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Improvements on IPD Algorithm for Triangular Mesh Reconstruction from 3D Point Cloud

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***Abstract* — A new algorithm is proposed for triangular mesh reconstruction from 3D scattered points based on the existing intrinsic property driven (IPD) method. The improvements include a new approach to determine the seed triangle, a new approach to define the influence region for active edge, and a new approach to select the best active point. The new triangle is also tested with the constraint of geometric integrity. Our algorithm has been tested on some unorganized 3D point clouds. From the experimental results it can be found that our approach has the ability to generate more accurate details in the recovered surfaces.**

Keywords - Surface reconstruction; Triangle mesh; Region growing; Point cloud

I. INTRODUCTION

Surface reconstruction has many applications in the fields of visualization in scientific computing, computer graphics, reverse engineering, medical imaging, virtual reality, etc. Currently, there are four typical approaches for surface reconstruction from the scattered 3D point cloud: implicit surface, surface deformation, space subdivision, region growing. The interpolation method is used in both implicit surface and surface deformation, and has limitations in the application of CAD. Delaunay triangulation, Voronoi diagram and α-shape are usually used in space subdivision approach [1-3], but these techniques need the intermediate representation and thus have high computational cost. Region growing approach starts with a seed unit, considers a new point and joins it to the existing region boundary, and then continues until all points have been considered. Region growing approach is computational more efficient because a 2-manifold structure is recovered incrementally and no intermediate representation is necessary. The method for triangular mesh recovery proposed in our paper also belongs to region growing approach.

The key problem of region growing approach is how to select a point to form a new triangle with an active edge. In the BPA algorithm [4], a ball with user specified radius pivots around an active edge until it touches another point in the point cloud, and the point being touched is selected. Huang and Menq [5] projected the k nearest points of each endpoint of an active edge respectively onto the plane defined by the triangle adjacent to the active edge. A point is chosen among the k points based on the criterion of minimal length to form a triangle with the active edge. Petitjean and Boyer presented another method based on regular interpolation [6]. Starting with a seed triangle, the algorithm of Lin et al. [7] grows a partially reconstructed triangle mesh by selecting a new point based on an intrinsic property of the scattered point cloud, namely, the sampling uniformity degree. The reconstructed triangular mesh is essentially an approximate minimum-weight triangulation to the point cloud constrained to be on a 2D manifold.

Our paper presents improvements on existing intrinsic property driven (IPD) algorithm of [7]. The rest of our paper is organized as follows: related definitions and point cloud preprocessing are proposed in section 2, improvements on method [7] are described in section 3, experimental results are presented in section 4, and a brief conclusion is given in section 5.

II. DEFINITIONS AND DATA PREPROCESSING

A. *Related Definitions*

The following definitions are applied in our method for triangular mesh reconstruction:
(1) Active edge: each newly recovered edge without being processed;
(2) Influence region: a region to search for a new point to form a new triangle with an active edge, which may or may not contain any new point;
(3) Inner edge: the edge with two adjacent faces;
(4) Fixed point: a point whose incident edges are all inner edges;
(5) Boundary edge: one edge whose influence region contains no point except for fixed points, i.e. the edge has only one face adjacent to it;
(6) Active point: the point with no edge incident to it, or there is an active edge incident to it.

B. *Preprocessing of Point Cloud*

In the method of region growing, searching for the best active point is the most time consuming step. For the unorganized 3D points without any topological information, time complexity of global search from the entire point cloud is $O(N^2)$. The best active point lies in the neighboring region of the related active edge, i.e. the local area of its two vertices. Therefore, to avoid the global search unnecessary for the best active point, preprocessing techniques are applied to determine the local region of each scattered point, i.e. the k nearest neighbors.

The usually utilized approaches for the local region's determination include bounding box, octree, kd tree and clustering approach [8-10]. The bounding box method is

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adopted and a 3D cubic cell based algorithm is implemented to search for the k nearest neighbors, which is the local search region for the best active point. The value of k directly affects the efficiency and precision, if k is a small value, the local region is small and there will be genus; if k is a large value, the local region is large and there will be improperly intersected meshes especially in the 3D model with sharp angles. Based on our experiments, k is assigned with the value from 20 to 50.

III. Improvements on IPD Algorithm

A. Determination of The Seed Triangle

For region growing approach, the better quality of the seed triangle, the more helpful for the triangular mesh reconstruction. To select an ideal seed triangle, we use the following method:

Step 1. Search for the point P whose z-coordinate is the maximum in the point cloud;

Step 2. Search for point Q that is nearest to P and form a line segment L between them;

Step 3. Search for the point R from the k nearest neighbors of point P and point Q to make the energy function $E_0 = (d_{PQ}^2 + d_{PR}^2 + d_{QR}^2) \bullet (d_{PR}^2 + d_{QR}^2 - d_{PQ}^2) / A_{P,Q,R}$, where d_{PQ} , d_{PR} and d_{QR} are lengths of segments PQ, PR and QR while $A_{P,Q,R}$ is the area of triangle PQR, be minimum, therefore point R can satisfy with two principles of "maximum angle" and "minimum length", while in Reference [7] only the principle of "minimum length" with $d_{PR} + d_{QR}$ is considered;

Step 4. Take triangle PQR as the seed triangle.

Then the normal vector of the seed triangle is adjusted to be outward. If the inner product of the normal vector of the seed triangle and the vector (0, 0, 1) is positive, it points outward; otherwise direction of the normal vector is reversed. Once the outward normal vector of the seed triangle is known, we can similarly determine the direction of the normal vector of each newly generated triangle and adjust it to be outward too.

B. Definition of The Influence Region for Active Edge

To keep the topological consistency, the best active point for the active edge should be in the front of the existing triangle and should satisfy with the principles of "maximum angle" and "minimum length" at the same time. Therefore, not all the k nearest neighbors meets such geometrical constraints, and we define the influence region to filter the nearest neighbors.

Reference [7] defined the sampling uniformity degree at a point as the ratio of the lengths of the longest edge and shortest edge incident to the point, and used it to define the close influence region for one active edge. The method has the following disadvantages:

(1) If the sampling uniformity degrees for two vertices of one active edge are small, the influence region for the active edge is small, thus it will be taken as the boundary edge if the best active point cannot be found and a small hole will be generated;

(2) With the determination of new neighbor edges, the sampling uniformity degrees for the vertices of a boundary edge may increase, and the new found best active point may improperly lie in the opposite side of the 3D model with sharp angles;

(3) The sampling uniformity degrees for one active edge can vary with the adding of new neighbor edges, but in IPD algorithm [7] the influence region for the active edge is only decided by the sampling uniformity degree at one certain time, thus a previously assigned boundary edge may become one inner edge with new sampling uniformity degrees;

(4) For the sliver triangle, the sampling uniformity degrees for its vertices are very large and thus will affect the reconstructed results of the triangular mesh.

Different with method [7], we use the open influence region defined by three faces F1, F2 and F3, as shown in Figure 1. Angle θ is used to control the open influence region, and each face for the region can be represented by one point in the face and the normal vector of the face, as

$$F_1(P_i, N_1 = norm(N_{ij} \times P_iP_j)) \quad (1)$$

$$F_2(P_i, N_2 = norm((N_1 + tg\theta \bullet norm(P_jP_i)) \times N_{ij}) \quad (2)$$

$$F_3(P_j, N_3 = norm(N_{ij} \times (N_1 + tg\theta \bullet norm(P_iP_j))) \quad (3)$$

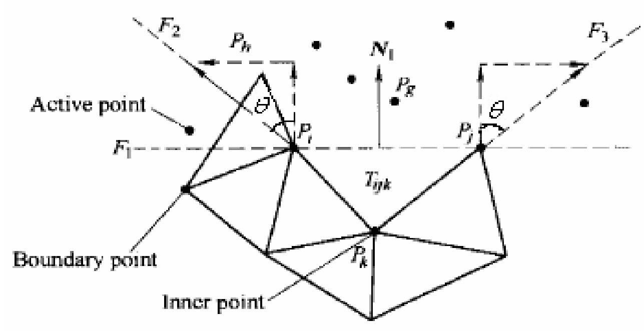

Figure 1. The open influence region

To make sure the geometrical completeness of the reconstructed triangle mesh, the intersection between the newly generated triangle and the existing triangles is null or is the existing active edge or boundary edge. Therefore, among the edges incident to point *Pi* (*Pj*), if there are other edges lie in the same side of face F2 (F3) with the edge *PiPj*, the face F2 (F3) should be renewed. As shown in Figure 1, face F2 is changed as

$$F_2^{'}(P_i, N_2 = norm(P_iP_h \times N_{ij})) \quad (4)$$

C. Selection of The Best Active Point

There are some active points lying in the influence region of the active edge, one of them is selected and used to construct a new triangle with the active edge in each step of the region growing method. The often used criterions to select the best active point include criterion of minimal area [11] and criterion of minimal length [12]. The reconstructed triangular mesh using minimal length criterion has better visual result, but the topological difference between the reconstructed surface and the original point cloud is usually relative large. Thus, IPD algorithm [7] applies the weighted energy function

$$E = k_{i,j} \| P_i - P_j \|^2 + k_{i,g} \| P_i - P_g \|^2 + k_{j,g} \| P_j - P_g \|^2 \quad (5)$$

$$k_{i,j} = (L_{i,k}^2 + L_{j,k}^2 - L_{i,j}^2)/A_{i,j,k} + (L_{i,g}^2 + L_{j,g}^2 - L_{i,j}^2)/A_{i,j,g} \quad (6)$$

$$k_{i,g} = k_{j,m} = 2 \times (L_{i,g}^2 + L_{j,g}^2 - L_{i,j}^2)/A_{i,j,g} \quad (7)$$

where P_i, P_j, P_k, P_g are 3D coordinates of the related points, $L_{i,j}$, $L_{i,k}$, $L_{j,k}$, $L_{i,g}$, $L_{j,g}$ are lengths of edges PiPj, PiPk, PjPk, PiPg, PjPg, $A_{i,j,k}$, $A_{i,j,g}$ are areas of triangles PiPjPk and PiPjPg.

However, based on Reference [13], precondition of energy function (5) is that there are two new edges for the new generated triangle. But in the generation of triangles, there may be only one new edge for the new triangle. Considering the problem, we propose a new energy function to select the active point

$$\begin{aligned} E' = (\| P_i - P_j \|^2 + \| P_i - P_g \|^2 + \| P_j - P_g \|^2) \\ \bullet (L_{i,g}^2 + L_{j,g}^2 - L_{i,j}^2)/A_{i,j,g} \end{aligned} \quad (8)$$

D. Constraint of Geometric Integrity

For one active edge, the active points in its influence region are checked one by one. The active point having the minimum value of Equation (8) is tested with the constraint of geometric integrity. If the constraint is satisfied, the active point is chosen to generate a new triangle with the active edge; otherwise the other active points are checked. If none of the active points is satisfied with the geometric integrity, the active edge is taken as one boundary edge. It is very critical to maintain the geometric integrity for triangular mesh reconstruction. As the active point has different kinds of situations, corresponding treatments have to be proposed for them.

IV. Experimental Results

Our algorithm has been tested with experiments that are performed on the PC with 1.61GHz AMD Sempron(th) 2800+, 448MB RAM, Windows XP and Microsoft Visual Stdio .Net 2005. As shown in Figure 2, six sets of point cloud are used as experimental data, and the numbers of points in them are 766, 10042, 11702, 32562, 39231 and 146218 respectively. In our experiments, the value of k is assigned with 30, and angle θ is assigned with 45 degrees. The recovered triangular meshes of the six models are illustrated in Figure 3. From the experimental results, it can be found that our algorithm can generate reconstructed surface with good quality.

Our approach is also compared with IPD algorithm [7] on the model of Bunny with 35944 points. As shown in Figure 4, the first column are point cloud of bunny and points of its bottom, the second column are recovered surfaces from IPD algorithm [7], the third column are recovered surfaces from our method. It can be found that our method has the ability to generate better details in local surface, e.g. avoid the happening of sliver triangles in the two holes of bottom surface. Therefore our approach can produce triangular mesh from the scattered 3D points while preserving very good topological coherence with the point cloud.

V. Conclusion

Based on the existing algorithm [7], three improvements are proposed in our paper including new approaches to determine the seed triangle, define the influence region for the active edge, and then select the best active point. The presented new method can recover triangular mesh from 3D scattered point cloud with good quality. Compared with IPD algorithm [7], our approach has the ability to reconstruct the surface preserving more accurate topological coherence with the point cloud.

In the future, more kinds of unorganized 3D point clouds will be utilized in our experiments to test the accuracy and efficiency of the proposed new IPD algorithm for triangular mesh reconstruction.

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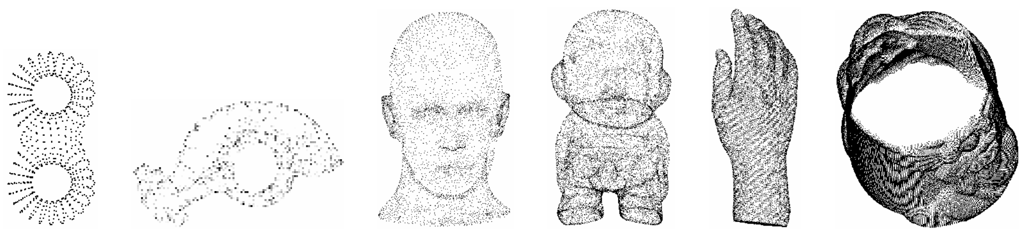

Figure 2. Six unorganized 3D point clouds

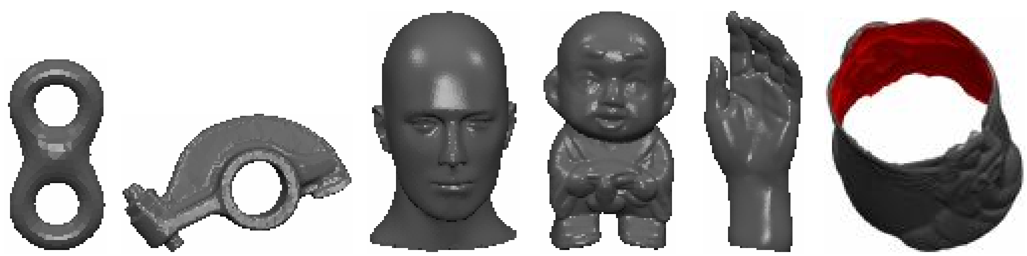

Figure 3. The reconstructed triangular meshes

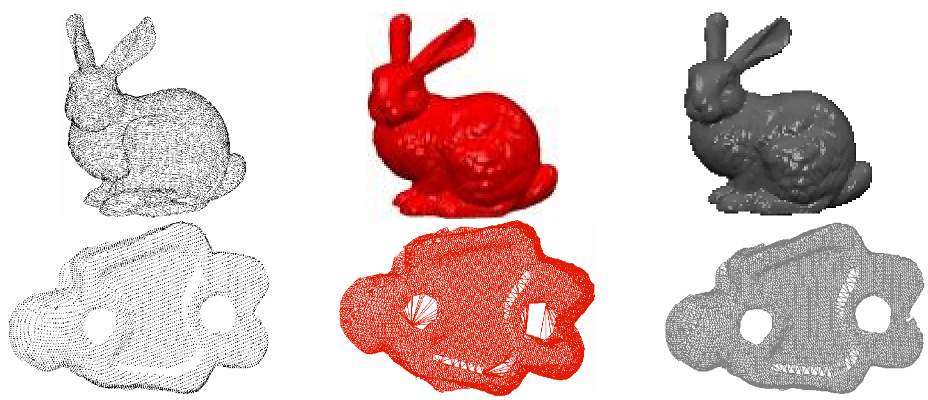

Figure 4. Comparison between IPD algorithm [7] and our method