3D Point Cloud Surface Reconstruction Based on Divide-and-Conquer Method in Laser Scanner

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ABSTRACT As to the problem of surface reconstruction in 3D laser scanner, we propose a divide-and-conquer based method, and realize the continuing growth of the reconstructed surface through comprehensive analysis of the correlations of scanning line point cloud data. First of all, filter the scanning line point cloud data, then confirm the relationship between the newly-insert point and the generated surface by using the local search algorithm based on adaptive point cloud segmentation, and finally, classify the newly-inserted points as sparse points, density points, growth points and flyback points by using the given maximum and minimum distance thresholds, and then the specific surface reconstruction is performed according to the point's classification. The experimental results show that the local search algorithm greatly reduces the calculation of the insert location of the point cloud compared with the global traversal search algorithm; the proposed method can process the flyback points, enhancing the repairability and the expandability of the reconstructed 3D surface compared with the traditional method. Furthermore, the quality of the reconstructed 3D surface, the generating speed and the occupation of storage space can all be controlled by adjusting the maximum and minimum distance thresholds according to actual demand.

1. INTRODUCTION
Point cloud is the only data that describes the surface features of the object in 3D scanning technology\cite{1-3}. The degree of analysis and cognition of point cloud and the processing and modeling ability of data structure \cite{4-5} directly determine whether the 3D scanning technology can truly restore the shape attributes of the object. At present, there are mainly three kinds of surface reconstruction methods: surface subdivision method based on triangular mesh \cite{6-7}, 3D surface fitting reconstruction method \cite{8}, and surface reconstruction algorithm based on regional expansion \cite{9-10}. As to the first method as described above, in which we have to carry on delaunay triangulation to point cloud data, large computational complexity and noise, and low efficiency are always accompanied in the application process, because information fusion between 2D scattered points and 3D point cloud is difficult to achieve. 3D surface generated by the second method does not pass each scattered point, and there are inevitable errors between the reconstruction result and the real object, since the 3D surface generated by this method does not pass through every scattered point. Difficulty of the third method is how to determine the initial triangle and the scattered points for surface extension.
Meanwhile, the above methods deal with the whole process of all the obtained point cloud of the measured objects. Even if one point is added to the point cloud data, the whole surface needs to be recalculated. Obviously, this method is not conducive to the synchronization of point cloud acquisition and surface reconstruction, and it also restricts the continuous utilization of the reconstructed surface.

To solve the above problem, we propose a surface reconstruction method based on point cloud divide-and-conquer for 3D laser scanning by using the scanning line point cloud data with timing information. In this method, instead of obtaining all the scattered points before generating surface, we process the point cloud data line by line and point by point, according to the access order of scanning line and the spatial location of scattered point in the scanning line. During the processing, the newly inserted points are divided into four cases: over sparse point, over density point, growth point and flyback point, according to the relative position relationship between the new inserted point and the generated surface. And then we adopt different surface generation algorithms to process the newly inserted points and obtain the final 3D surface by using the scattered point distribution characteristics of each case.

2. SURFACE RECONSTRUCTION METHOD BASED ON 3D POINT CLOUD DIVIDE-AND-CONQUER

Flow chart of the proposed method in this paper is as shown in Figure 1. First of all, obtain a set of scan lines using the scanning equipment, and pretreat the point cloud data through average filtering and point cloud downsizing. The median filter can remove the system error introduced by the scanning process, and the point cloud downsizing can reduce the point cloud data redundancy. Then determine whether the set of point clouds is on the first scan line: if the result is true, constitute the initial surface by connecting directly the scattered points end-to-end according to the relationship between the location of the storage; else position the scattered point with the local search algorithm based on adaptive point cloud segmentation proposed in this paper, then the new inserted points are divided and conquered according to the relative position relationship between the newly inserted points and the generated surface.

2.1 Data Pretreatment

We use the neighborhood average method to perform mean-filtering to scanning line point cloud data in this paper, and the width of one-dimensional sliding window is 21 points. We deal the undulating areas of the surface of the object with streamline curvature and the relatively flat areas with uniform sampling. The vector angle formed by the point to filter and its two scattered points before and after as the curvature. If the curvature of the point to filter is less than the threshold, which indicates that the point is located in the dramatic changing area of the object, the point is reserved, else the point is located in a relatively flat area and uniform sampling should be carried out. In uniform sampling, if the distance from the current point to the previous point is greater than the maximum distance threshold, the point will be reserved, otherwise, the point is deleted.
2.2 Position the Inserted Point

We should make sure the location relationship between every scattered point and surface before increase the surface, which means that we should find the point in the surface which is closest to the newly inserted point. A local search algorithm based on adaptive point cloud segmentation is proposed according to the changing characteristics of the point cloud region. In the algorithm, all scattered points are firstly projected onto the X-O-Y plane, the projection region of the first scanning line point cloud data are segmented at equal intervals (as shown in figure 2(a)). Then, each newly inserted point of the next set of scanning line will be processed continuely (as shown in figure 2 (b)), if the projection position of the newly inserted point is out of the range of the original segmentation interval (the three points on the left side of the y axis and points in the interval parts numbered 16, 17 and 18 as shown in figure 2 (b)), is to increase the number of segmentation intervals and renumber them.

So far, we have assigned all the input point cloud data into multiple equally spaced segmentation intervals by the adaptive point cloud segmentation algorithm. When we need the proximal point of some point, only the segmentation interval in which the point is and the proximal segmentation intervals are searched. As the density of point cloud data obtained by the laser scanning system is relatively homogeneous, and the number of scattered points is basically the same, therefore, the amount of computation does not increase with the increase of the total number of scattered points in the search process.

Figure 1. Flow chart of the proposed method.

Figure 2. Schematic of the adaptive point cloud segmentation algorithm.
2.3 Divide-and-Conquer Process of Scattered Point

2.3.1 Processing of Density Points
As to the density point, we delete the point directly in this paper. Then, the previous point of the same scanning line with this point will become the end point of the scanning line if the newly inserted point is not the first point of the scanning line. The end point processing module is added in this paper to ensure the smoothness of the edge of 3D surface. When the newly inserted point, timely the third point on the k-th scanning line, is judged as the density point, as shown in figure 3 (a), we will delete the point (as shown in figure 3 (b)), and deal with the second point on the k-th scanning line as the end point, which should be used to form the triangle mesh as possible with the points those satisfy the conditions for forming a triangle in the maximum distance threshold scope, as shown in figure 3 (c).

![Figure 3. Flow chart of the density point processing.](image)

To ensure the local flatness of 3D surface in the optimization of the spatial triangle mesh, the area of the triangles that constitutes 3D surface should be small (the side of the triangle is usually less than 1 mm), then such small area is relatively flat even in the undulating 3D surface. For this reason, we put forward a triangle mesh optimization criterion of the maximum dihedral angle. For the optimization of two adjacent triangles $\triangle ABC$ and $\triangle BCD$, if dihedral angle $A\cdot BC\cdot AD\cdot C$ is greater than the dihedral angle $B\cdot AD\cdot C$, then the two triangles will be judged for optimal, without the need of optimization; Otherwise, remove the common edge BC of $\triangle ABC$ and $\triangle BCD$, and join points A and D, so that $\triangle ABC$ and $\triangle BCD$ are optimized to $\triangle ABD$ and $\triangle ACD$. During the generation of 3D surface, triangle optimization based on the dihedral angle maximization criterion is carried out after the grid structure of each scattered point is changed.

2.3.2 Processing of Over Sparse Points
If the newly inserted point is judged as the over sparse point, which indicates that there is no proper matching point near that point to form a triangle. At this point, determine whether that point is the first point on the scanning line, if the result is true, then we save the point directly, otherwise calculate the distance between that point and the front point of the same scanning line. If the distance is less than the maximum distance threshold, then connect the two points; if the distance is greater than the maximum distance threshold, then save that point and deal the front point of the same scanning line with the end-point processing and optimization described in section 2.3.1.

2.3.3 Processing of Growth Points
Flow diagram of the growth point, which suggests that point will be used to form the triangular mesh to achieve the growth of 3D surface, is shown in figure 4, and all kinds of situation in the process is as shown in figure 5.
Figure 4. Process flow chart of growth point.

Points A and B in Figure 5 denote respectively the growth point and its adjacent point, point C is the previous point on the same scanning line as point A, points D and E are the edge points of 3D surface, which are in turn linked to point C, and the dotted lines in the figure 5 need to be connected. During the processing procedure (as shown in figure 4), if point A is the first point on a scanning line, then connect point A and point B (as shown in figure 5 (a)), otherwise, continue to judge whether C is an over sparse point. If the point C is an over sparse point and the distance between point A and point C is less than the maximum distance threshold, then connect the lines AB and AC (as shown in figure 5 (b)). If point C is an over sparse point and the distance between point A to point C is greater than the maximum distance threshold, then connect point A and point B (as shown in figure 5 (c)). For the case when point C is not an over sparse point, if the distance between point A and point C is greater than the maximum distance threshold, then point A and point B are connected and point C is processed and optimized as the end point (as shown in figure 5(d)). If the distance between point A and point C is less than the maximum distance threshold, triangles are generated under the criterion of the dihedral angle maximization. First of all, as shown in figure 5 (e), find points D and E which constitute a triangle, then compare the dihedral angles A-CE-D and C-AD-E, if the dihedral angle A-CE-D is larger, then connect points C and E, otherwise, connect lines AC and AD. If we failed to find point E in the process of generating triangles, then directly connect points A and D (as shown in figure 5 (f)). Cycling treatment in accordance with the above process until at least one line connects a growth point with 3D surface.

Figure 5. Process schematic map of growth point.
2.3.4 Processing of Fly-back Points
We adopt the iteration method to process the flyback points, as shown in figure 6 (a), point A, which is a flyback point, is projected in No. 0 triangle of the generated triangles. In the iteration process, we delete and reconstruct triangles with the No. 0 triangle as the center in accordance with the adjacency relations. In the first iteration, optimize respectively the space quadrilaterals constituted of point A and the three vertices of the triangles No. 1, 2 and 3 using the dihedral maximization criterion, and the result of the first iteration is as shown in figure 6 (b), from which we can see that triangles numbered 2 and 3 need to be optimized, and a new triangle is generated. In the second iteration, continue to optimize the triangles adjacent to the newly generated triangle, the result is shown in figure 6(c), and only No. 9 triangle needs to be processed, and the iteration ends when all triangles adjacent to the newly generated triangle in the previous iteration do not need to be processed.

![Image](image1.png)

**Figure 6.** Process flow chart of flyback point.

3. EXPERIMENTAL RESULTS
We use 3D laser scanner to obtain the point cloud data of a real bump surface shown in figure 7 in the experiment. During the scanning process, we first scan the object from top to bottom, and then from bottom to top, realizing sequential scanning and reverse scanning, and 155 scanning lines are contained as the point cloud data. The curvature threshold and distance threshold in the simplification process are respectively 20° and 0.5 mm. Pretreatment can not only delete the redundant points of the original data but also make the scanning lines more smooth. The reduced ratio of the point cloud data is 56.12% in the experiment.

Relationship between the interval size and the surface generation time in the local search algorithm based on adaptive point cloud segmentation is shown in figure 8, from which we can see that the number of scattered points projected in each interval segmentation gradually increased as the integral interval increases, leading to the increase of the calculation amount and the surface generation time in the local search algorithm. When the division range is larger than 21 mm, the local search algorithm is a global traversal search algorithm, because most of the scattered points are projected in one interval segmentation, so the surface generation time no longer changes obviously. When the division range is 1.5 mm, the surface generation time of the proposed algorithm is only 16.85% of that of the global traversal search algorithm.

![Image](image2.png)

**Figure 7.** Scanning environment.
Figure 8. Surface generation time versus segmentation interval.

Triangular mesh generated by the traditional method [11] is as shown in figure 9. As the traditional triangular mesh generation method based on scanning point cloud data can only handle the sequential sampling line data but the reverse scanning data, the area enclosed by the curve shown in figure 9, which has lost the texture information as the result of sparse point cloud data, could not be repaired through reverse scanning.

When the maximum and minimum distance threshold values are respectively 2 mm and 0.3 mm, the generated triangular mesh by the proposed method is as shown in figure 10, in which the circles represent the point cloud data obtained from sequential scanning (the same as those in figure 9), the squares represent the point cloud data obtained from reverse scanning. Compared figure 9 with figure 10 we can see that the proposed method in this paper can effectively fuse data of the sequential scanning and reverse scanning, enhancing the texture feature of 3D surface. Display effect of the point cloud 3D reconstruction system based on VC and Open GL of the triangular mesh in figure 10 is as shown in figure 11, which includes 9473 triangles. Compared figure 7 with figure 11 we can see that the reconstructed 3D surface by the proposed method in this paper can successfully reproduce the structural characteristics of the scanned object.

Figure 9. Triangular meshes generated by the traditional method.

Figure 10. Triangular meshes generated by the proposed method.
We set the maximum and minimum distance threshold values to define the relationship between the scattered point and the surface in the process of classifying the newly inserted points. Relationship surface among the minimum distance threshold value, the surface generation time and the number of triangle when the maximum distance threshold is 2 mm is as shown in figure 12, from which we can see that, for a given set of scattered data, increases of the minimum distance threshold will lead to simplification of the triangular mesh and the improvement of the surface generation speed by reducing the amount of scattered point in calculating.

The maximum distance threshold mainly affects the integrity and generation speed of 3D surface. The generated 3D surface when the maximum and minimum distance thresholds are 0.8mm and 0.3mm is shown in figure 13. When the maximum distance threshold is too small, correlation among the scattered points will be reduced, leading to the cracks in the 3D surface. Relationship among the maximum distance threshold, the surface generation time and the number of triangle is as shown in figure 14, which indicates that the change of the maximum distance threshold will not affect the production of 3D surface quality (number of the triangle) in the case of ensuring the integrity of the 3D surface, but it will affect the speed of surface generation. Compared figure 12 with figure 14 we can see that relationship among surface quality, generation speed and storage space can be balanced by adjusting algorithm parameters according to practical applications.
4. Conclusions
We propose a divide-and-conquer reconstruction method of 3D surface using the scanning line in the laser scanning system. Pretreatment of the point can effectively extract the feature points and reduce the data redundancy, under the constraint of curvature threshold and distance threshold, and the streamlined proportion is 56.12%. Compared with the global traversal search algorithm, the proposed local search algorithm based on adaptive point cloud segmentation can reduce the surface generation time by 83.15%. Compared with the traditional surface generation method based on scanning point cloud data, the proposed method can effectively add the flyback data to the generated triangular mesh, enhancing the repairability of reconstructed surface. Compared with the surface reconstruction method, which analyze and process all scattered points as a whole, when 3D surface need expansion or repair, we just need to process the changed points but the whole surface data. The proposed method, in the experiment, can realize the function of surface streamline by setting the maximum and minimum distance thresholds, and reduce the number of triangles by 58.69% by changing the threshold parameter, reducing the surface generation time by 94.51%.

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