AN EFFICIENT CODING ALGORITHM FOR COLOR AND NORMAL DATA OF THREE-DIMENSIONAL MESH MODELS

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ABSTRACT

Three-dimensional (3-D) mesh models have attribute data, such as colors, normal vectors, and texture coordinates to render or shade the surface of the mesh. Although several coding schemes have been developed to represent the topology and geometry information of the 3-D mesh, coding of the attribute data has received less attention. In this paper, we propose a new predictive coding scheme for colors and normal vectors of the 3-D mesh model, where we predict colors and normals based on several ancestors along the vertex ordering. In order to encode the color information, we define a mapping table that specifies how colors are mapped into other vertices. The mapping table can represent frequently occurring color patterns efficiently. For normal vectors, we also propose an average predictor and the 6-4 subdivision quantizer in the spherical coordinate system. The proposed scheme has demonstrated good coding efficiency for various VRML test data.

1. INTRODUCTION

In recent days, 3-D models are popularly used in various applications, such as Internet services, computer graphics, and synthetic imaging systems. The 3-D model usually requires a large number of polygons to represent details of the model accurately. Since transmission bandwidth and storage capacity are limited in many applications, we need to find compact representation of the 3-D model. Polygonal meshes are frequently used to represent surfaces of 3-D objects for fast interactive visualization.

In general, 3-D mesh models have connectivity, geometry, and attribute data. While the connectivity data describe the connection relationship among vertices and characterize the topology of the 3-D model, the geometry data specify locations of the vertices in the 3-D space. The attribute data comprise normal vectors, colors and texture coordinates which are needed to paint and shade the 3-D model. The attribute data is often attached to vertices, faces, or corners of the 3-D mesh model.

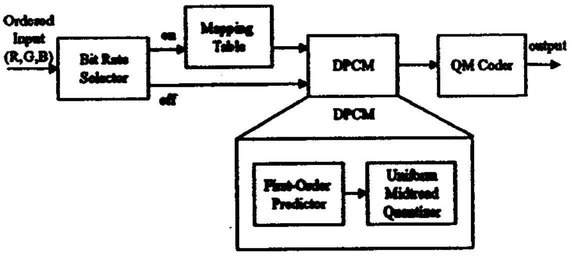

Fig. 1. Block diagram of a color encoder

Under the limited network bandwidth, we need to reduce the number of transmission bits as much as possible, while maintai ing reasonable reconstruction quality. Since the geometry and a tribute data specified by floating-point numbers are the major pa of the 3-D model representation, coding of those information is e fective in reducing the total number of bits. Although current research for the 3-D mesh representation has focused on connectivity and geometry coding, coding of the attribute data has received less attention. In this paper, we propose a new predictive coding scheme for colors and normal vectors.

2. COLOR COMPRESSION

Color information can be attached to vertices, faces, or corners in the 3-D mesh model. In this work, we propose a compression algorithm for color data with per-vertex binding.

Fig. 1 shows the block diagram of the proposed color encoder. After color data are reordered in the traversal order, the bit rate selector chooses whether color data are compressed by a mapping table or not. Specifically, if the overall size of the mapping table is larger than the required bit rate, the color data is encoded by DPCM with a large quantizer step size. Otherwise, the mapping table is employed to encode frequently recurring colors efficiently.

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(a) HUMIDITY (b) SPHERE

(c) BRAIN (d) C-SKULL

Fig. 2. Test models for color compression

2.1. Mapping Table

3-D mesh models can be obtained by a laser scanning system or generated using an authoring tool. In these cases, some parts are often painted with the same color due to the limited precision of the system. In other words, 3-D models often have only a small set of colors that recur frequently over many vertices. For instance, the HUMIDITY model in Fig. 2(a) contains 39,072 vertices painted with only 401 different colors. The proposed mapping table scheme can provide a high coding gain for such 3-D models that have frequently recurring colors.

In the mapping table, a color value is encoded only once when it appears first during the traversal. When the same color recurs on another vertex later, the encoder records the index of the last vertex with the same color, instead of the color value itself. The mapping table can reduce the bit rate for color data significantly, since it avoids the duplicated encoding of the same color.

2.2. Differential Pulse Coded Modulation

We employ the first-order predictor with unity prediction coefficient to encode color data differentially. In other words, each color is simply predicted by only one preceding color. Generally, between two adjacent vertices, the color correlation is higher than the position correlation.

After we estimate the current color value based on the previously coded color value, the prediction error is uniformly quantized. As the dynamic range of prediction errors is limited to $[-1,1]\times[-1,1]\times[-1,1]$, we employ the uniform midtread quantizer of M levels with step size $\Delta = 2/(M-1)$, and encode the quantizer index with the QM coder.

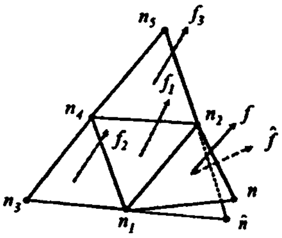


Fig. 3. Average prediction rule

3. NORMAL VECTOR COMPRESSION

We propose a compression algorithm for normal vector data with per-vertex binding. Since we only consider the normal vector of length 1, any normal vector on the unit sphere can be represented by $(1, \theta, \phi)$ in the spherical coordinate system. Thus, it is sufficient to encode only θ and ϕ coordinate values. In order to improve the coding gain for normal vectors, we predict each normal vector using the average prediction scheme, and quantize the prediction error using the 6-4 subdivision scheme.

3.1. Average Prediction

The proposed average prediction is based on the following two assumptions: 1) the face normal vector of a triangle is given by the average of the three vertex normal vectors of the triangle. 2) the face normal vector of a triangle can be approximated by the average of the face normal vectors of the neighboring triangles.

Using these two assumptions, we can apply a prediction rule for each vertex normal vector. Fig. 3 shows an example of the average prediction, where f_i denotes a face normal vector and n_i denotes a vertex normal vector. Suppose that the vertex normals n_1, n_2, n_3, n_4, and n_5 are already encoded, and the vertex normal n is to be encoded, and the surface normal f is also unknown. By the second assumption, we have $f_1 \simeq \frac{(f+f_2+f_3)}{3}$. In other words, we can predict f by

$$\hat{f} = 3f_1 - f_2 - f_3. \tag{1}$$

Let $\hat{n}$ denote the prediction of n. Then, by the first assumption, Eq. (1) can be rewritten in terms of the vertex normal vectors, and then $\hat{n}$ is given by

$$\hat{n} = n_1 + n_2 - n_3 + n_4 - n_5, \tag{2}$$

and the prediction residual is obtained by

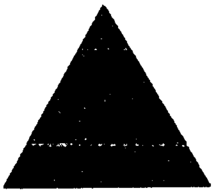
$$\begin{aligned} \Delta n &= n - \hat{n} = (1,\theta,\phi) - (1,\hat{\theta},\hat{\phi}) \\ &= (0, \Delta\theta, \Delta\phi). \end{aligned} \tag{3}$$

3.2. Subdivision Quantization

In MPEG-4 3DMC, the normal vector $(1, \theta, \phi)$ is pre-quantized using the 8-4 subdivision scheme [1,2]. After the unit sphere is divided into eight octants, as shown in Fig. 4(a), each octant is approximated by a base triangle, which is subdivided n times recursively. Thus, we represent the normal vector by its octant number and triangle index using the index pattern shown in Fig. 4(b).

However, this approach has some shortcomings. Since the unit cube is approximated by an octahedron, quantized normal vectors

(a) Three subdivisions of the base octahedron



(b) Index pattern

Fig. 4. Normal vector compression in MPEG-4 3DMC

are not ideally distributed. In other words, quantized normal vectors are uniformly distributed over an octahedron, instead of over the unit sphere. In addition, the index pattern in Fig. 4(b) is not suitable for differential coding. Since the triangles in each octant are represented by one-dimensional indices, neighboring triangles can have dissimilar indices. For example, in Fig. 4(b), although the triangles 3 and 9 are adjacent, their index difference is as large as 6. Furthermore, there is discontinuity of indices along the boundary between two octants.

In order to overcome these limitations, we adopt the 6-4 subdivision scheme [4] to quantize the normal vectors. As shown in Fig. 5(a), the surface of the unit sphere is divided into six disjoint regions, called sextants, of the identical shape. The centers of these regions are located at (1,0,0), (-1,0,0), (0,1,0), (0,-1,0), (0,0,1) and (0,0,-1). For example, the region with a center at (0,0,1) is given by $\{(1,\theta,\phi) : -\pi/4 < \theta < \pi/4 \text{ and } -\pi/4 < \phi < \pi/4\}$. Then, we divide each sextant into 2^{2n} cells by uniformly quantizing θ and ϕ into 2^n levels respectively.

Using the 6-4 subdivision quantization, we can encode the prediction residual Δn in Eq. (3) efficiently. Around the sextant containing the prediction vector $\hat{n}$, we can unfold the unit sphere, as shown in Fig. 5(b). Then, each cell is enumerated by a 2-D index, which indicates which row and column the cell lies on. Then, the 2-D index difference between n and $\hat{n}$ is encoded by the QM coder. In this way, we can prevent the discontinuity problem in the MPEG-4 3DMC algorithm, and we exploit the redundancy in normal vectors more effectively and improve the coding gain.

4. EXPERIMENTAL RESULTS

We investigate the performances of the proposed color and normal algorithms on several test models, which have been collected and used by the MPEG-4 3DMC group.

4.1. Error Metric

In many cases, simple measures are used, such as the mean square error or the maximum error. In the field of image coding, the root mean squared error (RMSE) or the peak-signal-to-noise ratio (PSNR) is popularly employed as an objective distortion measure.

For colors, the Euclidean distance seems appropriate. For normal vectors, the dihedral angle is computed to measure the distortion using dot product. Although probably not being very close to the actual visual quality a subject would perceive, the simple distortion metric has the advantage of being easily and quickly computable.

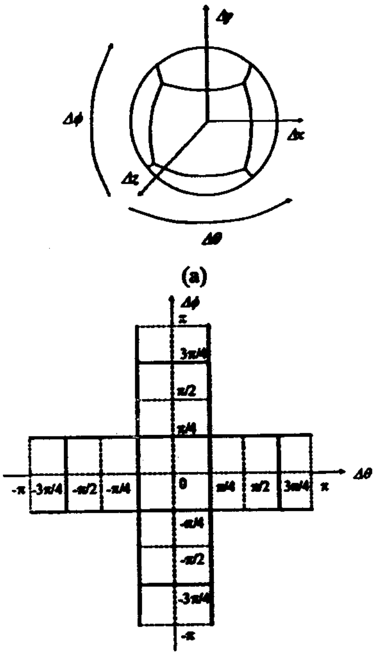


Fig. 5. 6-4 subdivision: (a) sextant partitioning; (b) further partitioning

Table 1. Test models for color compression

Model	nV	nF	nC	nCS
HUMIDITY	39,072	77,504	39,072	401
SPHERE	41,369	82,734	41,369	337
BRAIN	34,278	69,180	34,278	9,419
C-SKULL	84,635	172,002	84,635	16,775

4.2. Color Coding

Fig. 2 shows 3-D test models for color compression and Table 1 summarizes their properties. In Table 1, nV is the number of vertices, nF is the number of faces, nC is the number of listed colors to describe the model, and nCS is the number of different colors used to paint the model. In these models, the color value is assigned to each vertex; hence $nC = nV$. Note that nCS is much smaller than nC, which implies that the same color recurrs frequently to paint several vertices in these models.

In Table 2, we compare performance of the proposed color compression algorithm to that of the MPEG-4 3DMC algorithm. There are two options in the proposed algorithm. If the overall size of the mapping table is larger than the required bit rate, the color data is encoded by the DPCM scheme with a large quantizer step size. Otherwise, the mapping table scheme is employed to encode frequently recurring colors effectively. In general, when we use

Table 2. Simulation results for color compression (RMSE errors).

Model	bpc	MPEG-4	Proposed	Option
HUMIDITY	5	0.00420	0.00410	DPCM
	8	0.00052	0.00033	DPCM
	10	0.00013	0	mapping table
SPHERE	5	0.3793	0.1820	DPCM
	7	0.1435	0.0931	DPCM
	10	0.0641	0.0004	mapping table
BRAIN	6	0.1441	0.1135	DPCM
	11	0.0234	0.0224	DPCM
	17	0.0036	0.0005	mapping table
C-SKULL	4	0.2162	0.1704	DPCM
	8	0.0539	0.0524	DPCM
	10	0.0332	0.0012	mapping table

Table 3. Test models for normal vector compression

Model	nV	nF	nN
TWO-CYLINDERS	410	816	410
LEGS	3,600	1,200	3,600

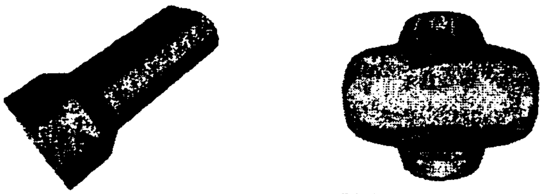
the mapping table, 9-15 bits per color (bpc) are required.

From Table 2, we can observe that the DPCM scheme provides slightly lower distortions than the MPEG-4 3DMC algorithm. At higher bit rates, the proposed algorithm yields significantly lower distortions by employing the mapping table. For example, the proposed algorithm provides about 160 times lower distortion than the MPEG-4 3DMC algorithm, when the SPHERE model is encoded at 10 bits per color (bpc).

4.3. Normal Vector Coding

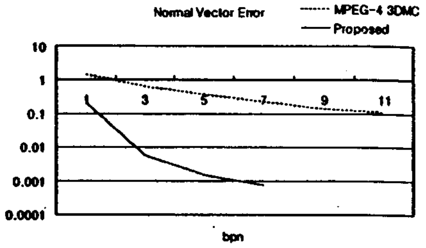
The proposed normal compression algorithm is tested on LEGS and TWO-CYLINDER models, shown in Fig. 6. Table 3 summarizes the properties of these test models, where nN is the number of normal vectors. $nN = nV$, since a normal vector is assigned to each vertex. While the LEGS model consists of flat regions, and the TWO-CYLINDER model has curved surfaces.

Performance of the proposed algorithm is compared to those of the MPEG-4 3DMC algorithm in Fig. 7, where the horizontal axis represents the bits per normal (bpn) and the vertical axis represents the normal error in the logarithm scale. From Fig. 7, we observe that the proposed algorithm provides higher coding gains than the MPEG-4 3DMC algorithm on all the test models. Especially, we achieve a high coding gain for the LEGS model because the normal vectors in the LEGS model are highly correlated, and thus can be effectively predicted by the proposed algorithm.

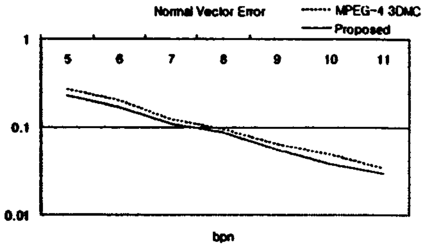


(a) LEGS (b) TWO-CYLINDER

Fig. 6. Test models for normal vectors



(a) LEGS



(b) TWO-CYLINDER

Fig. 7. Simulation results for normal vector compression

Our simulation results indicate that the proposed algorithms for color and normal data coding of 3-D mesh models are quite promising.

5. CONCLUSIONS

We proposed the compression algorithms for the colors and normal vectors of 3-D mesh models, based on the DPCM structure. Conventional works employ geometry predictor and quantizer to code colors and normal vectors. However, colors and normal vectors have their own characteristics. Thus, we developed different predictors and quantizers for colors and normal vectors according to their characteristics. For color data, we have proposed a coding scheme using a mapping table to encode frequently recurring patterns effectively. For normal vectors, we have presented an average predictor and the 6-4 subdivision quantizer. Simulation results have demonstrated that the proposed coding schemes outperform the MPEG-4 3DMC standard for various test models.

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