AN ENHANCED EDGEBREAKER COMPRESSION ALGORITHM FOR THE CONNECTIVITY OF TRIANGULAR MESHES

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Abstract: Compression of digital geometry models is the answer to an industrial demand. Over the last years, many exciting ideas and new theoretical insights have been devoted to finding ways of reducing the amount of storage such models absorb. EdgeBreaker is one of the effective lossless single-rate connectivity compression techniques for triangular meshes. This paper presents an enhanced EdgeBreaker encoding algorithm which solves the problem of non-linearity of EdgeBreaker decoding procedure while reconstructing the mesh triangles in the same order they were traversed during the encoding phase. The new enhancement is based on the same data structure: the corner-table used by EdgeBreaker however, it eliminates some of the computational overhead exhibited by EdgeBreaker compression. This enhanced technique also yields to significantly smaller rates for connectivity compression than EdgeBreaker. It achieves an average compression ratio of 1.8 bit per triangle and 3.57 bit per vertex for the used benchmark 3D models.

1 INTRODUCTION

Interactive display of 3D content has been extensively used in many applications ranging from electronic commerce to the virtual game industry. Among several representations, polygonal meshes are used most often as surface representation (Abd El-Latif, Ghaleb and Hussein, 2006) because of their wide spread support in many file formats and graphics libraries. These large and complex meshes are becoming commonplace because of the increasing capabilities of the computing environments, visualization hardware, modern interactive modelling tools and semi automatic 3D data acquisition systems. The complexity of these models poses basic problems of efficient storage in file servers, transmission over computer networks, rendering, analysis, processing etc. for these reasons it was desirable to compress polygonal meshes to reduce storage and transmission time requirements.

Geometry compression techniques for such very large 3D geometric models have thus become a subject of intense study in recent years. The compression approach is one of the primarily approaches for reducing the size of a mesh. It depends on deriving a new encoding for the polygonal mesh such that the total number of bits needed in the new encoding is much lower than the number needed for the uncompressed representation. Large body of compression research has concentrated on clever encoding of the mesh connectivity. Typically (Shikhare, 2000), the number of triangles in a mesh is roughly twice the number of vertices and each vertex is referenced in 5 to 7 triangles, which means that large part of the representation of the model is in the definition of connectivity. Also the combinatorial graph structure of the mesh connectivity allows it to be coded losslessly, so it can be restored to the original model after decoding.

Prior Works. Much of the work in the area of single-rate connectivity compression has been concerned with triangle meshes only (Allie and Gotsman, 2005) This is because the triangle is the basic geometric primitive for standard graphics rendering hardware and also it can be easily derived from other surface representations. Many compression schemes have been emerged recently using different approaches such as focusing on hardware decoding (Deering, 1995 and Chow, 1997), applying mesh traversal (Gumhold and Strasser, 1998 and Rossignac, 1999) and using valence-based incidence compression (Touma and Gotsman, 1998 and Alliez and Desbrun 2001).

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Among these techniques, EdgeBreaker (Rossignac, 1999) is considered one of the best connectivity compression techniques for compressing simple manifold triangular meshes that are homeomorphic to a sphere. It achieved bit rates of 2 bit per triangle (bpt) and 4 bit per vertex (bpv). As this result was the best achieved so far, many derivatives of the EdgeBreaker algorithm had appeared. Using a slightly more complex code, King and Rossignac (King and Rossignac, 1999) guaranteed that the compressed file will not exceed 1.83t bits and 3.67v bits. The algorithm was further optimized for meshes with regular connectivity (Szymczak, King and Rossignac, 2001). In (Rossignac, Safonova and Szymczak, 2002) the same algorithm was introduced with a simple data structure, the Corner-Table for representing the connectivity of triangle meshes. Again the algorithm was extended with a simple formulation to deal with triangulated surfaces with handles (Lopes, Rossignac, Safonova, Szymczak and Tavares, 2003). Finally the authors in (Lewiner, Lopes, Rossignac, and Vieira 2004) provided efficient extensions of the EdgeBreaker compression which enables to use the EdgeBreaker algorithm to encode the connectivity of a surface, possibly having any number of connected components, handles or boundary curves.

While the encoding scheme of EdgeBreaker (Rossignac, 1999) exhibits a linear storage cost, some preliminary preprocessing steps were required in the decoding phase making it exhibits a non-linear time complexity of $O(n^2)$. More recent work (Rossignac and Szymczak, 1999) eliminated the need for this look-ahead procedure and improved the worst case complexity to $O(n)$. However this algorithm requires multiple traversals of the mesh triangles for meshes with handles and an initial traversal of the encoding for meshes with boundary. Another simple decoding technique (Isenburg and Snoeyink, 2001) was developed that recreates the triangles encoded by EdgeBreaker in linear time unless this was done in the reverse order these triangles were encoded.

Contributions. The main work of this paper is based on the work of EdgeBreaker (Rossignac, Safonova and Szymczak, 2002) developed by Rossignac et al. The EdgeBreaker encoding procedure is enhanced to allow the decoding phase to be implemented in linear time complexity without any additional preprocessing and in the same order the mesh is traversed during the encoding phase. Further more, this enhancement eliminates the computational overhead implemented by using extra data structures and also improves the compression ratio generated by the original procedure (Rossignac, 1999) to 1.8 bpt and 3.57 bpv.

The remainder of this paper is organized as follows: in the next section the EdgeBreaker encoding and decoding schemes are explained. A detailed description of the algorithm can be found in (Rossignac, 1999 and Rossignac, Safonova and Szymczak, 2002). Section 3 illustrates the new improvement done to the encoding algorithm of EdgeBreaker. The results and discussions are presented in section 4 and we conclude in section 5.

2 EDGEBREAKER ENCODING AND DECODING

The EdgeBreaker encoding process visits the triangles in a spiraling (depth-first) order and produces a CLERS string. The CLERS string includes five different operations called C, L, E, R, and S. The encoding process starts off with picking an arbitrary triangle of the mesh as an initial active boundary. One of the three initial boundary edges is defined to be the gate of the boundary. An initially empty stack is used to temporarily store boundaries. This process terminates after t-1 operations, with t being the number of mesh triangles. Which operation is chosen depends on how the respective triangle is attached to the active boundary at the moment it is processed (Figure 1). If its third vertex is not on the active boundary then operation C is used and the new gate is the right edge of the old gate. If the third vertex is the next boundary vertex then operation R is used. If it is the previous boundary vertex then operation L is used. In both R and L operations the new gate is the inserted boundary edge. If the third vertex is some other boundary vertex, then operation S is used. The left edge of the old gate is pushed on the stack and the other becomes the active gate. If the third vertex is the previous and the next boundary vertex then operation E is used. This can only happen for an active boundary of length three.

For triangle meshes with v vertices and t triangles that are homeomorphic to a sphere, t equals $2v$-4 (Rossignac, 2003). Because, except for the first two vertices, there is a one-to-one mapping between each C triangle and each vertex, the number of C triangles is v–2. Consequently, the number of non-C triangles in a simple mesh is t–(v–2), which is also v–2. Thus exactly half of the triangles are of type C. using A straight-forward compression scheme that uses the following simple binary code for the labels

(C=0, L=110, E=111, R=101, S=100) is guaranteed to use no more than $2t$ or $4v$ bits.

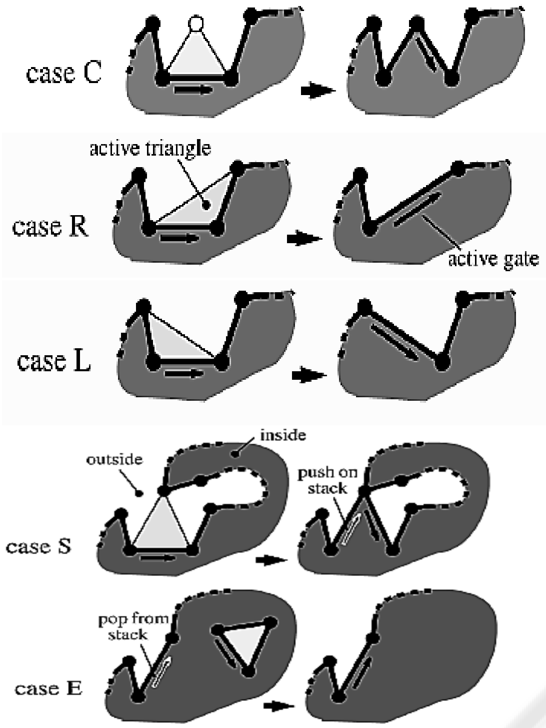


Figure 1: EdgeBreaker encoding operations.

The EdgeBreaker decoding process starts with a CLERS string and produces a triangulated mesh. Two traversals of the CLERS string are needed: The preprocessing phase computes an offset value for every S operation. The offset value is the distance between the active gate and the tip vertex along the active boundary. These offset values are calculated by adding up the resulting change in boundary length for all operations following an S operation until and including its corresponding E operation. Since pairs of S and E operations are always nested, the offset values for all S operations can be computed in a single traversal (Figure 2).

The other decoding phase is the generation phase which creates the triangles in the same order they were encoded by the EdgeBreaker encoding process. It starts with creating the initial triangle. The active boundary and the gate are identified and the CLERS string is processed. For the C operation a new vertex is created. For all other operations a vertex from the active boundary is used. For the R operation the third vertex is the next vertex on the active boundary and for the L operation the third vertex is the previous vertex on the active boundary. For the S operation the precomputed offset value is used. When the E operation occurs, the active boundary consists of only three boundary edges leaving no choice for the third vertex. If the active boundary is maintained in a linear data structure, each S operation will require a linear search for the vertex specified by the offset implying an asymptotic worst case time complexity of $O(n^2)$ for the EdgeBreaker decoding.

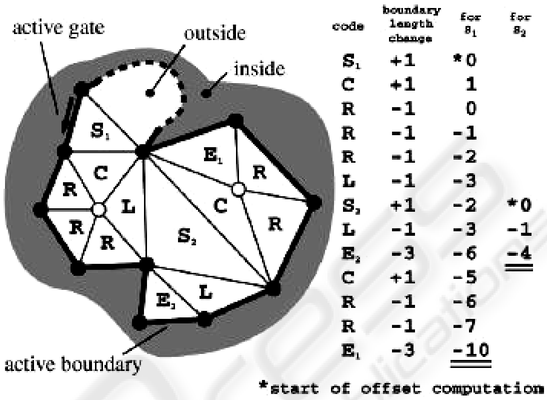
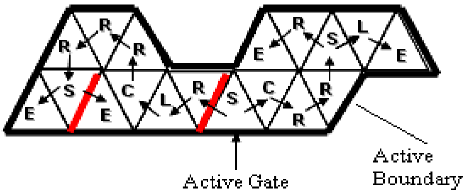


Figure 2: EdgeBreaker decoding operations.

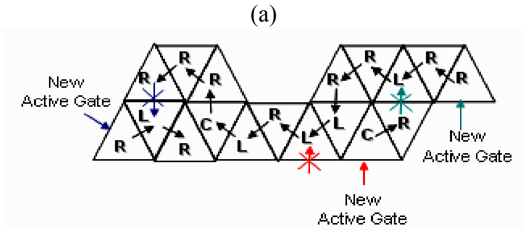
3 ENHANCED EDGEBREAKER ENCODING

The breakthrough of EdgeBreaker lies in the discovery that the locations of the tips of the S triangles need to be stored neither as integer references nor as offsets which separate the gate from the tip location in the current loop. They discovered that these offsets can be recomputed by the decoding algorithm from the CLERS string itself. This solution minimizes the encoding size and improves the compression ratio while it leads for the nonlinearity of the decoding algorithm. The new enhancement of EdgeBreaker tries to keep advantage of not saving the offsets as part of the encoding while in the same time eliminate the need of computing them as a preprocessing stage during decompression.

The S triangle in EdgeBreaker compression scheme splits the active boundary into two, one on each side of the S triangle. The algorithm then tends to fill the hole generated in the mesh surface on the right side of the S triangle before returning to the left one. This required keeping a stack for storing the left edge of every S triangle to be the next active gate (Figure 3a). The new enhancement developed here performs the same traversal of the EdgeBreaker compression but only differs in the way it deals with the S triangles. Whenever an S triangle is reached, the algorithm tends to ignore encoding it at the moment and the active gate is changed to another location and then the traverse keeps going on. This is done by moving on the active boundary one step to the right of the current active gate (Figure 3b).



(a)

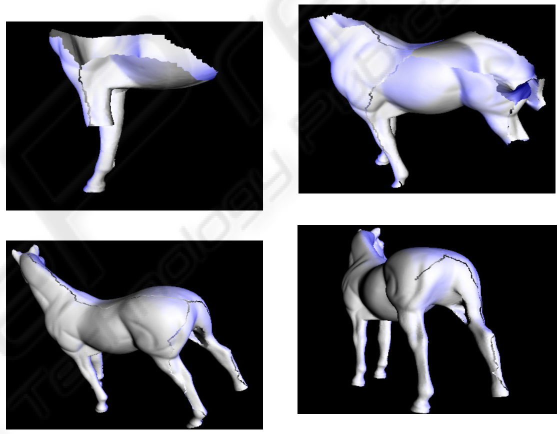


(b)

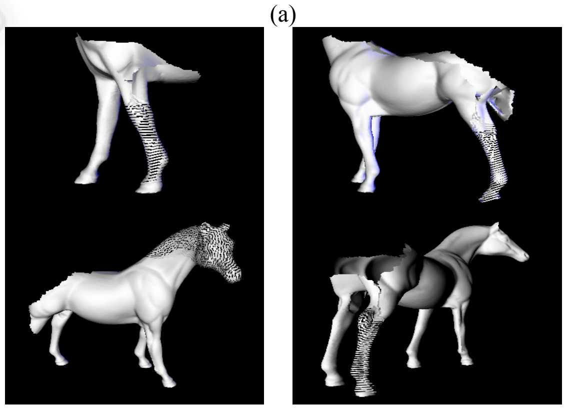
Figure 3: Encoding example of the final eighteen operations of a mesh. (a) EdgeBreaker encoding, The red edges show the ones being stored in the stack; (b) Enhanced EdgeBreaker encoding, The arrows show how the active edge is changed during traversal.

This approach ensures that all the previously ignored S triangles are going to be revisited again as long as they are not encoded so far but from another gate – usually the pervious right edge – which will change the triangle state to an L triangle. This enhancement eliminates the case of S and E triangles from the CLERS string while it presents another symbol M that does not interpret a triangle case but only tells the decoding algorithm that the current active gate will be changed to another location some where on the active boundary just right to the current one. Keeping the same notations of the C, L and R triangles, the encoding string has been changed to the CLRM string. The elimination of the S case from the encoding string makes the active boundary never split. The algorithm in this case needs only to maintain one circular linear list for active boundary during compression and decompression. In addition, the enhanced technique has eliminated both the recursive overhead exhibited by the original EdgeBreaker compression algorithm and the computational overhead needed by the stack to keep list of new active gates generated after splitting. During the decompression process it eliminates the need for the preprocessing step, the algorithm only traverses the encoded string once to regenerate the mesh triangles in the same order they were encoded and thus maintaining a linear time complexity of the decoding process *O*(n).

While the first version of the developed enhancement algorithm adopted the idea of moving to the right of the active gate whenever an S triangle is reached, a serious problem has emerged. The original encoding algorithm of EdgeBreaker ensures that all the triangles in the hole generated to the right of the S triangle are visited before directing to the left one. Instead the modification applied here so far by the enhanced algorithm does not maintain this feature, meaning that the algorithm can traverse part of the mesh right to the S triangle and then bypass it in its reverse course - without encoding - to the other part of the mesh surface on its left. While the implemented linear list of boundary edges is circular, it means that this track can be repeated for many levels. At each level both areas of the mesh surface to the left and right of the original S triangle is being shrinking, giving a chance for other S triangles to appear until leading to a very long strip of consecutive S triangles.



(a)



(b)

Figure 4: Steps of mesh generation for the Horse model. (a) Using the CLRM string; (b) using the CLRGF string.

Notice the long line of un-encoded triangles generated along the mesh while traverse (figure 4a). This line begins to appear in parts of the mesh wherever the boundary tends to meet at a closed point. In the horse example the line first begins to appear in the front left leg, extends to the horse neck, the back left leg and then to the back right leg respectively. This long strip will not be encoded until one of the mesh surfaces on the right or the left of the original S triangle is encoded completely. This long strip which is traversed many times will result in much increase in the encoding string size and hence lead to minimize the compression ratio instead of trying to maximize it.

In order to solve the emerging problem of the long chain of S triangles, the second version of the enhanced algorithm updated the procedure to allow moving along the active boundary either to the right or to the left of the current active gate whenever an S triangle is reached. This choice is decided according to which boundary on the right or the left is shorter in length. The boundary length is calculated by the number of edges it contains. The M symbol is now replaced by other two symbols G and F which are used to differentiate between either to move one step to the right or to the left of the current active gate. The final encoding string introduced by the enhanced EdgeBreaker compression scheme becomes the CLRGF string. Figure 4b shows that the problem of the long chain of un-encoded triangles previously mentioned does not exist any more. Each of the four parts of the horse example is encoded completely before directing to another part of the mesh. The pseudo-code of the proposed encoding procedure is provided in the frame below.

Input:
  Connectivity and geometry of the mesh in the CornerTable format.
Output:
  CLRGF string that contains one symbol per triangle except for the first triangle.
Procedure Compress()
 While (**True**)
  If tip vertex is not visited **Then**
   Append encoding of C to the CLRGF string,
   Add tip vertex to the list of vertices,
   Mark triangle and tip vertex as visited,
   Update active gate to the right edge of the old gate input
  Else If right triangle was visited **Then**
   Append encoding of R to the CLRGF string,
   Mark triangle as visited,
   If left triangle was visited **Then**
    End Procedure
   Else
    Update active gate to the new inserted boundary edge
  Else If left triangle was visited **Then**
    Append encoding of L to the CLRGF string,
    Mark triangle as visited,
    Update active gate to the new inserted boundary edge
  Else
   Calculate right and left boundary lengths
   If the right boundary length is less than the left boundary length **Then**
    Append encoding of G to the CLRGF string,
    Update active gate to the right edge of the old one
   Else
    Append encoding of F to the CLRGF string,
    Update active gate to the left edge of the old one

4 RESULTS AND DISCUSSION

Table 1 presents the data of the test case meshes shown in Figure 5. All the meshes are triangular, manifold, without boundary, holes or handles. Associating the following binary code based upon Huffman coding (Huffman, 1952) for the labels (C=0, R=10, L=110, G=1110, F=1111) used in the CLRGF string leads to the best compression ratio that can be achieved. This selection is based on a study of the average percentage each symbol consumes from an encoding file generated to each of the 3D models used.

Table 1: Used benchmark 3D models.

File name	File size	No of triangles	No of vertices
Retinal	240 KB	7,282	3,643
Cow2	304 KB	8,626	4,315
Smooth-feature	416 KB	12,350	6,177
Egea	534 KB	16,532	8,268
Head	1 MB	32,744	16,374
Horse	4.62 MB	96,966	48,485
Armadillo	11.9 MB	345,944	172,974
Vase-Lion	14.6 MB	400,000	200,002

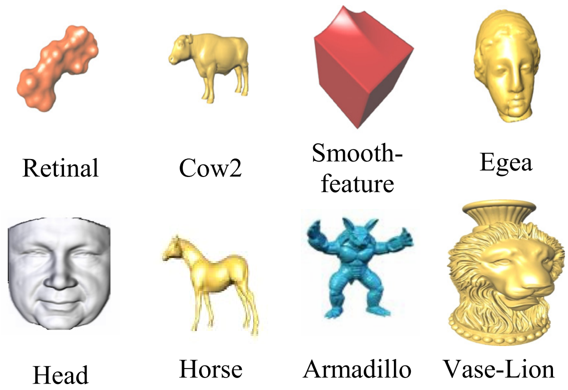


Figure 5: Benchmark 3D models.

It is apparent from figure 6 that the largest percentage of the triangles is of type C; this is because each C triangle is related with the introduction of a new vertex in the sequence of mesh vertices. The percentage of R triangles is very close from the C one; they both consume about 88.72 % on the average from the total number of symbols used to encode a mesh. The rest of the symbols is distributed between L triangles and symbols G and F which give an indication of finding an S triangle and so the need of movement along the boundary list. The two percentages of L; and G plus F together are very close. This ensures that most of the S triangles which were ignored for the first time during traversal are encoded afterwards as L triangles.

Table 2 lists the compressed file size written in binary format and the compression ratio achieved in file size, per triangle and per vertex for every test case of the 3D models used. The compression results vary from 1.52 bpt and 3.04 bpv (Head example) to 2.16 bpt and 4.31 bpv (Cow2 example). This variation is due to the different percentage of S triangles occurrence during mesh traversal which leads to the addition of symbols G or F to the encoding string (Figure 6).

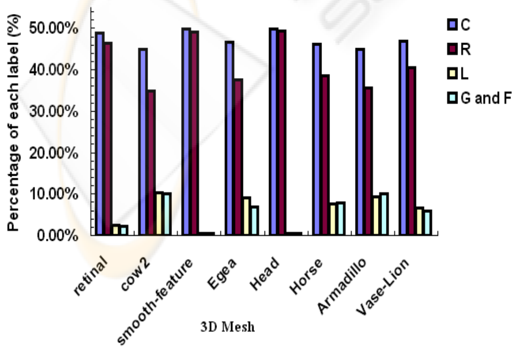


Figure 6: Frequency percentage each symbol consumes from encoding data file.

This percentage of occurrence depends mainly on the shape characteristics and it represents the main parameter controlling the compression ratio that can be achieved to the mesh. It appears from the used examples that the largest occurrence which leads to the smallest compression ratio in file size happens to the Cow2, Armadillo and Horse examples respectively. This is due to their shape characteristics; legs of the Horse and Cow2 examples and legs and arms of the Armadillo example.

Table 2: Comprssion results.

File name	Connectivity size		Compression ratio		
	Uncompressed	**Compressed KB**	**file size %**	**bpt**	**bpv**
Retinal	124 KB	1.47	98.8	1.61	3.23
Cow2	172 KB	2.3	98.65	2.16	4.31
Smooth-feature	222 KB	2.35	98.94	1.52	3.05
Egea	304 KB	4	98.68	1.89	3.77
Head	608 KB	6	99.01	1.52	3.04
Horse	1.87 MB	24.21	98.7	1.99	3.99
Armadillo	6.95 MB	93.04	98.66	2.15	4.30
Vase-Lion	8.9 MB	91.26	98.97	1.83	3.65
Average			98.92	1.8	3.57

According to the binary code associated to each symbol, an average compression ratio of 1.8 bit per triangle and 3.57 bit per vertex is achieved. This result is improved over the results obtained by EdgeBreaker (Rossignac, 1999) and its derivative (King and Rossignac, 1999). Connectivity information is compressed according to the file size with an average of 98.92%. The encoding algorithm is also barely sensitive to the seed triangle; therefore a random face can be selected without affecting the achieved results much. The compression ratios of connectivity file size, in bit per triangle and in bit per vertex are calculated according to equations 1, 2 and 3 respectively.

$$\frac{\text{No. of uncompressed bits - no. of compressed bits}}{\text{No. of uncompressed bits}} \quad (1)$$

$$\frac{\text{No.of compressed connectiv ity bits}}{\text{No.of triangles}} \quad (2)$$

$$\frac{\text{No.of compressed connectiv ity bits}}{\text{No.of vertices}} \quad (3)$$

5 CONCLUSION

In this paper, we described an enhanced lossless single-resolution connectivity encoding algorithm that is based on the algorithm of EdgeBreaker (Rossignac, 1999) and uses the same data structure of (Rossignac, Safonova and Szymczak, 2002). The enhanced algorithm allowed the decoding procedure to run in linear time complexity and the triangles to be generated in the same order they were encoded. It eliminates the computational overhead consumed by stack operation and the recursive procedure of traversing. The new enhancement led to the elimination of both S and E cases and introducing new symbols G and F which results in changing the encoding string used to the CLRGF string. The achieved result was encouraging as it improved the late achieved results into 1.8t and 3.57v bits for representing the mesh connectivity. This enhancement can be further applied to meshes with boundary, holes and non-manifold meshes. The future work is to extend the algorithm to non-triangular meshes.

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