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A robust and rapid algorithm for generating and transmitting multi-resolution three-dimensional models

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Abstract Recent advances in 3D spatial data capture, such as high resolution satellite images and laser scanning as well as corresponding data processing and modeling technologies, have led to the generation of large amounts of datasets on terrains, buildings, roads and other features. The rapid transmission and visualization of 3D models has become a ‘bottleneck’ of internet-based applications. This paper proposes a robust algorithm to generate multi-resolution models for rapid visualization and network transmission of 3D models. Experiments were undertaken to evaluate the performance of the proposed algorithm. Experimental results demonstrate that the proposed algorithm achieves good performance in terms of running speed, accuracy, encoding of multi-resolution models, and network transmission.

Keywords: multi-resolution models, network transmission, visualization, multi-resolution algorithms.

Recent advances in 3D spatial data capture, such as high resolution satellite images and laser scanning, as well as corresponding data processing and modeling technologies have led to the generation of large amounts of datasets on terrains, buildings, roads and other features. On the one hand, the internet has become a popular platform for data sharing, data transmission, distributing computation, and visualization. However, the volume of data is far beyond the processing capabilities of current workstation and rapid network transmission (e.g. rapid 3D visualization, and rapid transmission). On the other hand, users have to wait a long time for data downloading from server side to client side after querying operation is invoked, and they can not implement any operations on the spatial data until the downloading is finished. It is also impossible for them to first access the data with a lower resolution data version, then to get a higher resolution data version until the whole data are downloaded. Investigation shows that most users have difficulty to accept such long waits. To solve this problem, one promising solution is to deliver the spatial datasets at increasing levels of detail (LoD) from the server to the client (a process called progressive transmission). The most important advantage of progressive transmission methods is that they are capable of giving users a rapid preliminary view of spatial data. Moreover, users can navigate through the data during the transmission procedure, e.g. through zooming, panning, spatial queries, and so on. Triangle-based 3D model begins to receive more attention because it has simple data structure and is easy to be rendered by common graphics cards. This paper proposes a rapid and robust algorithm to construct multi-resolution 3D models and to progressively transmit triangle based 3D data models over the internet. The algorithm has better performance in terms of the efficiency of generating multi-resolution 3D models, encoding and storage of 3D models, validity check of topological relationship, and features preservation and accuracy evaluation of multi-resolution 3D models.

1 Previous work

Multi-resolution models have been a focus of research in many areas such as the visualization of terrain[1], progressive transmission and 3D compression[2−5]. At present, there are three categories of algorithms that pertain to the multi-resolution model and deal directly with triangle meshes. These are the algorithms that (1) simplify a mesh by removing the vertex; (2) simplify a mesh by removing the edge; and (3) simplify a mesh by removing triangulation[6]. Other related studies include the hierarchical triangle model[7], the transformation of wavelets methods[8,9], the generation of multi-resolution models[10], and the visualization of 3D data field[11]. Several methods and algorithms have been developed for constructing multi-resolution models[3,7,12−14]. A review and an analysis of the existing solutions were made by Heckbert and Garland[15].

De Floriani *et al.*[3] developed a system based on the hierarchical triangle model, which was proposed by De Floriani[7] to construct multi-resolution TINs (Triangulated Irregular Network). Algorithms on hierarchical triangle models were addressed by Heller[16], Soucy and Laurendeau[17], De Floriani *et al.*[2], and Voigtmann *et al.*[18]. The principle of this category of algorithm is to iteratively insert a vertex into the regions of a TIN model with a lower level of accuracy based on the Delaunnay triangle algorithm. However, it is still hard to control global errors and it is possible for triangles with a long and thin shape to appear during the modeling of such a TIN. Vertex decimation solution [19, 20] was proposed, which dramatically improved the speed of performance. However, the original topological relationship may change when recovering a TIN model from a lower to a higher resolution. Wavelet methods provide a fairly clean mathematical framework for decomposing a surface into a base shape plus a sequence of successively finer surface details. Approximations can be generated by discarding the least significant details. The major principle of wavelet based methods is to generate a wavelet decomposition of surfaces with subdivision connectivity. Consequently, the resulting approximations may be relatively far from being optimal because they may use a large number of triangles simply to preserve subdivision connectivity. The iterative edge contraction algorithm[12,21−24] is another kind of algorithm to construct multi-resolution TIN models. The major difference among these solutions is in the selection of the candidate edges and calculation of errors of models. For example, Hoppe[12] used minimum energy cost, while Garland and Heckbert[21] used quadric error metrics, and based on this, developed Qslim software[25]. Kim and Lee[24] developed the edge collapse/vertex split based on the concept of dual piece. The advantage of the iterative edge contraction algorithm is its hierarchical structure. Generating a hierarchical structure is essential, as it is a precondition to retain the topological relationship of the original TIN model. Moreover, the storing of a hierarchical structure and the judgment of the vertex dependency relationship have a significant effect on rendering speed and data storage. Xia *et al.*[22] stored the explicit relationship of the vertex dependencies. EI-Sana and Varshney[23] improved the storage of data by storing the data implicitly. In fact, EI-Sana and Varshney's approach is unnecessarily restrictive[26], and can prevent a further simplification of the original model. Another important aspect to be considered is the "quality" of a multi-resolution model. Here, quality is described by the indicator of the root mean square error (RMSE) of elevation, the valid topological relationship and shape of the triangles in a multi-resolution TIN model. Most current studies of multi-resolution models have focused on speed of performance and data structure. However, an important aspect, evaluating the quality of a model, is normally ignored. The proposed algorithm in this paper falls into the category of edge collapses and vertex splits. The algorithm extends the work in Yang *et al.*[27] and further explores the accuracy and encoding of multi-resolution models, and network transmission efficiency.

2 Algorithm for generating multi-resolution model

We suppose that the topological relationship between vertex, edge, and triangle in 3D models is valid. Hence, a 3D model can be represented as follows:

$$M = \langle F, E\rangle, E = \langle e1, e2, \cdots, en\rangle, F = \langle f1, f2, \cdots, fn\rangle ei = \langle vj, vk\rangle, fi = \langle ej, ek, el\rangle \ vi = \langle xi, yi, zi\rangle.$$

The concept and principles of edge collapses are illustrated in Fig. 1. Three key steps are encompassed in the algorithm: (1) selection of candidate edges, (2) edge collapses and validity check of topological relationship, (3) storage and encoding of multi-resolution model.

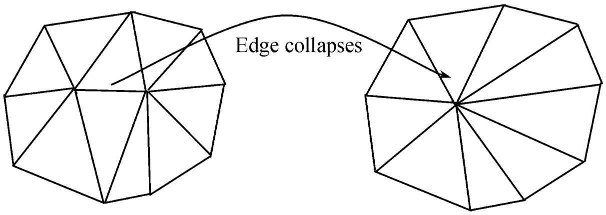

Fig. 1. Principle of edge collapses.

According to the principle of edge collapses, a multi-resolution model can be represented as

$$\mathrm{M}\xrightarrow{\text{edge collapses}}\mathrm{M}_1\xrightarrow{\text{edge collapses}}\mathrm{M}_2\cdots\cdots\xrightarrow{\text{edge collapses}}\mathrm{M}_n,$$

where M denotes the original model.

2.1 Selection of the candidate edges

The algorithm proposed in this paper firstly constructs topological relationship between vertex, edge, and triangle in 3D models. Then, the distance from the vertex to the average plane is calculated according to the method by Schroeder *et al.*[19] (Fig. 2).

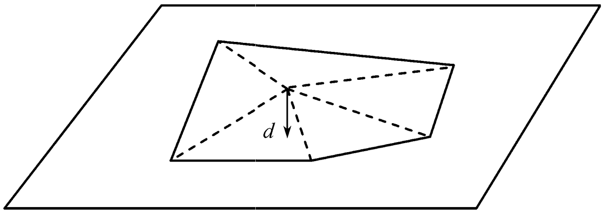

Fig. 2. Average plane of vertex.

For one edge $<v_1, v_2>$, suppose d_1 and d_2 are the distances of vertices v_1 and v_2 to the average plane, respectively. The distance of the edge $<v_1, v_2>$ to its average plane can be represented by

$$E(\text{dis}) = (d_1 + d_2)/2. \tag{1}$$

By using this method, the distance of all of the edges to their average planes can be ranked based on the distance values stored in a stack structure. The edge with the minimum distance to the average plane will be firstly popped from the stack for potential collapsed.

Although the criterion based on the distance from a vertex to a plane is viable, an additional criterion is added to control the quality of the model when an edge collapses in the proposed algorithm. In Fig. 3, the edge in solid line is the common edge of two triangles. When the edge is collapsed, the two triangles disappear. Suppose that the normal of the two triangles are n_i and n_j respectively; the angle between the two triangles can then be calculated by

$$\theta = Arc\cos\left(\frac{n_i \cdot n_j}{|n_i| \cdot |n_j|}\right), \tag{2}$$

where n_i and n_j are the normal of the two triangles.

During the procedure of collapsing edges, the angle between two triangles can be an additional criterion for the selection of the candidate edges. For example, 60° can be set as a threshold. If the angle is beyond the threshold, the selected candidate edge is invalid for an edge collapse. This criterion is useful for retaining those feature lines, such as geomorphological features like ridge lines, in the original model.

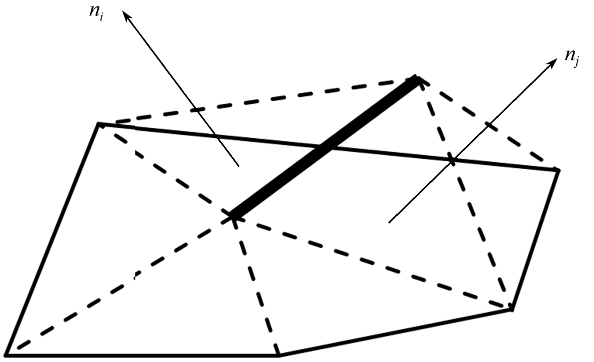

Fig. 3. Judging feature edges.

To control the preservation of feature edges in a multi-resolution model, we define the weights of feature edges according to the angles related to the feature edges. The larger the angle, the heavier the weight is. The following formula is defined to evaluate the importance of feature edges in a 3D model. Hence, it is easy to decide which feature edges will be preserved and to control the accuracy of a multi-resolution model:

$$I(e) = \text{Length}(e) * w(e) / \sum_{i=1}^{n} w(ei), \tag{3}$$

where Length(e) is the length of edge e, $w(e)$ is the weight of the edge.

2.2 *Validity rules of topological relationship*

According to the principle of the proposed algorithm, whenever an edge collapse occurs, the local topological relationship between vertex, edge, and triangle will change (e.g. triangles disappear). Hence, it is necessary to maintain correct topological relationship. When one edge is deleted, the vertex in the edge with larger error will be preserved. To avoid invalid topological relationship, we define the following rules. We first define the following concept.

Concept 1. Influent region of a vertex: This is defined as the polygon (as illustrated in Fig. 4), which is constructed using all of the vertices, where each vertex of all the vertices and the vertex consists of one edge of the multi-resolution model.

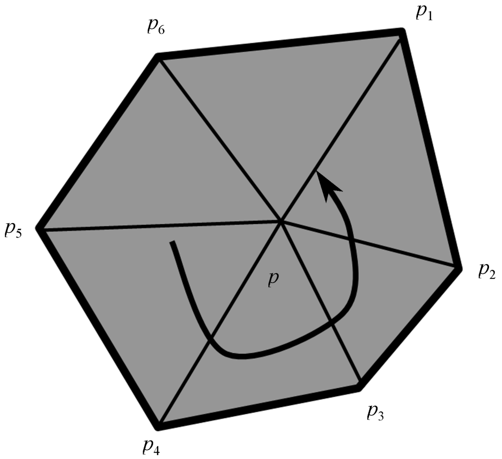

Fig. 4. Influent region of vertex.

Rule 1. Only when the influent region of vertex v_b is a convex polygon, can vertex v_b be collapsed to vertex v_a.

Proof of rule 1. We assume that the vertices in the influent region of vertex v_b are $\bigcup_{i=0}^{n} v_i$, and vertex v_a is within this vertex set. According to the principle of edge collapse, the new edges will be generated by connecting vertex v_a to another vertex v_i in the vertex set ($v_i \neq v_a$). Because the polygon composed by the vertex set

$\bigcup_{i=0}^{n} v_i$ is a convex polygon, the new edges will not intersect with other edges in this polygon. It is thus a safe solution to collapse an edge.

2.3 Storage and encoding of multi-resolution model

The storage of multi-resolution models is directly related to the efficiencies of the algorithm and network transmission. The general bracket[28] that uses 0 and 1 to represent left and right brackets is adopted to encode a multi-resolution model. The method is able to reduce the storage space of multi-resolution model[5]. Hence, each vertex can be encoded with 2 bits by the general bracket method as illustrated in Fig. 5.

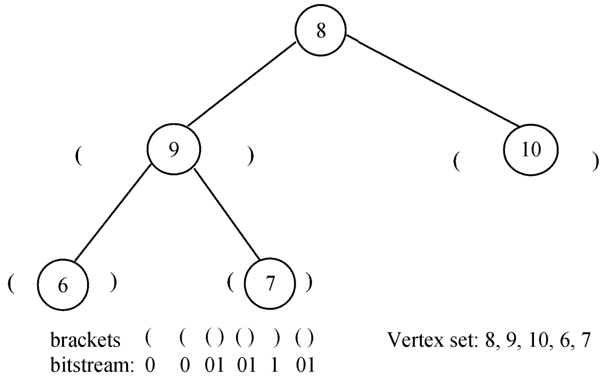

Fig. 5. Principle of the general bracket method.

During the running of the proposed algorithm, edge collapses may occur continuously, which generates a binary tree (as illustrated in Fig. 6(a)). As a result, a large number of binary trees need to be recorded and managed. In order to encode and store the binary trees, we propose vertex tree to fulfill requirements. Fig. 6(b) illustrates an example of vertex tree, where a virtual vertex is inserted as the root node of the vertex tree. Therefore, the vertex tree can be encoded by the general bracket. Based on the bracketing method, the vertex tree can be encoded by a set of recorded vertices and a set of brackets (bit-stream of 0 and 1). Compared with traditional methods, the method based on the general bracket can reduce storage space greatly. Fig. 7 illustrates the encoding result based on the general bracket method.

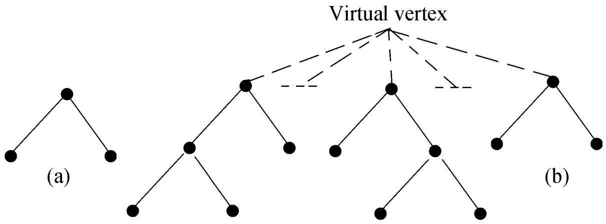

Fig. 6. A vertex tree.

3 Progressive transmission of multi-resolution models

An original model can be represented with a vertex tree and a low-resolution model according to the algorithm proposed in the paper. Then, the low-resolution model will be transmitted firstly to client side. As the low-resolution model has less data volume compared with the original model, the client side is able to get a preliminary view in a short time span. On the other hand, two threads will run in parallel. One is used to

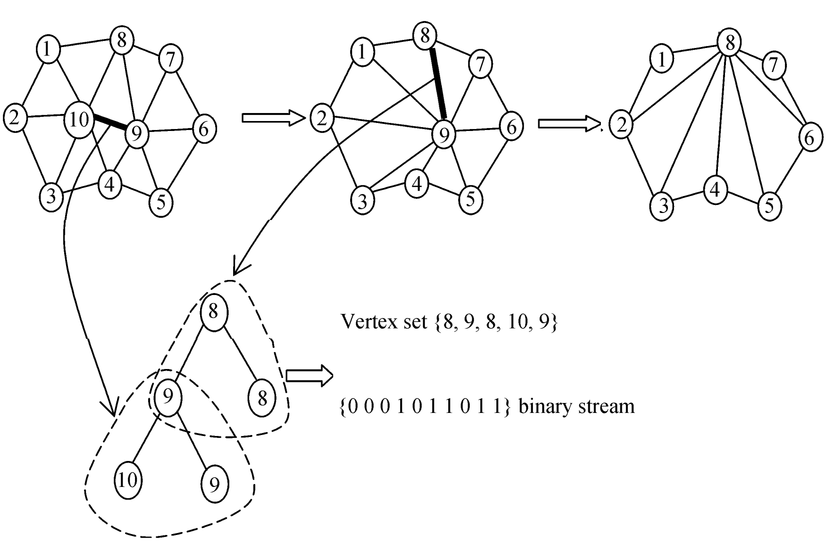

Fig. 7. Encoding a vertex tree based on the general bracket.

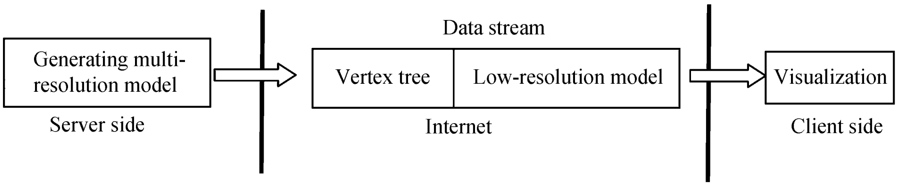

Fig. 8. Procedure of 3D model network transmission.

transmit the low-resolution model; the other is used to transmit the vertex tree. Hence, the resolution of the low-resolution model will become higher and higher when users browse or visualize the low-resolution model. The procedure of transmission of 3D models is illustrated in Fig. 8.

4 Experiments

Two datasets were chosen to evaluate the performance of the algorithm proposed in this paper in terms of efficiency of generating multi-resolution model, accuracy, and network transmission. Table 1 lists the data volumes of experimental datasets and configuration of experiment. Client side connects the internet with a 56K Modem. Fig. 9 and Fig. 10 compare the efficiency of generating multi-resolution models for the two datasets with the Qslim2.0 and the algorithm proposed in this paper. Fig. 11 and Fig. 12 compare the accuracy of multi-resolution models generated by the Qslim2.0 and the algorithm proposed in this paper. Here, we use RMSE of vertex elevation to evaluate the accuracy of the multi-resolution model.

Table 1 Experimental datasets and configuration of experiment

	Number of vertices	Number of triangles	Configuration of experiment
Dataset-1	100000	199114	CPU: Pentium-4
Dataset-2	125417	250214	Memory: 256 Mb

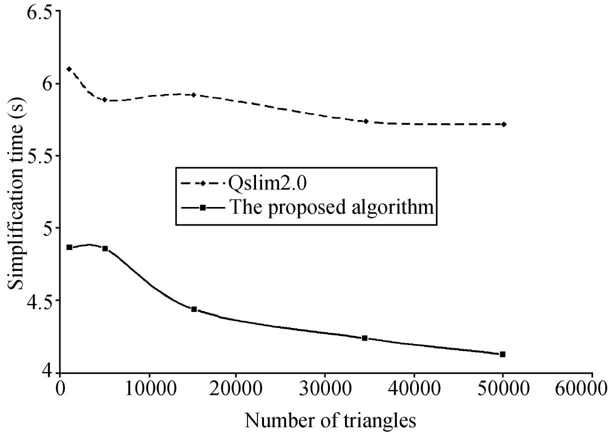

Fig. 9. Efficiency of generating multi-resolution model with the Qslim2.0 and the algorithm proposed in this paper (dataset-1).

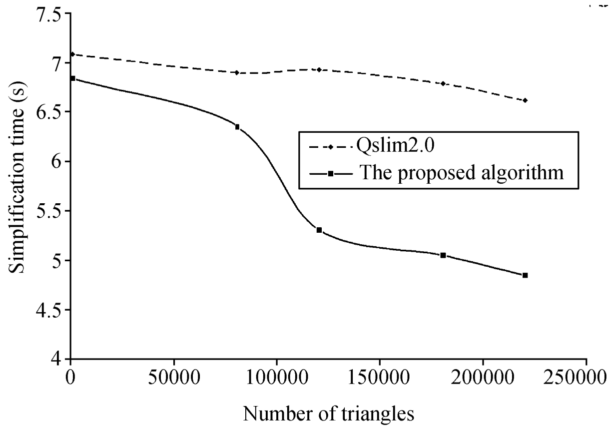

Fig. 10. Efficiency of generating multi-resolution model with the Qslim2.0 and the algorithm proposed in this paper (dataset-2).

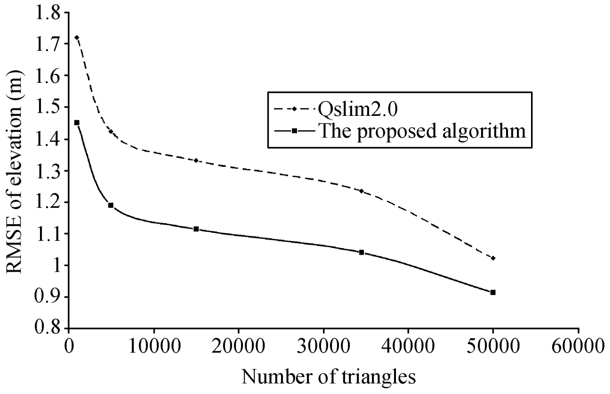

Fig. 11. Accuracy of multi-resolution model generated by the Qslim2.0 and the algorithm proposed in this paper (dataset-1).

Figs. 9—12 clearly illustrate that the accuracy of multi-resolution model generated by the algorithm proposed in this paper is higher than that generated by the Qslim2.0. Moreover, the efficiency of the algorithm proposed in this paper is 0.6—0.8 times fast than that of the Qslim2.0. The experimental results demonstrate that the algorithm proposed in this paper is able to generate multi-resolution model with high performance. Fig. 13 and Fig. 14 show the progressive transmission visualization of two datasets on client side. It demonstrates that client side is able to access remote 3D mod-

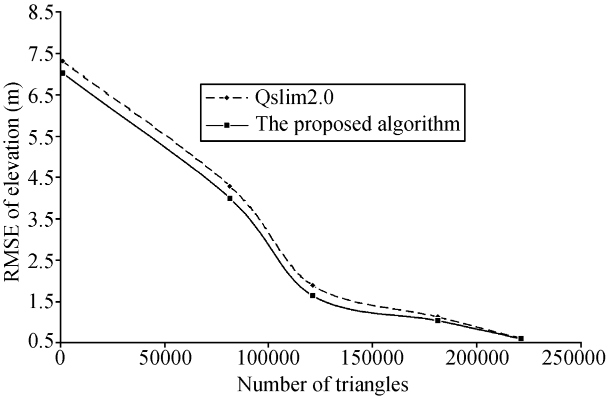

Fig. 12. Accuracy of multi-resolution model generated by the Qslim2.0 and the algorithm proposed in this paper(dataset-2).

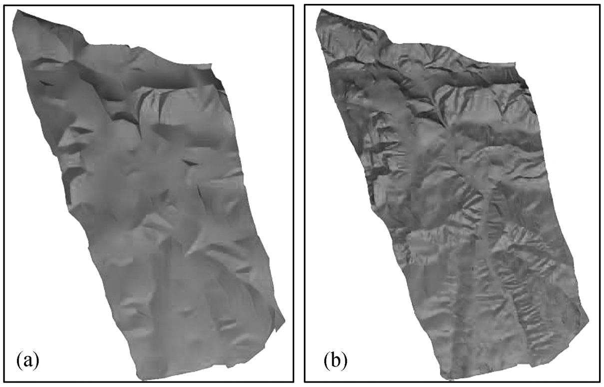

Fig. 13. Progressive transmission of dataset-1. (a) Number of vertices is 500; (b) number of vertices is 5000.

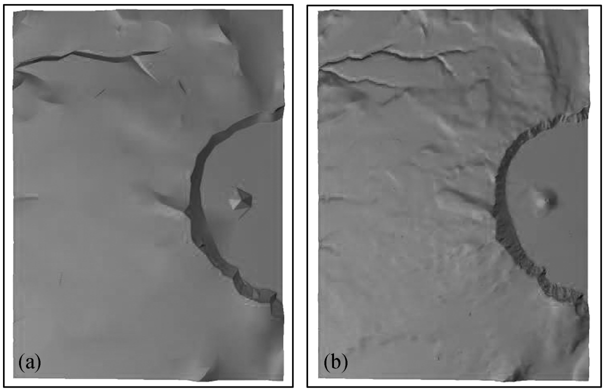

Fig. 14. Progressive transmission of dataset-2. (a) Number of vertices is 500; (b) number of vertices is 5000.

els in a short time and full-resolution 3D models can be recovered rapidly. Compared with traditional network transmission methods—first download and then browse, the algorithm proposed in this paper provides a new transmission method—downloading and browsing, which has better performance in terms of flexibility and short waits, particularly, when the network bandwidth is narrow and data volume is huge.

5 Conclusions and remarks

Rapid network transmission of huge 3D models has become a bottleneck of internet-based visualization. This paper proposes a rapid and robust algorithm for the generation of multi-resolution 3D models and network transmission. The algorithm achieved better properties, which are listed as follows: (1) better efficiency for the generation of multi-resolution models; (2) an efficient encoding method. The algorithm adopts the general bracket method to encode multi-resolution models. The encoding method is able to reduce the space of data storage and encode each vertex with 2 bits; (3) the rigid validity rules for topological relationship check, which are able to avoid invalid topological relationship in a multi-resolution model; and (4) the multi-resolution models generated by the algorithm can be progressively transmitted over the internet. Hence, the new transmission method, downloading and browsing, reduces waiting time when accessing remote 3D models.

Network transmission of multi-resolution 3D models still faces more challenging issues, such as the security and loss of data, the compression of multi-resolution model, and view-dependent network transmission. These issues need further investigation.

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