



Filling Simple Holes of Triangular Mesh by using Enhanced Advancing Front Mesh (EAFM) method

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Abstract

Triangular meshes are extensively used to represent 3D models. Some surfaces cannot be digitised due to various reasons such as inadequacy of the scanner, and this generally occurs for glossy, hollow surfaces and dark-coloured surfaces. This cause triangular meshes to contain holes and it becomes difficult for numerous successive operations such as model prototyping, model rebuilding, and finite element analysis. Hence, it is necessary to fill these holes in a practical manner. In this paper, the Enhanced Advancing Front Mesh (EAFM) method was introduced for recovering missing simple holes in an object. The first step in this research was to extract the feature vertices around a hole on a 3D test data function. Then the Advancing Front Mesh (AFM) method was used to fill the holes. When conflicts occurred during construction of the triangle, the EAFM method was introduced to enhance the method. The results of the study show that the enhanced method is simple, efficient and suitable for dealing with simple hole problems.

Keywords: Triangular, Hollow, Holes, Mesh, Surfaces

1. Introduction

The reverse engineering model transforms the current physical or product model into a conceptual or engineering design prototype. With the development and application of computer technology; especially the theories and techniques of computer aided geometric design, reverse engineering has become an important means to obtain three dimensional models. Reverse engineering includes data acquisition, data processing and surface reconstruction, which have become key technologies in reverse engineering [1,2]. There are two model types of surface reconstruction, namely discrete grid and parametric surface. For the discrete grid model, the definition of triangular mesh is relatively simple. The ability description of the complex topology is strong, and related algorithms are more mature; thus, triangular mesh has become the more common model representation.

The triangular mesh can be considered as the most sought after output of surface reconstruction, as the primary issue of surface reconstruction is to depict the topology. The triangular mesh can successfully represent the topology in a simple and efficient manner. However, if more elaborate representation is required, more properties are needed. The triangular mesh data can be derived through different ways such as optical flow, 3 dimensional (3D) scanner, and computer-aided design software. Data points can be categorised as structured (dense) or unstructured (scattered) data points. The research focused on the data obtained from a 3D scanner; predominantly as scattered data points [3].

The scattered data points are the points that have no structure or order between their relative locations. There are three key sources of scattered data: computational values, measured values of physical quantities and experimental results [4]. However, due to the

limitations of the scanner, some surfaces cannot be digitised, usually for dark-coloured, glossy or hollow surfaces. Hence, the consequent triangular mesh models cannot be used directly by other applications, mostly due to their incomplete structure, that is, the presence of defects such as holes, gaps, self-intersecting triangles, etc. in the structure [5].

There are two key kinds of holes, classified as ring holes and simple holes. This research emphasises on a simple hole, i.e. a hole of any shape with just one boundary loop [6]. Simple holes have no feature vertices except those who share common boundary vertices with other holes [7]. Simple holes can be filled with planar triangulations which are executable when all boundary edges can be projected into a plane, without self-intersection [8,9].

Latest research on filling simple holes was discovered by many researcher [10-14]. Several researchers also have conducted a great deal of research on AFM. One of the study introduced AFM technique to fill simple and complex holes. Next, the normal vector of each triangle was used to solve a Poisson equation according to the normal vector and hole-boundary points, which then adjusted the position of the new points. However, when there were too many points, the Poisson equation solution would be too time-consuming [15]. In another research, triangulated holes using the improved AFM method and a series of initial patch meshes over the holes, were obtained and a weighted bi-umbrella operator was used to optimize the initial patch. The main constraint of this algorithm is that the filling result may lose some geometric details for holes that are too big [16].

A study by one researcher use Genetic Algorithm to obtain a valid and optimal initial triangulation then a customized Advancing Front meshing was performed over the approximated holes to generate an unstructured triangular mesh over the region [6]. A

research on filling holes in triangular mesh by the modified AFM, together by finding the normals combining with Laplacian coordinate, the boundary vertices was classified as concave-convexity feature, then optimal vertices are carefully computed and new triangles are created to fill the holes [17]. The technique was further use by [18] to filled the holes by a smooth patch and the fine-scaled details are added by fitting quadric surface from the boundary of the hole to its center. To enable the model to be water-tight, the hole need to be patch before taking these models into actual application. Motivated from the previous researcher, the AFM method need to be enhanced to be applicable for any types of holes.

2. Experimental Procedure

In this work, we adopt the advancing front mesh (AFM) technique to generate an initial patch mesh over the hole [16]. The method consists of the following six steps:

- Step 1 : Initialize the front using the boundary vertices of the hole.
 Step 2: Calculate the angle θ_i between two adjacent boundary edges (e_{i-1} and e_{i+1}) at each vertex v_i on the front.
 Step 3: Starting from the vertex v_i , new triangles was created according to three angle criteria. The angle criteria to create new triangle was defined by three points defined as points A, B and C as shown in Figure 1.

- a) If $\theta \leq 75^\circ$, the new triangle was created by connecting point A and C, thus $\triangle ABC$ is directly constructed.
 b) If $75^\circ < \theta < 135^\circ$, one new point (NP1) was created and it create two triangles.
 c) If $\theta \geq 135^\circ$, two new points NP1 and NP2 was inserted and it create three triangles.

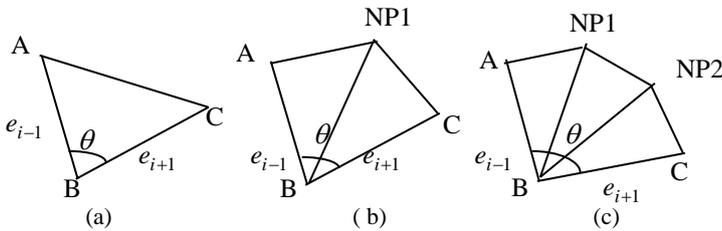


Fig. 1: Three rules of angle in AFM
 (a) $\theta \leq 75^\circ$ (b) $75^\circ < \theta < 135^\circ$ (c) $\theta \geq 135^\circ$

- Step 4: Compute the distance between each newly created vertex and every related boundary vertex. If the distance between them is less than the given threshold, they are merged as in (1)

$$Threshold = \frac{1}{4} \times (\overline{NP1B} \text{ or } \overline{NP2B}) \quad (1)$$

($\overline{NP1B}$ or $\overline{NP2B}$ is the distance between new vertex and related boundary vertex).

Step 5: Update the front.

Step 6: Repeat step 1 through step 4 until the whole region of holes has been patched by new triangle.

The recommended hole filling algorithm has been deployed with MATLAB2016. Two simple holes problems have been used to gauge the robustness, precision and accuracy of the approach. The holes were triangulated using the original AFM method and two EAFM methods were introduced for the problem. Table 1 shows

36 data points that were used as test data for the two simple holes problem in this research [19].

Table 1: 36 Data Points

No	Coordinates		No	Coordinates	
	x	y		x	y
1	0.00	0.00	19	0.80	0.85
2	0.50	0.00	20	0.85	0.65
3	1.00	0.00	21	1.00	0.50
4	0.15	0.15	22	1.00	1.00
5	0.70	0.15	23	0.50	1.00
6	0.50	0.20	24	0.10	0.85
7	0.25	0.30	25	0.00	1.00
8	0.40	0.30	26	0.25	0.00
9	0.75	0.40	27	0.75	0.00
10	0.85	0.25	28	0.25	1.00
11	0.55	0.45	29	0.00	0.25
12	0.00	0.50	30	0.75	1.00
13	0.20	0.45	31	0.00	0.75
14	0.45	0.55	32	1.00	0.25
15	0.60	0.65	33	1.00	0.75
16	0.25	0.70	34	0.19	0.19
17	0.40	0.80	35	0.32	0.75
18	0.65	0.75	36	0.79	0.46

However, in some cases, there exist a condition which do not satisfy all normal cases of AFM. Figure 2 illustrate two simple holes problem that do not satisfy the threshold case in the normal AFM algorithm. The problem occurs when the newly constructed point does not connect to any nearest active node, and during construction of the triangle, no node lies within the threshold value that is appropriate to replace the new point.

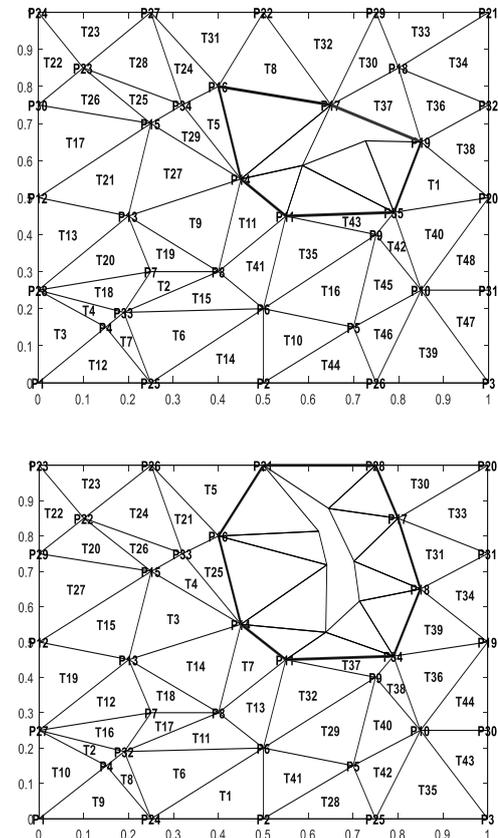


Fig. 2: Simple holes problem 1 and 2

3. Experimental Result

3.1. Normal Cases of AFM method

Case 1

The three points of the triangle was chosen as the initial front and cosines rules was used to find the θ . A new node was selected to form the new triangle element listed in the AFM; according to three different angle criteria. The first triangle created was $\theta \geq 135^\circ$, second $\theta \leq 75^\circ$ followed by third triangle $75^\circ < \theta < 135^\circ$ as shown in Figure 3).

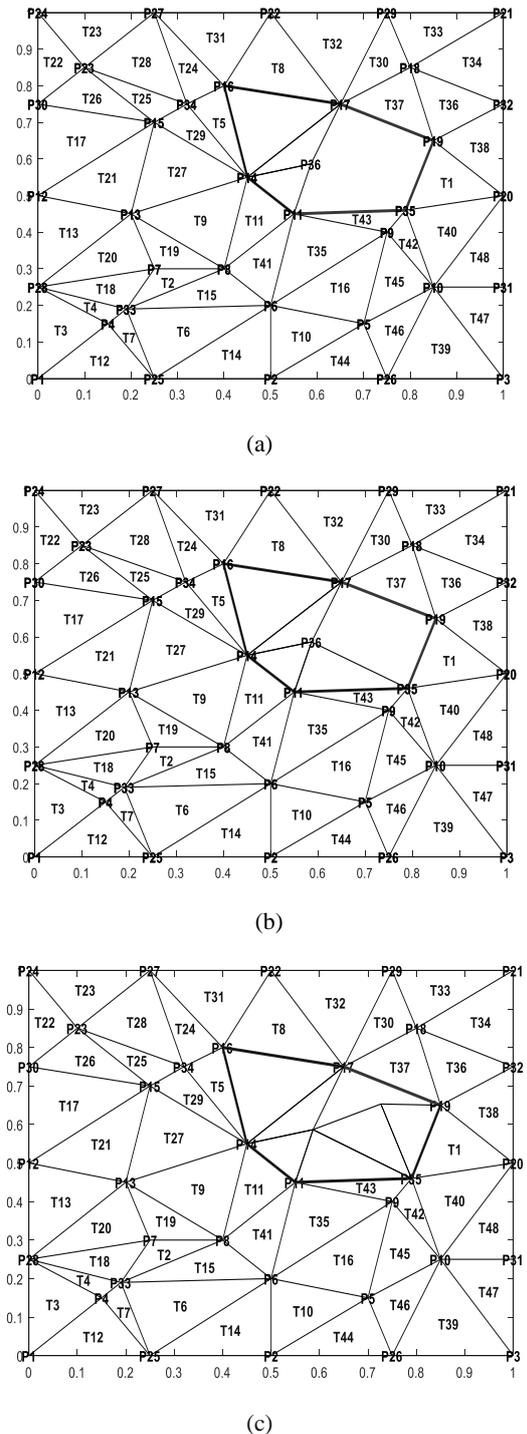


Fig. 3: Triangular element according to angle criteria
 (a) $\theta \geq 135^\circ$ (b) $\theta \leq 75^\circ$ (c) $75^\circ < \theta < 135^\circ$

Case 2

If the distance between new point (NP) and the active nodes is less than a given threshold as in (1), the point is connected and defined as a new node. For example, according to Figure 4, the angle was calculated and defined as $\theta \geq 135^\circ$, two new points was obtained. The closest node to the first new point was point P17 and it was less than the threshold value. Therefore, P17 was selected as the first new point and P36 was left unchanged as the second new point since there is no nearest point.

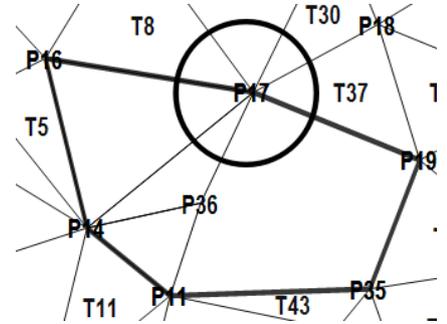


Fig. 4: Nearest Point connected

3.2. EAFM method

Case 3

There are some cases where the distance between the new point and active nodes is greater than the given threshold. An empirical formula[20] was proposed as a reference to find a new point. A circle with centre at the NP and radius r given by the empirical formula as in (2) is $r = 0.8 \times \delta'$ where:

$$\delta' = \begin{cases} 0.55 \times l & \text{if } \delta < 0.55 \times l \\ l & \text{if } 0.55 \times l \leq \delta \leq 2.0 \times l \\ 2.0 \times l & \text{if } \delta > 2.0 \times l \end{cases}$$

(2) l is the shortest side in the front and δ is size parameter of the triangular grid cell in Figure 5.

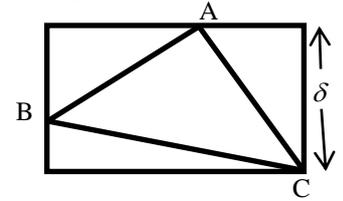


Fig. 5: Size parameter of triangular grid cell

In this paper, the value of the length l use was according to the distance of new vertex to point B. It was difference from the original formula since the original formula was used for AFM that considered two point only with shortest sides.

Besides that, the difference value of coefficient for radius was used in order to search for the best coefficient. The coefficient use was 0.8, 0.7, 0.6, 0.5 and 0.4. Among all the active nodes the coefficient 0.6 was chosen as the best radius. The active nodes lies within this circle of radius was listed in terms of minimum distance.

In simple hole problem 1 and 2, the minimum closest node was selected as the new nodes among other active nodes (as shown in Figures 6 and 7). In Figure 6a, the third triangle was created but there were no active nodes within the normal threshold. Therefore, the new algorithm searches for the nearest point, where P17 is considered as the new nodes (Figure 6b). The second simple holes problems implement the same procedure and select the nearest point to close the triangular element created. The point P37 was chosen, since it was the nearest compared to the other active nodes (Figure 7b).

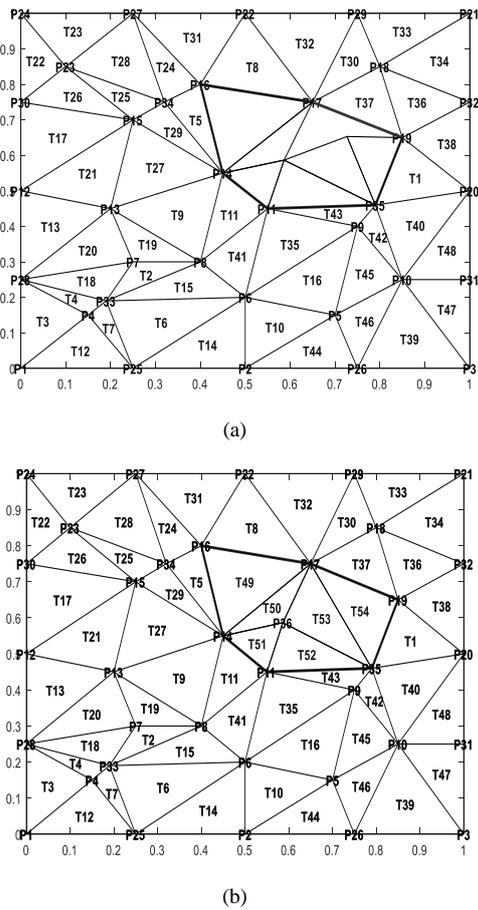


Fig. 6: Simple holes problem 1 result
a) before b)after

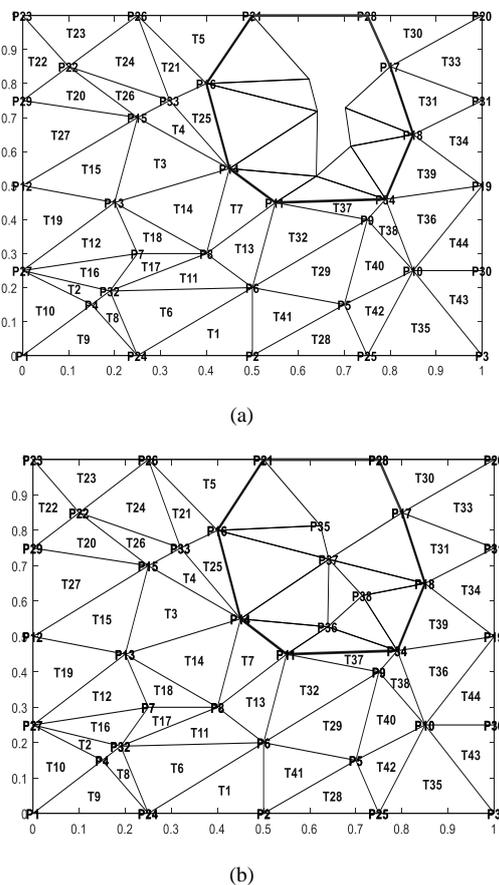


Fig. 7: Simple holes problem 2 result
a) before b)after

Case 4

There is also a condition where another triangular element is automatically constructed since the three edges are connected to themselves. As shown in Figure 8, the triangle T58 was automatically constructed when points P36, P37 and P38 were formed. The three edges were connected to themselves and became the sides of the new triangular element. This was the same algorithms that use as the extension of cases in EAFT-1[21].

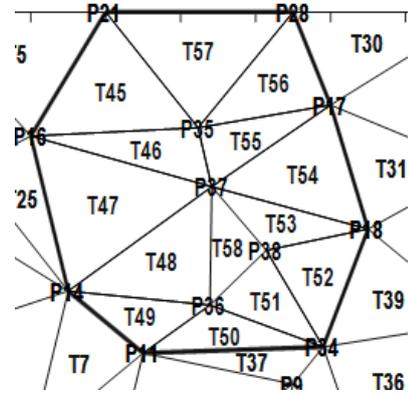


Fig. 8: Three edges connected

3.3. Error Evaluation

Table 2 lists the vertices and triangle number before and after filling patch for two simple holes problems. The number of vertices and triangles was unchanged for the first simple holes problem. The number of vertices and triangle increase when apply on bigger holes. If more number of points generated then it can represent the surface efficiently. Thus, the algorithm worked well in connecting the filling patch when the holes needing to be filled became greater.

Table 3 shows the different value of radius with different coefficient used for the first and second holes. Among the radius calculated, radius = 0.6 was chosen to be the best radius where only few points need to be calculated to find the nearest active point within the circumscribing circles.

Hence by choosing good coefficient, the process of searching for suitable active point become easier and calculation for nearest point become faster compared to bigger radius.

Table 2: Vertices and triangle number before and after filling patch

Simple holes	Vertices number of filling patch		Triangle number on filling patch	
	before	after	before	after
First	7	7	6	6
Second	10	12	10	14

Table 3: Radius with different coefficient

Simple holes	Radius				
	0.8	0.7	0.6	0.5	0.4
First	0.1755	0.1536	0.1316	0.1097	0.0878
Second	0.1385	0.1212	0.1039	0.0866	0.0692

4. Conclusion

The 36 test data was used to create a simple holes and represent in two simple holes problems in order to test the accuracy of the EAFM method. Two new AFM methods were introduced to the original AFM method known as EAFM1. EAFM1 introduced new method to find nearest point when the distance between the new point and active nodes is greater than the given threshold. The new length and best radius coefficient was chosen and able to reduce the computation time to search for nearest active nodes. As the conclusion, the methods able to enhanced the process of filling

holes in simple hole problems which will be used for application on real3D objects later.

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