

Research on Adaptive Point Cloud Simplification and Compression Technology Based on Curvature estimation of Energy Function

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Abstract

Researched domestic and foreign simplification and compression algorithm of scattered point cloud data, analyzed their advantages and disadvantages, the paper proposed an adaptive method of simplifying point cloud data based on curvature estimation of energy function. The method quickly builds neighborhood point set for scattered point cloud data by KDTree algorithm, and fits the neighborhood point set with osculating sphere. Under energy function achieving minimum value through Powell algorithm, the curvature estimation can be realized to sample points. According to the curvature estimation values, the scattered point cloud data may simplify and compress adaptively. The method can be embodied through visualization software by MFC and Open Inventor software compiling, which got verification on point cloud data of ancient architecture walls and complex surfaces, and obtained good compression effect.

Keywords: simplification and compression, curvature estimation, energy function, Powell algorithm.

1. INTRODUCTION

At present, three-dimensional Laser Scanning-TLS technology has been widely used in spatial information acquisitions, and provides a decision basis for the Digital City-DC, Reverse Engineering-RE, Geographic Information Systems-GIS, complex terrain mapping, Traditional Architecture-TA and Cultural Relics-CR protection. However, the scattered point cloud data contains too much detail information by TLS, massive data is not only huge storage space, and not conducive to transmission, but also for data processing inconvenience, and low efficiency. Therefore, under the premise of maintaining the object features and data processing efficiency and accuracy, it is necessary to retain the useful point of three dimensional 3D model reconstruction, reduce the scattered point cloud data, which reduces the storage of information, enhance the data processing speed and ensure the accuracy of the geometric model. This requires simplifying and compressing massive scattered point cloud data. In recent years, domestic and foreign experts and scholars put forward different methods on point cloud data simplification and compression.

As early as 1986, it has been applied for the bounding box method to simplify the unordered point cloud, which has better efficiency, but can not simplify the non-uniform point cloud data (Filip et al., 1986). The point cloud is also simplified according to the influence degree of reference point on the least square surface (Alexa et al., 2001). It can use geometrical information to reduce three dimensional laser scanning point based on the normal vector value of three dimensional grid points (Lee et al., 2001). HUR has put forward the reduction method of delaunay triangulation of point data. This method can reduce the model error and calculation time, at the same time, ensure the accuracy of the RP model (Hur et al., 2002; Hu and Wang, 2016). It is a method to simplify and compress massive point cloud data through the chord on each layer and slice (Fang and Cheng, 2013). The minimum distance method and the triangular mesh method are combined to simplify the point cloud and get good results (Xi and Shi, 2014; Lv and Feng, 2015). Song et al. proposed a method to distinguish smooth points and boundary points in the neighborhood of data points based on geometric data analysis. But it is need to smooth data(Song et al., 2009). Lu et al. used curvature estimation and polygon approximation to extract contour feature points of industrial CT image(Lu et al., 2013). Clustering algorithm can also be used to simplify the point cloud from coarse to fine (Benhabiles et al., 2013). Lan et al. made the original point cloud assign to the cubic mesh, and the center points of each cubic mesh are determined and preserved. If the curvature difference between a point and a center point in the cubic grid is greater than the curvature threshold, the point is reserved (Lan et al., 2013). In addition, for the scattered point cloud data, the covariance method of the statistics...
is used to estimate the attributes of normal and curvature at the sampling points. This covariance method is a Principal Component Analysis-PCA (Lange, 2005; Rafiee and Sadeghiazad, 2015). With the least square method, PCA applies the plane at the sampling point to fit the neighborhood point set and make the fitting error minimum. Thus, it can measure the curvature change at a point according to surface variation which value depends on the size of the sampling point neighborhood. But this method is more complicated, time consuming and inefficient to estimate the principal curvature of scattered point model.

In summary, these studies mainly focus on the simplified and compressed method of maintaining features and no features. The simplified and compressed methods keeping no features are simple sampling method, grid sampling and angle method, and so on. These methods have the advantages of simplicity and high efficiency, but its common disadvantage is that it is insensitive to features. Because of loss of features, they are difficult to be applied in depth. The simplified and compressed method of keeping features is mainly curvature sampling. Its principle is to retain small amount points of small curvature region, and enough points of large curvature region, which can accurately and perfectly represent the surface feature. So, the method keeping features is to simply point cloud measurement data according to the geometric features of objects, these methods can accurately maintain the surface features and effectively reduce the data points, but the disadvantage is mainly low processing efficiency. The energy function applies the local position of osculating sphere to fit the neighborhood point set at each sampling points (Amenta and Kil, 2004), when energy function takes minimum, it can be performed to the curvature estimation of sampling points, and can reflect the fitting quality and curvature slight variation of each sampling point on model surface, its intrinsic geometric features of the surface are also described in more detail. Thus, for scattered point cloud data, the paper introduced and researched the method of energy function, and applied Powell method to process the minimum value of energy function which should be better than PCA. Research shows that it has higher fitting accuracy, more accurate curvature estimation.

2. CURVATURE ESTIMATION BASED ON ENERGY FUNCTION

In the process of osculating sphere fitting neighborhood point set at sampling points, osculating sphere depends on the normal N and radius R. Thus, the energy function is a multidimensional function which can measure the fitting degree is good or bad (Amenta and Kil, 2005). For scattered point cloud data, suppose the point set P equals \{P_i, i=0, 1, ..., n-1\}, and P_i neighborhood point set M_i equals \{P_j, j=0, 1, ..., n_i-1\}. In order to study the osculating sphere fitting, we introduced a multidimensional energy function:

\[
E(P_0) = \sum_{P_j \in M_i} (D(P_j, P_0) - D(P_j, P_0))^2 G(P_j, P_i)
\]  
(1)

Where D(., .) represents the euclidean distance, P_0 represents centre point of osculating sphere, G(., .) represents the Gauss weight factor:

\[
G(P_j, P_i) = e^{-\frac{-D^2(P_j, P_i)}{h^2}}
\]  
(2)

Where h represents the scaling factor that is determined by the size of the neighborhood area of the sampling point.

Figure 1. Osculating sphere fitting neighborhood point set at sampling points
In order to obtain the best fitting, the appropriate radius needs to be selected for osculating sphere. We can find the minimization of energy function, which is a derivative of 0, therefore, the osculating sphere centre $P_0$ can be found on the best fitting degree, and the normal $N_i$ and radius $R_i$ can be estimated in the sampling point:

$$ R_i = D(P_i, P_0), \quad N_i = (P_i - P_0) / R_i $$

So, the curvature of the sampling point $P_i$ is:

$$ K(P_i) = 1 / R_i $$

3. POWELL METHOD CALCULATED MINIMUM VALUE PRINCIPLE OF ENERGY FUNCTION

Superstition was with me at that moment; but it was not yet her hour for complete victory: my blood was still warm; the mood of the revolted slave was still bracing me with its bitter vigour; I had to stem a rapid rush of retrospective thought before I quailed to the dismal present.

Powell algorithm is a direction set method (Brent, 1974; Zhang et al., 2015). It can deal with multidimensional nonlinear fitting and optimization problems. Its principle is to assume $m$ $m$-dimensional conjugate vectors, and the minimum can be searched along the direction of each vector, then any $m$ element function can calculate the minimum value by one-dimensional search method. When the objective function is so complex that there is no way to grasp the characteristic of objective function, this algorithm can solve this kind of optimization problem specially. It is very useful for practical engineering and scientific computation. First, the direction set $U_i$ is initialized to the coordinate axis vector: $U_i = e_v, i=0, 1, ..., m-1$; and then repeat the following steps until the function value is no longer reduced:

1. Set the initial position to $Q_0$;

2. By $i=0, 1, ..., m-1$, move $Q_i$ to the minimum point of the objective function along the $U_i$ direction, and recorded as $Q_{i+1}$;

3. By $i=0, 1, ..., m-2$, Make $U_i = U_{i+1}$;

4. Set $U_{m-1} = Q_m - Q_0$;

5. Move $Q_m$ to the minimum point of the function along the $U_{m-1}$ direction, and recorded as $Q_0$.

After $m$ iterations according to the above basic steps, one-dimensional search should be carried out $m(m+1)$ times, and the minimum of a quadratic form can be found accurately until the function value is no longer reduced. According to the calculation formula (2) of Powell algorithm, the following is the minimization calculation steps of energy function:

1. Set $P = \{P_i, i=0, 1, ..., n-1\}, M_i = \{P_j, j=0, 1, ..., n-1\}, M_i$ is the neighborhood point set of $P_i$, by $v=0, 1, 2$ (0, 1, 2 respresents x, y, z three axises),we can get initial coordinate axis vector $U_v = e_v$. And then set the threshold epsilon-$\epsilon$;

2. Remember initial position is $P_i$, make $p = P_i$;

3. By $v=0, 1, 2$, put $P_j$ into the formula (2), move $P_j$ to the minimum point of the energy function along the $U_v$ direction, and recorded as $P_{j+1}$;

4. By $v=0, 1, 2$, make $U_v = U_v + 1$;

5. Make $U_{v,1} = P_m - P_i$;
4. ADAPTIVE SIMPLIFICATION AND COMPRESSION OF SCATTERED POINT CLOUD DATA BASED ON CURVATURE

In scattered point cloud data, curvature is the internal attribute of each data point. It represents the surface features of point cloud data. So, the curvature can be used as a benchmark to simplify and compress point cloud data, which not only preserves the surface features of the point cloud data, and does not distort, but also meets the requirements of subsequent modeling accuracy. Based on the curvature the core content of point cloud data simplification and compression likes this: firstly, the strategy needs to be quickly and efficiently established to search data point neighborhood in scattered point cloud data which has no topological relationship; secondly, it is to calculate the curvature of the data points in the field. This paper researches and uses KDTree to search data points, and sets up data points, which can improve the search efficiency for the energy function minimization principle to calculate curvature.

Because there are more feature information in large curvature region, point cloud data points should be properly compressed to avoid distortion. But in small curvature region, such as plains, few points can represent great area, so, lots of redundant data points need to be removed. The paper retains a few points in small curvature region, and enough points in large curvature region. By such a method, the surface features can be represented accurately and completely. According to this principle, According to this principle, the scattered point cloud data can be simplified and compressed by the following processes.

(1) Calculate the curvature value \( f_i \) for neighborhood points of all data points, and obtain their mean curvature value:

\[
f_p = \frac{\sum_{i=0}^{n-1} f_i}{n} \tag{5}
\]

(2) Set neighborhood point set \( k-N(P) \) for point cloud data points, and calculate its local mean curvature value:

\[
f_k = \frac{\sum_{j=0}^{k-1} f_j}{k} \tag{6}
\]

Among them, \( N \) represents neighborhood point set of \( P \), which has \( k \) points.

(3) Determine whether the local mean curvature \( f_k \) is less than the mean curvature \( f_p \) of the whole point cloud. If so, it shows that the neighborhood points of the data points is relatively gentle, retain data points, and delete all points in the neighborhood field. If not, it shows that the neighborhood points of the data points is relatively steep, the data points would be ascended according to the curvature value, if the compression ratio or curvature value is greater than threshold \( \epsilon_r \), or mean curvature \( f_{mv} \), these big points are saved, and smaller points are removed from neighborhood point set.

According to the principle of KDTree, the curvature calculation under the energy function minimization, and the principles of simplification for compressed point cloud data based on curvature, Figure 2 can be obtained, which shows the process and principle of simplification and compression of the scattered point cloud data.
5. SIMPLIFICATION AND COMPRESSION SOFTWARE SYSTEM DESIGN

5.1 Open Inventor brief introduction

Open Inventor is an object-oriented software development package, which encapsulated OpenGL main functions. Open Inventor also provides a programming model and user interface for OpenGL programs, which is composed of a series of object modules. The application programs can exchange data through the built-in 3D exchange file format. Through the scene structure, object concept description and means, developers can quickly and concisely develop various types of interactive three-dimensional graphics program.

Open Inventor is object-oriented application strategy based on OpenGL, which provides a programming model and user interface for OpenGL program and is composed of a series of object modules. Through built-in 3D exchange file formats, data can be exchanged between application programs. Figure 3 is system structure of Open Inventor.

5.2 Software development based on MFC and Open Inventor

Open Inventor can be developed under Windows or Unix operating systems. Table 1 describes Open Inventor applies the kernel constructs name prefixes in different systems, that is, the prefixes used in the header file
names. From the table we can see the development of Win32 applications or MFC visualization, Open Inventor applies kernel SoWin component class.

<table>
<thead>
<tr>
<th>operating system</th>
<th>Open Inventor Prefixes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unix/Linx</td>
<td>SoXt</td>
</tr>
<tr>
<td>Windows</td>
<td>SoWin</td>
</tr>
</tbody>
</table>

In Windows systems, the general step of developing an application program with MFC, Open Inventor is:

1. Set up the class library path, connect the class header file, and initialize the corresponding expansion packet;
2. Initialize scene database of Open Inventor;
3. Design user interface and window based on MFC;
4. Design 3D scene output mode;
5. Design an interactive response mechanism for user actions, including receiving user action events, feeding back the scene database content modification.

### 5.3 Software developing on point cloud data simplification and compression

Based on MFC of Microsoft Visual Studio 2015 and Open Inventor, combined with SIM's Coin3D OIV class library, according to the algorithm principle of above sections, the paper developed the software on point cloud data simplification and compression. Figure 4 shows the flow of software design and function. Software file organization is divided into reading class file, output and save class file, KDTree file, data operation class file, Open Inventor class file, global function library file, etc..

![Figure 4. Software design flow and function on point cloud optimization](image)

### 5.4 Point cloud data adaptive simplification and compression algorithm validation

Figure 5 and figure 6 show the optimization compression results of a historical ancient architecture when the neighborhood point number k is set to be 10 and 20. Since the basic wall is flat, the graph can not see the curvature changes in the compression of the point cloud, and can not well reflect adaptive characteristics too.
The surface change in Figure 7 is more complex, which shows the superiority of the algorithm. When the surface changes gently, the point cloud compression ratio is large, and when the surface change is steep, the point cloud compression ratio is relatively small, which can retain more details. This process ensures the surface features of the original scanning object.

![Figure 5. Point cloud graph after Simplifying and Compressing when neighborhood point number k=10](image)

![Figure 6. Point cloud graph after adaptive Simplification and Compression when neighborhood point number k=20](image)

![Figure 7. Point cloud graph of complex surface after adaptive Simplifying and Compressing](image)

6. CONCLUSION

The paper introduced the energy function to fit the neighborhood points set at each sampling point, used Powell algorithm to calculate the minimum value of energy function, and combined with KDTree algorithm, realized fastly and accurately fitting and curvature estimation of scattered point cloud data. The method is proved to be high adaptive and efficient, at the same time, retains the details and feature information as far as possible. Compared with the bounding box algorithm, chord algorithm, uniform grid method, random sampling and so on, its compression effect has obvious advantages, compression effect is good.

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