact with our system through correcting the crest lines, adjusting the feature points defined by the crest lines and the hole boundaries, pairing the feature points or specifying the corner hole locations. The adjustment of the location of the crest lines by users results in modification in the shape of the patch mesh which is later stitched to the original model, as holes are filled using different geometric information. To validate our approach, we have tested our technique on different mesh models with many possible cases, and the results show that our methods effectively reconstruct the sharp features. Most approaches for hole filling in literature do not reconstruct these fine details due to the interpolation schemes used. We overcome this limitation by including additional information on the object shape in areas of high curvature and by limited user intervention.

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