MULTIPLE DESCRIPTION CODING OF 3D GEOMETRY WITH FORWARD ERROR CORRECTION CODES

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ABSTRACT

This work presents a multiple description coding (MDC) scheme for compressed three dimensional (3D) meshes based on forward error correction (FEC). It allows flexible allocation of coding redundancy for reliable transmission over error-prone channels. The proposed scheme is based on progressive geometry compression, which is performed by using wavelet transform and modified SPIHT algorithm. The proposed algorithm is optimized for varying packet loss rates (PLR) and channel bandwidth. Modeling distortion-rate function considerably decreases computational complexity of bit allocation.

***Index Terms*—** Multiple description coding, 3D geometry, computer graphics, wavelets, FEC.

1. INTRODUCTION

With an increasing demand for visualizing and simulating three dimensional (3D) objects in applications such as video gaming, engineering design, architectural walkthrough, virtual reality, e-commerce, scientific visualization and 3DTV, there has been a great amount of research for efficient representation of 3D data [1] [2]. Among different representations, triangular 3D meshes are very effective and widely used. Typically 3D mesh data consist of geometry and connectivity data. While the geometry data specify 3D coordinates of vertices, connectivity data describes the adjacency information between vertices.

To maintain a convincing level of realism, many applications require highly detailed complex models represented by 3D meshes consisting of huge number of triangles. Due to storage space and transmission bandwidth limitations, there has been a great effort of research on efficient compression of 3D meshes [1] [2]. On the other hand, problem of transmitting 3D meshes through error-prone channels is not tackled as seriously. For example, in a typical network packets may be lost or delayed because of congestions and buffer overflow. In this paper, we propose a Multiple Description Coding method for efficient transmission of 3D meshes in a packet loss network in which packets are either received correctly or lost independently of each other with a given probability. Aim is to achieve best reconstruction quality with respect to channel bandwidth and probability of loss rate.

Multiple Description Coding (MDC) is an error-resilient coding method suitable for information, which can be represented with different levels of quality. The source is encoded into several bitstreams (i.e. multiple descriptions to be transmitted via independent channels). In the receiver, source can be reconstructed by any single bitstream at lower but still acceptable quality. Higher quality is achieved if more bitstreams are received. Representing the source with different levels of quality makes MDC similar to layered coding. However, while the latter requires correct reception of the base layer for the enhancement layers to be useful, the former can reconstruct the source from any subset of bitstreams. Some of the areas where MDC can be used are combatting packet losses, transmission through multipath channels and distributed storage [3].

Research for MDC of meshes is not as mature as MDC of images or video. In [4], multiple descriptions are generated by splitting the mesh geometry into submeshes and including the whole connectivity information in each description. In [5], multiple description scalar quantization (MDSQ) is applied to wavelet coefficients of a multiresolution compression scheme. The obtained two sets of coefficients are then independently compressed by the SPIHT coder. However, in those MDC schemes, descriptions are created with heuristic methods and no optimum solutions are proposed for varying network conditions. In [6], wavelet coefficient trees obtained by Progressive Geometry Compression (PGC) [7] algorithm are partitioned into multiple descriptions. Each set of trees are independently coded with SPIHT [8]. In this scheme, bit-rate for each set is optimized for a given PLR.

In this paper, we propose a MDC scheme for packet-loss resilient coding of 3D geometry data. Our algorithm is based on unequal protection of embedded coded bitstream with forward error correction (FEC) codes. Embedded coded bitstream is obtained by compressing 3D mesh with PGC which makes use of wavelet transform and coding of zero-trees with SPIHT.

2. PROGRESSIVE GEOMETRY COMPRESSION

Our algorithm is based on PGC scheme [7]. PGC is a progressive compression scheme for arbitrary topology, highly detailed and densely sampled meshes arising from geometry scanning. The original model in PGC is remeshed to have a semi-regular structure which allows subdivision based wavelet transform. The obtained semi-regular mesh undergoes a loop-based or butterfly-based wavelet decomposition to produce a coarsest level mesh and wavelet coefficients [7]. Since coarsest level connectivity is irregular, it is coded by Touma and Gotsman (TG) coder. Zero-trees consisting of wavelet coefficients are coded with SPIHT algorithm. For improved progressivity, a predetermined number of bit-planes of the coarsest level geometry can be transmitted initially with the coarsest level connectivity and refinement bit-planes can be transmitted as the SPIHT coder descends a given bit-plane of wavelet coefficients [7].

3. ALGORITHM

The application of FEC-MDC algorithm to image coding is described in [9]. The basic idea of the algorithm is to assign unequal amounts of FEC symbols to different parts of the bitstream of a progressive coder according to their contributions to overall reconstruction quality. If the compression algorithm generates an embedded bitstream (e.g. SPIHT [8]), classification of importance of compressed data symbols is obtained due to embedded coding structure, i.e. order of importance of bytes and order of bytes in the bitstream are the same.

An example FEC assignment for a SPIHT coded bitstream is illustrated in Table 1. In this example 17 data symbols are coded with 8 FEC symbols; thus, a total of 25 symbols is transmitted. Since early parts of the bitstream are more important, more FEC symbols are assigned. Receiving any two descriptions allows to decode symbols 1 and 2. Similarly, receiving any three of descriptions allows to decode symbols 1 to 8. As Reed-Solomon (RS) codes are used for FEC, only the number of the received descriptions matters for reconstruction.

	D_1	D_2	D_3	D_4	D_5
Code 1	1	2	FEC	FEC	FEC
Code 2	3	4	5	FEC	FEC
Code 3	6	7	8	FEC	FEC
Code 4	9	10	11	12	FEC
Code 5	13	14	15	16	17

Table 1. The example of FEC-MDC. In this example D_j means Description j and Code i means RS code (n, k_i) with $n = 5$ and k_i is equal to the number of non-FEC symbols in the i-th row.

Bitstream of 3D geometry codes used in this paper starts with compressed coarsest level connectivity as it is the most important part. The whole mesh connectivity depends on coarsest level connectivity due to semi-regular structure. Thus, even loss of one bit makes the whole connectivity and geometry information useless. The next part of the bit-stream is a predetermined number of bit-planes of the coarsest level geometry. Wavelet coefficients are used in the process of subdivision of the coarsest level mesh. Therefore, wavelet coefficient data are meaningless without coarsest level geometry. Remaining part of the bit-stream consists of the output of SPIHT algorithm and remaining bit-planes of coarsest level geometry, which are inserted at the end of each refinement pass of SPIHT algorithm.

Then, algorithm assigns optimum set of FEC symbols in order to minimize the expected distortion subject to a packet loss probability model. For the optimization of bit allocation, algorithm from [10] is used in this paper. The channel is simulated by a simple packet loss model. Each packet is assigned a probability of loss (packet loss rate) independently of other packets.

4. DISTORTION METRIC

There is no immediate objective distortion metric in 3D meshes like mean-square error in images. One of the most popular and robust objective distortion metric is L^2 distance between two surfaces. L^2 between two surfaces X and Y is defined as

$$d(X,Y) = \left(\frac{1}{area(X)} \int_{x \in X} d(x,Y)^2 dx \right)^{1/2}, \quad (1)$$

where $d(x, Y)$ is the Euclidean distance from a point x on X to the closest point on Y. Since the distance is not symmetric, it is symmetrized by taking maximum of $d(X, Y)$ and $d(Y, X)$. Usually this distance is calculated by sampling vertices, edges and triangles and taking root mean square value of shortest distances from points in X to surface Y. We use Metro tool [11] to calculate the distance. However after the samplings, calculation of the distance becomes an expensive operation. Therefore, long off-line computations are required because FEC assignment algorithm [10] requires a distortion-rate (D-R) $D(R)$ curve of the compressed 3D mesh. Therefore we approximate L^2 distance by disabling sampling of edges and triangles to accelerate distortion computation at the expense of poorer approximation. Then, distortion simply becomes root mean square of shortest distances from original vertices to target surface. Although speed of L^2 distance computation is considerably increased with this scheme, still for every $D(R)$ point, inverse wavelet transform should be taken that causes long processing time.

5. DISTORTION-RATE FUNCTION MODELING

To further increase the distortion calculation speed we employed the distortion-rate curve modeling presented in [12] for coding of images. We have found that output of PGC 3D-mesh coder can also be approximated with model from [12]. Only several D-R samples are required to approximate actual $D(R)$ curve that considerably decreases the amount of computations. In our experiments, we used a Weibull model [12]. The Weibull model is

$$D(R) = a - be^{-cR^d}, \quad (2)$$

where real numbers a, b, c, and d are parameters, which depend on the D-R characteristics of the source and the bit stream. As there are four parameters in this model, $D(R)$ curve can be found by using at minimum four points. This model can approximate both L^2 and PSNR curves. To fit this model to D-R samples, we used nonlinear least-squares regression.

Fig. 1 shows the comparison of true operational $D(R)$ curves and their Weibull models. The models are $D(R) = -412.047 + 412.047e^{0.469R^{-1.543}}$ and $D(R) = 82.78 - 142.05e^{-0.216R^{0.269}}$ for L^2-distance and PSNR correspondingly.

One can see that the model closely approximates the real data. Moreover, the model has a nice feature of convexity, which is desirable for bit allocation algorithm.

6. EXPERIMENTAL RESULTS

We have performed the experiments on model *Bunny*. In the experiments, model *Bunny* is coded at 22972 Bytes (5743 Bytes per each description). The reconstruction distortion is relative L^2 error, which is calculated with Metro tool [11]. Relative error is calculated by dividing L^2 distance to the original mesh bounding box diagonal. The error is shown in the figures in units of 10^{-4}. We also provide the same numbers in PSNR scale where PSNR $= 20 \log_{10} peak/d$, $peak$ is the bounding box diagonal of original model, and d is the L^2 error.

In the experiments, we compare the proposed coder with the coder TM-MDC of [6]. Fig. 2 shows reconstruction from different number of descriptions. In the figure, label L^2 *distance* method corresponds to using L^2 distance obtained by metro tool, *approximate* L^2 distance method corresponds to using approximate L^2 distance value obtained by disabling face and edge samplings in metro tool and label *Weibull model* method corresponds to using $D(R)$ curve obtained by modeling original $D(R)$ curve with 10 values of L^2 distances during optimization procedures. Both MDC coders are optimized for PLR = 5%. As one can see, both MD coders outperform unprotected SPIHT except for the case, when all the descriptions are received. The TM-MDC achieves higher PSNR for reconstruction from one description, but lower PSNR for reconstruction from three descriptions. We think that this can be strongly connected with the

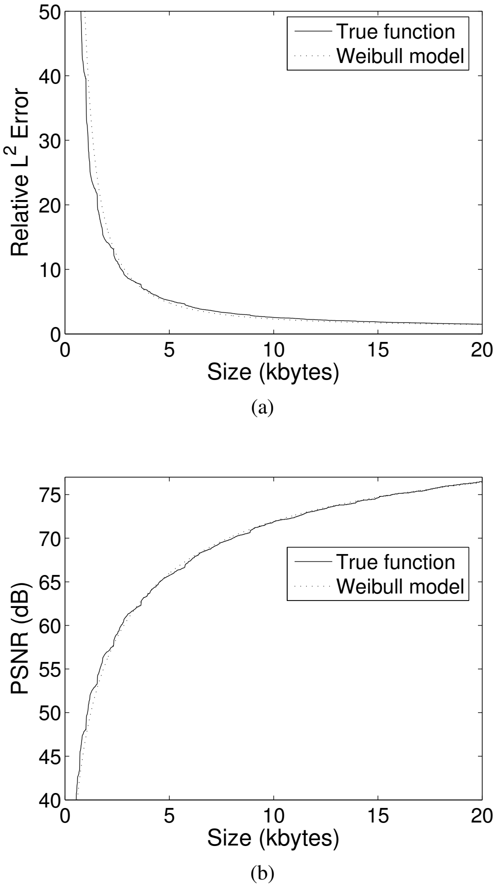


Fig. 1. Comparison between the Weibull model (10 points) and operational $D(R)$ curve (L^2) for *Bunny* model. (a) Relative L^2 error; (b) PSNR.

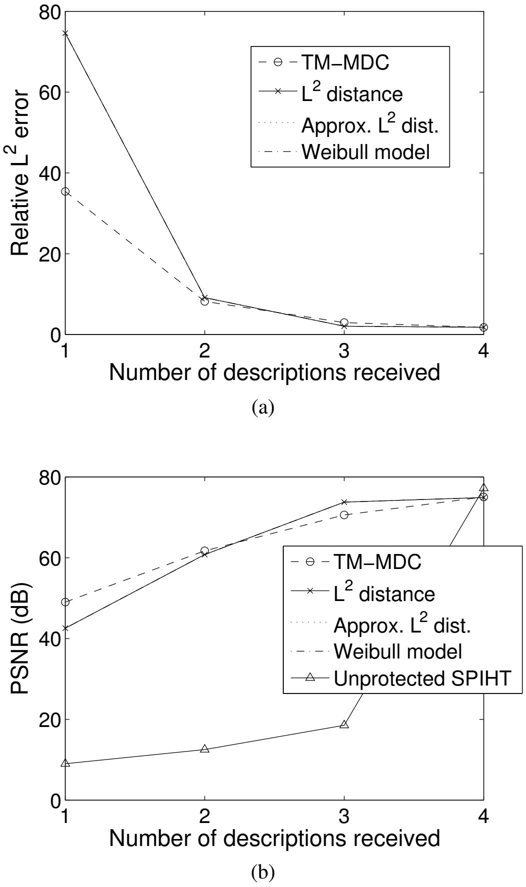


Fig. 2. Reconstruction from different number of descriptions (PSNR) for *Bunny* model. (a) Relative L^2 error; (b) PSNR.

fact that each description in TM-MDC method includes whole coarsest level geometry while descriptions in our method does not contain all bitplanes of coarsest level geometry. Another observation is that results of L^2 *distance*, *approximate* L^2 and *Weibull model* methods are indistinguishable in the figure which proves the success of modeling. Therefore in the rest of the paper, we present results of *Weibull model* method.

Fig. 3 compares the average performance in the lossy environment of the proposed coder using L^2 distance, approximate L^2 distance, Weibull model with the performance of unprotected SPIHT and TM-MDC coder from [6]. As seen in the figure, the proposed approach shows competitive results compared to approach [6] and considerably outperforms unprotected SPIHT.

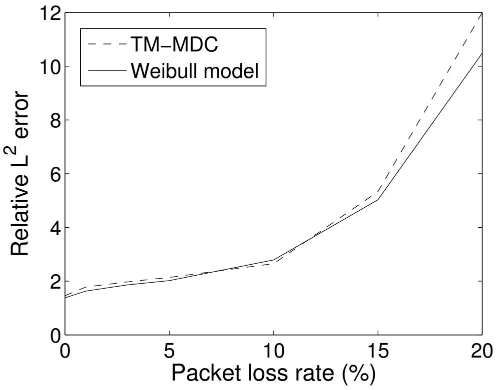
Although the proposed method shows similar performance with TM-MDC in terms of expected distortion, it has several advantages. While the proposed method generates one compressed bitstream to optimize FEC assignment for different total number of descriptions, TM-MDC needs to generate different compressed bitstream to optimize for different total number of descriptions. The reason is that the set of wavelet coefficient trees to be assigned to descriptions differs with respect to different total number of descriptions. Therefore our algorithm can produce any number descriptions using the same compressed bitstream whereas TM-MDC method needs to have the knowledge of total number of descriptions to be able to generate bitstreams for optimization of bit allocation for each description. Another advantage of our method is that TM-MDC needs to include whole coarsest level geometry in each description whereas our method spreads the bitplanes of coarsest level geometry according to their importances in compressed bitstream. In this way more important compressed wavelet coefficients are assigned more FECs than lower bitplanes of coarsest level geometry and these bitplanes are not included in each description unless they are assigned repetition codes by optimization algorithm.

Among three methods to obtain $D(R)$ curves for the optimization, L^2 distance method turns out to give slightly better results in terms of expected distortion as expectedly. While approximate L^2 method performs almost as good as L^2 method (0.02 dB worse), it runs much faster to obtain D-R pairs. Another observation is that Weibull model method with only 10 samples performances only slightly worse (0.07 dB) than L^2 distance method. With calculation of only 10 D-R samples, Weibull model method outperforms the other methods in terms of computation time. Therefore algorithm's speed is increased considerably at the expense of only 0.07 dB loss.

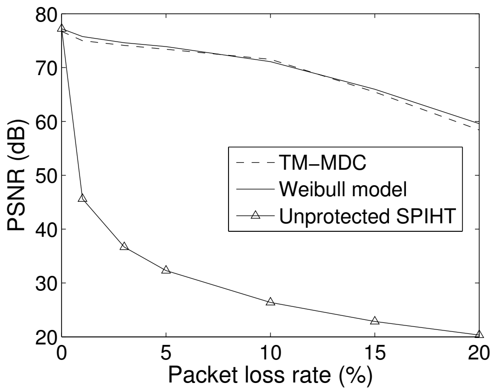
Finally, Table 2 shows redundancies obtained by bit allocation algorithm for different $D(R)$ curves and packet loss rates.

	Redundancy (%) for different PLR					
Packet loss rate	PLR=1%	PLR=3%	PLR=5%	PLR=10%	PLR=15%	PLR=20%
L^2 distance	13	23	32	43	47	53
Approx. L^2 distance	12	24	33	43	47	51
Weibull model	16	27	34	44	50	55

Table 2. Redundancy obtained by bit allocation algorithm for different PLR.



(a)



(b)

Fig. 3. The comparison of the proposed MD-FEC with TM-MDC coder from [6]. (a) Relative L^2 error; (b) PSNR.

7. CONCLUSIONS

We have proposed an MDC-FEC algorithm for coding 3D-meshes. Our MDC coder is based on the PGC scheme [7], in which wavelet transform is applied to the semi-regular remeshed model, and wavelet coefficients trees are coded with the SPIHT algorithm. Stronger FEC is allocated to the beginning of SPIHT stream, while less or no FEC bits are allocated to the end of bit-stream. The algorithm generates multiple descriptions and is optimized for changing packet loss rate and channel bandwidth. Using the Weibull model instead of the real $D(R)$ function during optimization considerably decreases the time needed for bit allocation while achieving similar average reconstruction quality.

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