웨이브릿 기반의 3차원 물체 LOD 표현
(Wavelet-Based Level-of-Detail Representation of 3D Objects)

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요 약 본 연구에서는 거리 영상에서 mesh를 만들고 그것에서 다양한 LOD(Level of Detail)의 mesh를 생성하는 3차원 물체 LOD 모델링 시스템을 제안하였다. Initial mesh 생성은 마칭 큐브 알고리즘을 사용하였다. 종래의 알고리즘을 다수의 거리 영상에서 효과적으로mesh를 생성하도록 개선하였다. Base mesh 생성에는 topology를 유지하면서 mesh를 간략화하는 decimation 알고리즘을 사용하였다. 마지막으로 Initial mash와 유사한 새로운 mesh를 생성할 때는 웨이블릿 변환을 적용하여 웨이블릿 개수를 개산하였다. 본 연구에서는 Base mesh를 생성할 때 mesh 간략화 방법을 사용함으로써 웨이블릿 기반의 치명적인 문제인 surface crease 문제를 해결하였다.
키워드 : 표면 표현, 계층적 변환, 거리 영상

Abstract In this paper, we propose a 3D object LOD(Level of Detail) modeling system that constructs a mesh from range images and generates the mesh of various LOD using the wavelet transform. In the initial mesh generation, we use the marching cube algorithm. We modify the original algorithm to apply it to construct the mesh from multiple range images efficiently. To get the base mesh we use the decimation algorithm which simplifies a mesh with preserving the topology. Finally, when reconstructing new mesh which is similar to initial mesh we calculate the wavelet coefficients by using the wavelet transform. We solve the critical problem of wavelet-based methods - the surface crease problem [1] - by using the mesh simplification as the base mesh generation method.
Key words : surface representation, hierarchy transformation, range data

1. INTRODUCTION

The 3D models obtained from real 3D objects are widely used in VR environments. Models generated with range sensors are constructed with lots of triangles to describe complex 3D objects in detail. The more the number of triangles is, the more exactly can the original object be described, but there is more need of operation costs. Though the power of computers increases very rapidly, it is not enough to render the complex 3D objects in real-time. We should generate and use the meshes that fit the performance of the rendering system.

To generate mesh with subdivision connectivity from an arbitrary mesh, an adaptive subdivision and analysis method was developed[2]. There is an algorithm that makes the new model by defining edge collapse and vertex split operation and applying it to the mesh[1]. A new format was used for saving and transmitting the triangulated geometric model[3]. Eck and Lounsbery's method can generate smooth parameterization at any LOD(Level of Detail), and can be applied to the multi-resolution surface editing[2]. These can construct guaranteed maximum error bound meshes and can compress the geometry and the color independently by using the wavelet transform property. These wavelet-based modeling methods have many advantages, so they have been studied

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actively. Wavelet is an effective tool for 3D modeling and for the other computer graphics applications[4][5].

But Wavelet-based LOD modeling methods proposed so far cannot recover the initial mesh exactly. They cannot deal effectively with surface creases so they produce approximated meshes of low quality for these cases. In this paper, we solve the problems by using mesh simplification as the base mesh generation method. Topology preserving mesh simplification methods can keep feature vertices and edges and represent complex areas as dense meshes and simple areas as sparse meshes.

1.1. System Architecture

The proposed system consists of two phases: the initial mesh generation phase that generates the initial mesh from the input range image and the LOD mesh generation phase that forms the LOD controllable mesh by using the wavelet. The latter consists of a mesh simplification module, a mesh subdivision module and a LOD mesh generation module. The mesh simplification module generates the simplest mesh the base mesh. The mesh subdivision module divides the base mesh to construct a similar mesh for the initial mesh with subdivision connectivity the regular mesh – and extracts the wavelet coefficients in this process. The LOD mesh generation module can generate the mesh of any LOD. The LOD of the mesh can be controlled by using the wavelet coefficients.

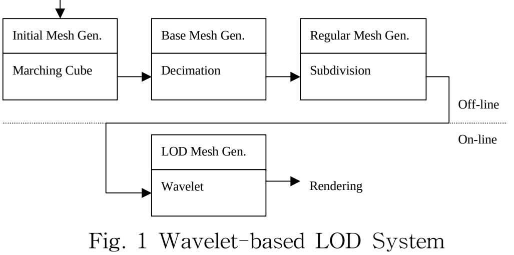

Fig. 1 Wavelet-based LOD System

The system architecture diagram is shown in Fig. 1. The system consists of four modules. The foremost three modules are processed in off-line and the last one in on-line. The wavelet coefficients are extracted and saved in the off-line process. Users can generate any LOD mesh by using the saved coefficients when the mesh is drawn in the application program. The wavelet transform analysis consists of extracting the coefficients and of generating LOD mesh.

2. BASE MESH GENERATION

2.1. Initial Mesh

Mesh generation methods from range images proposed so far can be classified into the following two types. One type is Marching Cube algorithm. The marching cube was proposed and used to construct 3D models from medical images like CT and MRI images[6]. It is used to construct 3D meshes from unorganized points[7]. Each point data are dealt independently in these methods and whole mesh is constructed at once. The other is zippering algorithm[8]. These make the mesh from each range image independently, and then zipper these meshes into one. Because not using the topological information like the range image lattice, the former is hard to find the connectivity of point data. But new point data is easy to be added. The latter is easy to construct the mesh from one range data. But the zippering is very expensive operation.

We use the marching cube algorithm to generate the mesh from range images. We improve this algorithm by using topological information like the latter method. It is difficult to find the normal of each triangle and we solve this problem as follows:

In our algorithm, the mesh is generated using each vertex′s signed distance which is defined by using the tangent plane. The tangent plane is calculated by using the relation between the adjacent points because the topology information is not used. The available directions of the tangent plane are two in this method, so an optimization process is used to choose the direction. But we use the topological structure of the data because it is assumed that the input data are 3D range images. Thus, any point of the input data has 4 adjacent points except for the boundary one because the 3D range images form a lattice. 4 triangles are drawn connecting these points as in Fig. 2. Each triangle's normal vector is calculated by cross product operation. The tangent plane normal is the average of these 4 normal vectors and the center point of the tangent plane is the value of the center input point.

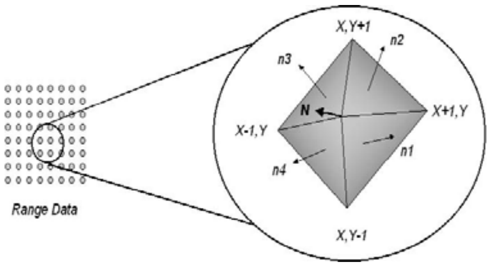

Fig. 2 Normal Vector Calculation from Range Image

2.2. Base Mesh

The base mesh is the simplest mesh whose the LOD is the lowest. In this paper, the base mesh is constructed by using the mesh simplification algorithm to preserve the topology of the original mesh. This relieves the surface crease problem. Progress in research on mesh simplification is rapid. The cost of the edge is measured by using the energy function in terms of the local tessellation error and of the local geometric error and the mesh is simplified by the region merging operator[9]. For geometric construction one need not measure error, and the simplification envelopes are defined and applied to generate a simple mesh[10]. Combining Ronford's method[9] and the reverse idea of Cohen's method[10] has been developed[11]. This algorithm measures the tolerance volume for the edge removal condition. The mesh is simplified by clustering the characteristic edges and the planar area[12]. After measuring the distance from each vertex to the local topology, if the distance is within threshold error, that vertex is decimated[13]. For the latticed range images from a 3D scanner, the simplification starts from a uniform plane to the mesh by the bisection or the quadrisection[14]. The greedy algorithm which includes three steps - superface generation, boundary linearization and superface triangulation - is developed[15]. Hinker's method is an algorithm that reduces the number of triangles by merging the flat similar and the normal planes[16]. After diffusing new vertices over the surface of the model, the new mesh is generated by mutual tessellation with the new vertices[17]. By optimizing the energy function including distance, vertex number and spring term, a simplified model is generated[18]. The surface error is maintained by calculating the quadric matrices[19]. The appearance-preserving simplification method is developed by defining the texture deviation metric[20].

The algorithm conditions for our system are as follows: speed and topology preservation. When these two conditions are met, the LOD mesh generation can be faster than the previous wavelet-based modeling[10] and can solve the surface crease problem[1]. We choose the decimation method[13] for these conditions, which was originally proposed for mesh simplification generated by the marching cube algorithm[6]. The error distance for each vertex is measured. If it is within the given tolerable error distance, the mesh is simplified by decimating that vertex.

The decimation algorithm consists of two steps the triangle classification step and the decimation step[13]. In the decimation step, we make the new triangle cover set to generate the regular mesh effectively later (3.2). The triangle cover set contains the triangles of the initial mesh. For each triangle in the initial mesh, there is one triangle cover set and it covers the newly generated triangles. When subdividing each triangle of the base mesh to make the regular mesh, we move the subdivided vertices with respect to the triangle cover set so that it will be similar to the initial mesh with the subdivision connectivity.

When generating new triangles in decimation step, the triangle cover sets of the removed triangles are added to the triangle cover set of the new triangle. If the triangle cover sets of removed triangles are overlapped, addition is performed by a union operation.

3. LOD MESH GENERATION USING WAVELET

3.1. Wavelet Transform

The wavelet transform is the analysis from the original mesh to the simplest model to calculate the wavelet coefficient corresponding to the detailed information. In other words this procedure is the multi-resolutional analysis.

The multi-resolutional analysis consists of two steps - defining the scaling function and calculating the wavelet coefficients. The subdivision procedure is applied to define the scaling function in mesh[2]. Each step of the subdivision procedure consists of two sub-steps. One is the split step that divides one triangle into four and the other is the averaging step that modifies the model by moving the new vertices resulting from the split step. If V^j is the vertices matrix of phase mesh j, there exists a matrix that P^j satisfies:

$$V^{j+1} = P^j V^j$$

This matrix P^j is called the subdivision matrix because it determines the subdivision features.

To define the scaling function by using the subdivision, the mesh parameterization function $S(x)$ is defined. Mesh parameterization is calculating the relationship between corresponding points in the mesh of different phases. This is shown in Fig. 3 [21].

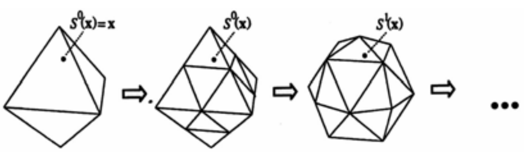

Fig. 3 Mesh Parameterization

Mesh parameterization function $S(x)$ can be defined by limiting process as follows[21]:

1. $S^0(x) := x,\ x \in M^0$

2. If $S^{s-1}(x)$ is located on barycentric coordinates (α, β, γ) inside triangle of $S^s(x) := \alpha v^s_a + \beta v^s_b + \gamma v^s_c$, where (v^s_a, v^s_b, v^s_c) is triangle of M^s corresponding to of

$$S(x) := \lim_{s\to\infty} S^s(x)$$

In[21], the following expression is satisfied:

$$S(x) = \Phi^j(x)V^j,$$
$$\Phi^j(x) = \Phi^{j+1}(x)P^j.$$

$\Phi^j(x)$ constructs vector space with refinablity and can be defined as a scaling function.

The second step of the multiresolutional analysis is defining the inner product. For 3D mesh, the inner product may be defined as follows:

$$< f, g > := \int_{x\in M^0} f(x)g(x)dx,$$

Where f and g are scaling functions and dx is the area[21].

Last, the wavelet is constructed. The scaling function $\Phi^{j+1}(x)$ can be expressed in the block matrix form of $(O^{j+1} N^{j+1})$. O^{j+1} is a function derived from $\Phi^j(x)$ and N^{j+1} is a newly formed part that is related with wavelet $\Psi^j(x)$. Therefore, N^{j+1} can be written as follows:

$$N^{j+1}(x) = \Phi^j(x)\alpha^j + \Psi^j(x).$$

Taking the inner product of each side with $\Phi^j(x)$ makes this result:

$$<\Phi^j(x), \Phi^j(x)>\alpha^j = <\Phi^j(x), N^{j+1}(x)>$$
$$= (P^j)^T < \Phi^{j+1}(x), N^{j+1}(x)>.$$

The coefficient α^j can be calculated by solving a system of these equations[21].

In the multiresolutional analysis, the synthesis filters are expressed as:

$$(\Phi^j(x)\Psi^j(x)) = \Phi^{j+1}(x)(P^jQ^j)$$

and the analysis filters are obtained from the inverse relation[21]

$$\begin{pmatrix} A^j \\ B^j \end{pmatrix} = (P^jQ^j)^{-1}.$$

It follows then from the wavelet definition that the synthesis filters can be written in block form as:

$$(P^jQ^j) = \begin{pmatrix} O^j & -O^j\alpha^j \\ N^j & \mathrm{I} - N^j\alpha^j \end{pmatrix},$$

where denotes the identity matrix[21]. For polyhedral subdivision, O^j is the identity matrix. So the filters are simplified as:

$$(P^jQ^j)=\begin{pmatrix} \mathrm{I} & -\alpha^j \\ N^j & \mathrm{I}-N^j\alpha^j \end{pmatrix}, \begin{pmatrix} A^j \\ B^j \end{pmatrix}=\begin{pmatrix} \mathrm{I}-N^j\alpha^j & \alpha^j \\ -N^j & \mathrm{I} \end{pmatrix}.$$

Using these filters, the multiresolutional analysis can be expressed as follows[21]:

$$V^j = A^jV^{j+1}, W^j = B^jV^{j+1}$$
$$V^{j+1} = P^jV^j + Q^jW^j$$

By filling the coefficients of these matrices in the regular mesh generation process, the 3D LOD model can be constructed.

3.2. Regular Mesh

To extract the wavelet coefficients (i.e. filters), the base mesh needs to be subdivided to construct the regular mesh. The regular mesh is the mesh similar to the initial mesh with the subdivision connectivity. To construct the regular mesh, the split and averaging steps are repeated. The split step divides one triangle into four and the averaging step modifies the mesh by moving the new vertices resulting from the split step.

We use the parametrically uniform resampling method[2] in the split step. In the averaging step, we modify the mesh by moving the new vertices according to the weight values of the surrounding triangles depend on the defined wavelet. We use a simply shaped wavelet that maximizes the center weight value and minimizes the value of the surrounding triangles.

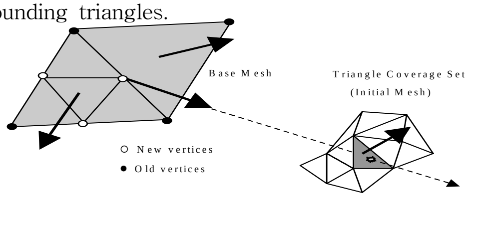

Fig. 4 Intersection Point Calculation using Triangle Coverage Set

In practice, the vertex is modified as in Fig. 4. The vertex is moved to the intersection point with the triangle of the initial mesh. When we construct the base mesh from the initial mesh, we make the triangle coverage set. The intersection point can be found by merely searching this set, so the search time is less than that of the entire mesh search time.

First, we calculate the normal vectors of the divided triangle and adjacent triangle that shares the divided vertex as shown in Fig. 4. Then we solve the equation of the line that is parallel to the average of the two normal vectors and pass through the divided vertex. We examine whether this line intersects with each triangle of the triangle coverage set. The intersecting point is what we want to move to divide the vertex. If the normal vector of the triangle of the triangle coverage set makes an obtuse angle to the average normal vector, it can be rejected without examination. The difference between the intersecting point and the original vertex is saved as the wavelet coefficient. After saving this, for all new vertices we move them to the intersecting points respectively and go on to the next level.

3.3. LOD Mesh Generation

After saving the wavelet coefficients resulting from the regular mesh subdivision, the mesh of desired LOD can be generated. The error threshold or the number of meshes and vertices to be expanded can be given. Finally, we construct the mesh by triangulating these vertices. The given input error is not useful because the range of error is diverse in each case.

The vertices are traversed recursively. If the vertex is within the given error bound, it is marked as expanded. It is problem when all the vertices in a triangle are not expanded and can be solved by an immediate vertex[21]. If we want to control the LOD of the mesh by the number of triangles, they can do so by sorting the error distance of the vertices.

4. EXPERIMENTAL RESULTS

The front and side views of mesh constructed from range images using the proposed system are shown in Fig. 5. The input range images are generated from the front, the left 90 degrees and the right 45 degrees. So, the front and left sides of mesh are well constructed but the right and rear sides are not so good. The whole mesh is well constructed when the range images from a rotating scanner are used. When the whole range data of an object are not used, or if the range data are sparse, these results show that our system can construct mesh well.

The result of implementing the base mesh generation algorithm is shown in Fig. 6. The initial mesh is constructed from range images and is formed of the detailed and regular pattern but the base mesh is made up of the sparse and irregular triangles. The number of mesh is reduced from 21879 to 3563. These results show that base mesh generation by the mesh simplification algorithm can solve the surface crease problem.

Fig. 5 Constructed Model using Marching Cube Algorithm (Beethoven)

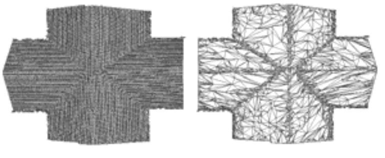

Fig. 6 Initial Mesh and Simplified Base Mesh (Cross)

The next figure shows the results of the whole system using the Cat statue. After the wavelet transform, the system can generate mesh of any LOD. The result of applying wavelet transform is shown in Fig. 7. The LOD of the mesh is given as a ratio of the number of triangles to the finest regular mesh in our system. The LOD of the mesh in Fig. 7 are 0, 20, 40, 60 and 100 % of the number of triangles from left to right.

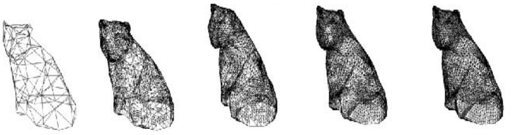

Fig. 7 Result of Applying Wavelet Transform : LOD = 0, 20, 40, 60, 100% (Cat)

5. CONCLUSION

In this paper, we proposed the 3D modeling system that constructs meshes from 3D range images and generated models of various level-of-detail using the wavelet transform. We solved the critical problem of the wavelet-based models - produces low quality meshes when the surface creases exist - by using the mesh simplification as the base mesh generation method. When constructing a mesh from a range image, we integrated the images from various viewpoints effectively by using the topology information. To apply the wavelet transform, we first generated the base mesh using the mesh simplification method, then constructed the regular mesh using subdivision and applied the wavelet transform. The resulting final mesh in this system described the original object well using fewer triangles than the initial mesh.

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