EFFICIENT FACE-BASED NON-SPLIT CONNECTIVITY COMPRESSION FOR QUAD AND TRIANGLE-QUAD MESHES

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Abstract: In this paper we present an efficient face-based connectivity coding technique for the special class of quadrilateral and the hybrid triangular-quadrilateral meshes. This work extends the main ideas of non-split encoding presented by the first contribution of the authors (Khattab, Abd El-Latif, Abdel Wahab and Tolba, 2007) for triangle meshes and improves over the compression results provided so far for existing face-based connectivity compression techniques. It achieves an average compression ratio of 2.17 bits per quad and per vertex for simple quadrilateral meshes and bit rates of 1.84 bits per polygon and 1.85 bits per vertex for the simple hybrid triangle-quad meshes.

1 INTRODUCTION

While a picture is often said to be worth a thousand words, a 3D model could be said to be worth a thousand pictures. Polygonal meshes are used most often as surface representation because of their wide spread support in many file formats and graphic 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. Therefore, efficient 3D mesh compression algorithms have been in high demand in the past few years to reduce the storage room needed for large, detailed 3D models and to consequently decrease transmission time over a network.

Much of the work done in the area of single-rate mesh connectivity compression has focused on triangle meshes only (Deering, 1995, Chow, 1997, Gumhold and Strasser 1998, Rossignac, 1999, Touma and Gotsman, 1998 and Alliez and Desbrun 2001). However there are a significant number of non-triangular meshes in use. These models contain a surprisingly small percentage of triangles likewise; few triangles are generated by tessellation routines in existing modelling software. The dominant element in these meshes is the quadrilateral, but pentagons, hexagons and higher degree faces are also common (Alliez and Gotsman, 2005). The extension of the previously mentioned algorithms to deal with non-triangular meshes is not obvious. Hence, in practice, non-triangular meshes are coded by triangulating them, coding the results using one of the methods of coding triangular meshes and storing additional information describing the extra edges introduced during the triangulation stage. These edges are discarded after decoding to restore the original polygonal model. This means that the code of a non-triangular mesh might be larger than that of the triangular version, instead of being shorter, as less connectivity information is present.

In addition, it is beneficial for storage purposes to keep a mesh in its native polygonal representation than to triangulate it. This is because most meshes have associated properties such as normal, colour, or texture information that account for a large portion of the storage cost. Triangulating a polygon mesh not only adds an extra processing step, but also increases the number of faces and corners and replicates their associated properties.

1.1 Related Work

To address the problem of compressing the connectivity of non-triangular meshes, several algorithms have been proposed to encode polygonal meshes directly without pre-triangulation. In this section we focus on recent coding methods for manifold meshes that grow a region over the mesh and incrementally encode the mesh elements and their incidence relations to the growing region. The methods are categorized as face-based, edge-based and vertex-based methods according to the type of mesh element playing the dominant role in the compression scheme.

King et al. (King, Rossignac and Szymczak, 1999) first proposed a connectivity coding algorithm for quad or mixed triangle-quad meshes, by generalizing the EdgeBreaker algorithm (Rossignac, 1999 and Rossignac and Szymczak, 1999) which is one of the triangle conquest methods. This method implicitly triangulates each quadrilateral to two triangles and uses sequences of the five basic EdgeBreaker labels (CLERS) to code the different possibilities which then arise. This introduced a compressed format based on entropy coding with a worst case of 2.67 b/v. Isenburg and Snoeyink (Isenburg and Snoeyink, 2000) proposed an edge-based technique called the Face-Fixer. They achieved a connectivity coding cost of 5 b/v for simple triangular meshes and 4 b/v for simple quadrilateral meshes.

Isenburg (Isenburg, 2002) and Khodakovsky et al. (Khodakovsky, Alliez, Desbrun and Schröder, 2002) independently proposed similar vertex-based algorithms to encode the connectivity of a manifold polygonal mesh. Their algorithms are extensions of the valence-driven approaches (Touma and Gotsman, 1998 and Alliez and Desbrun 2001). Isenburg's algorithm provides slightly better compression performance than Khodakovsky et al.'s. They both produce better results compared to the Face-Fixer. Another vertex-based technique is the Angle-Analyzer (Lee, Alliez and Desbrun, 2002). The algorithm focused on the hybrid triangle-quad mesh coding. On average, the algorithm yields 40% and 20% better compression ratios for connectivity and geometry data than the state-of-the-art triangular mesh coder given in (Touma and Gotsman, 1998).

As a face-based technique, Kronrod and Gotsman (Kronrod and Gotsman, 2000) introduced a general and direct technique for coding the connectivity of any non-triangular mesh with an upper bound on the resulting code length. The algorithm generalizes EdgeBreaker technique (Rossignac, 1999) for non-triangular meshes. They proved that for quadrilateral meshes a worst case of 3.5 bits per quad and per vertex can be achieved and a worst case of 4 bits per polygon can be achieved for quad meshes with few triangles.

Two enhancements over the bit rates of Kronrod and Gotsman algorithm were introduced. The enhanced technique of (Mukhopadhyay and Jing, 2003) proved with complex calculations that the bit rates can be reduced to less than 3 b/v. and by equivalence to the work done in (King, Rossignac and Szymczak, 1999) can be reduced to 2.67 b/v. the other enhancement (Kosicki and Mukhopadhyay, 2004) improved the results to 2.4 b/v using arithmetic coding.

1.2 Overview

In this paper we introduce an efficient face-based connectivity coding technique that extends the ideas of non-split coding presented by the authors' first contribution (Khattab, Abd El-Latif, Abdel Wahab and Tolba, 2007) for triangle meshes. The compression results achieved is the best compared to the state-of-the-art face-based techniques for compressing non-triangular meshes. These results are compared to those introduced by Kronrod and Gotsman (Kronrod and Gotsman, 2000) and their enhancements of (Mukhopadhyay and Jing, 2003 and Kosicki and Mukhopadhyay, 2004).

The remainder of this paper is organized as follows: section 2 explains the encoding scheme of Kronrod and Gotsman. Section 3 illustrates the proposed technique for applying the non-split encoding to non-triangular meshes. The results and discussions are presented in section 4 and we conclude in section 5.

2 KRONROD-GOTSMAN SCHEME

The Kronrod-Gotsman scheme (Kronrod and Gotsman, 2000) generalizes the CLRES labelling scheme of EdgeBreaker (Rossignac, 1999) to non-triangular meshes. Their main observation is that as we traverse a mesh in depth-first order, the interaction of each polygon with the rest of the mesh can be enumerated in a finite number of ways. For example, in a quad mesh each quad interacts with the rest of the mesh in one of thirteen types labelled from Q_1 to Q_{13} (figure 1) and hence this interaction can be coded in a unique manner. It is easy to enumerate all these interaction types if we note that each of the remaining three edges of the current quad either belongs to the mesh boundary or does not, and so also for the remaining two vertices.

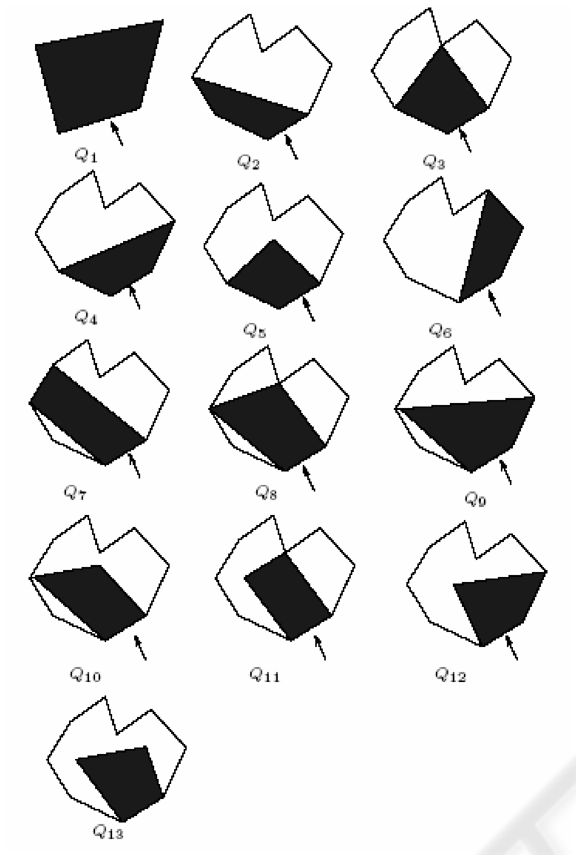


Figure 1: Interaction of a quad with the mesh. Arrows indicate the current gate.

The compression process traverses the mesh in depth- first order starting with a quad. It then records a code of the interaction type of the current quad with the boundary. After the quad is removed from the boundary, the boundary is updated and the procedure repeats. If the interaction type of the removed quad contains gaps (i.e., the quad has at least one touching vertex with the boundary) the boundary will split into two or more boundaries. The boundary is not stored explicitly; otherwise it is maintained implicitly as a stack of gate edges. The procedure terminates when the entire mesh is reduced to nothing. The output of the encoder is sufficient to reconstruct the connectivity data of the mesh. The time complexity of the encoding procedure is linear in the size of the mesh.

The decoding algorithm is inspired by the linear time Spirale Reversi decoder (Isenburg and Snoeyink, 2001). The algorithm is simple however; it processes the mesh in the reverse order of the encoding process. It means that mesh polygons will be reconstructed in an order opposite to which they were encoded. In the encoding process each interaction type defines exactly how this polygon is connected to all generated borders. Hence, if the decoder knows the connectivity in the interior of the boundary after the encoding step and the nature of the interaction between the encoded polygon and the active boundary, it is easy to reconstruct the connectivity of the interior of the active boundary as it was before the encoding step.

The authors provided explicit codes for the interaction types of pure quad mesh and a quad mesh with minority of triangles. For the case of a mesh containing only quads it admits thirteen different interaction types, which requires ($\log_2$ 13) = 4 bits/quad when coded using a fixed-length code. But as not all the interactions occur with equal frequencies they produced a more efficient variable-length prefix code which reduced the total code length to less than 3.5 bits/quad. For the case of hybrid quad and triangle mesh, it admits eighteen different interaction types, which are the summation of the thirteen interaction types of pure quad meshes and the five interaction types of triangular meshes generated by EdgeBreaker (Rossignac, 1999). Again the naïve coding will require ($\log_2$ 18) = 5 bits/quad but using the same variable-length prefix code it was reduced to less than 4 bits/poly.

3 NON-SPLIT ENCODING

The new encoding scheme presented in this paper adapts the main idea of not splitting the boundary while traversing the mesh. This idea was first presented by the authors in their first contribution by introducing an enhanced encoding technique for triangle meshes (Khattab, Abd El-Latif, Abdel Wahab and Tolba, 2007). This technique had updated the CLERS string generated by EdgeBreaker (Rossignac, 1999) to the CLRGF string. This was done by the elimination of S interaction type that causes the active boundary to be split and so the elimination of its delimiter E label. These two labels were replaced by another two labels G and F for moving on the active boundary to the left or the right of the current active gate. This choice was decided according to which boundary length is shorter. The next subsections explain how this idea can be extended for encoding quadrilateral and hybrid triangular-quadrilateral meshes.

3.1 Encoding Quadrilateral Meshes

For applying this technique on quad meshes, the algorithm tends to eliminate the six interaction types

(Q_3 Q_7 Q_8 Q_9 Q_{10} Q_{11}) that cause the boundary to be split from the thirteen interaction types defined by Kronrod and Gotsman (figure 1). This ensures that the active boundary will never split. The interaction type of Q_1 which defines the state of the last reached quad for every generated boundary after splitting will never occur except only once at the end of mesh traversal and so it can be replaced by the label Q_4. By this way the enhanced technique preserves only six interaction types from the whole group of thirteen interaction types defined by Kronrod and Gotsman. These six interaction types are reordered again from Q_1 to Q_6 as can be seen in figure 2.

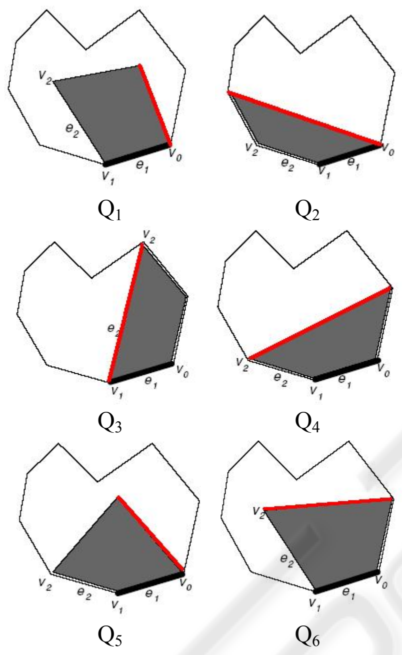


Figure 2: Remaining six interaction types of quad interaction with a mesh. Thick black edges show the current active gates. Thick red edges show the updated active gates for each interaction type.

The eliminated labels are replaced with G and F labels which indicate moving on the active boundary wherever a split case occurs. The encoding string is now changed to $Q_1Q_2Q_3Q_4Q_5Q_6$GF. The elimination of the split casess from encoding string saves for the encoding technique many advantages. The algorithm needs only to maintain one circular linked list for active boundary during compression and decompression. It also has eliminated both the recursive overhead and computational overhead needed by the stack to keep list of new active gates generated after splitting. The decompression processes is done in only one forward pass of traversing the encoding string and reconstructs the mesh quads in the same order they were encoded.

The pseudo-code of the proposed encoding procedure is provided in the frame below. After processing of each quad element, the active gate is updated to the first edge incident to an unprocessed element in the counter clock wise direction from the current active gate. This can be observed by the red edges shown in figure 2. This approach of updating the active gate allows the traversal to be done in a spiralling depth first clock wise order around the mesh faces.

```
Input:
 Geometry of the mesh as an array of floats to
 specify positions.
 Connectivity of the mesh as an array of integers
 containing indices into the position array to
 specify the faces.
Output:
 $Q_1Q_2Q_3Q_4Q_5Q_6$GF string that contains one
 label per quad except for the first one.
Procedure compress_quad()
 Assign flag to true
 While (flag)
     If both tip vertices are not visited Then
     Append code of $Q_1$ to the encoding string,
 Add both tip vertices to the list of vertices,
     Mark quad and tip vertices as visited,
     Update active gate.
     Else If both tip vertices lies on the boundary
 to the left of current active gate Then
     Append code of $Q_2$ to the encoding string,
 Mark quad as visited,
     Update active gate.
     Else If tip vertices lies on the boundary to
     the right of current active gate Then
     Append code of $Q_3$ to the encoding string,
 Mark quad as visited,
     Update active gate.
     Else If first tip vertex lies on the boundary
     to the left and second vertex lies to the right
 of the active gate Then
     Append code of $Q_4$ to the encoding string,
 Mark quad as visited,
     Update active gate.
     Else If first tip vertex lies on the boundary
     to the left of active gate and second tip
     vertex is not visited Then
     Append code of $Q_5$ to the encoding string,
 Mark quad and second tip vertex as
     visited,
     Add second tip vertex to the list of
     vertices,
    Update active gate.
    **Else If** first tip vertex is not visited and
    second tip vertex lies on the boundary to the
    right of active gate **Then**
    Append code of $Q_6$ to the encoding string,
    Mark quad and first tip vertex as visited,
    Add first tip vertex to the list of vertices,
    Update active gate.
    **Else**
    Calculate right and left boundary lengths
    **If** the right boundary is shorter in length
    **Then**
    Append encoding of G to the
    encoding string,
    Update active gate to the next right
    edge on the boundary.
    **Else If** the left boundary is shorter in
    length **Then**
    Append encoding of F to the
    encoding string,
    Update active gate to the next left
    edge on the boundary
    **If** all mesh quads are processed **then**
Assign flag to false
```

3.2 Encoding Hybrid Triangular-Quadrilateral Meshes

The only requirement needed in order to extend the technique for triangle-quad meshes is to generalize the data structure used by the encoding procedure to be able to store elements with arbitrary number of edges. The procedure checks for the current element type either it is a triangle or a quad. This checking distinct between two different subroutines responsible for checking the different cases of each type of elements and assigns the appropriate code for each element.

The generated encoding string will be a mixture of the six interaction types ($Q_1Q_2Q_3Q_4Q_5Q_6$) for encoding quad elements and the three interaction types of (CRL) for encoding triangle elements. By addition of the two labels of F and G, the generated encoding string becomes $Q_1Q_2Q_3Q_4Q_5Q_6$CLRGF. The general layout of the procedure is explained in the frame below.

```
**Input:**
 Geometry of the mesh as an array of floats to
 specify positions
 Connectivity of the mesh as an array of
 integers containing indices into the position
 array to specify the faces.
**Output:**
 $Q_1Q_2Q_3Q_4Q_5Q_6$CLRGF string that contains
 one label per polygon except for the first one.
**Procedure** Compress()
 Assign flag to true
 **While (flag)**
 **If** the current processed polygon is a triangle
 **then**
     Call procedure compress_triangle()
 **Else if** the current processed polygon is a quad
 **then**
     Call procedure compress_quad()
 **If** all mesh polygons are processed **then**
 Assign flag to false
```

4 RESULTS AND DISCUSSION

In this section the compression ratio achieved using the adapted non-split encoding technique is evaluated. Sample test cases of pure quad meshes (figure 3) and of quad meshes with few triangles (figure 4) were collected for this purpose and presented in Table 1. The meshes were selected to have a variety in size and shape except they all share the common characteristics of being manifold and simple without boundary, holes or handles.

Table 1: Used benchmark 3D models.

Model name	File size	No of Quads	No of triangles	No of vertices
Cow	1.35 MB	25,878	-	25,880
Bumpy sphere	1.41 MB	34,332	-	34,334
Egea	2.43 MB	49,596	-	49,598
Fandisk	3.55 MB	71,892	-	71,894
Head	4.94 MB	98,232	-	98,234
Horse	6.58 MB	119,09	-	119,096
Dente	6.95 MB	131,67	-	131,672
Eros	8.07 MB	153,91	-	153,914
Bimba	849 KB	15,532	238	15,653
Dragon	7.48 MB	126,77	1,540	127,571

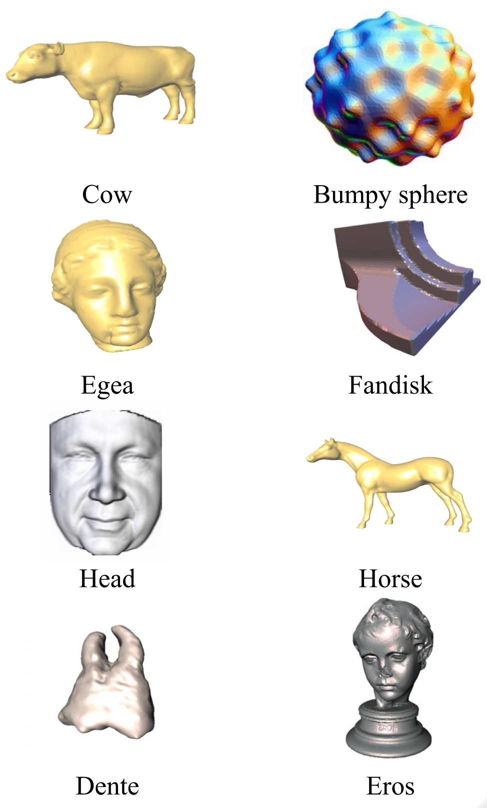


Figure 3: Benchmark 3D models of Quad meshes.

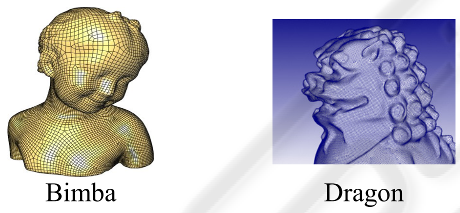


Figure 4: Benchmark 3D models of Quad meshes with few triangles.

In order for the compression ratio to be calculated a binary code has to be given to each of the encoding labels used for the encoding process. Following the fact that not all the codes occur with equal frequencies (Kronrod and Gotsman, 2000), a study over the average percentage each label consumes from the Encoding file was generated (Khattab, Abd El-Latif, Abdel Wahab and Tolba, 2007) to the entire models used (figure 5).

Figure 5 shows the frequency of occurrence of each encoding label in all meshes and the average percentage of each label over the whole group of meshes. The encoding labels are arranged in an ascending order according to their average percentage of occurrence. It is apparent from figure 5a that the largest percentages of quad interaction types are Q_6, Q_1 and Q_3 respectively. This result reflects the behaviour of the encoding technique that emphasis on traversing the mesh in a spiralling clock wise order of polygons. The same result is obtained with triangle-quad meshes (figure 5b) again the label R has the largest percentage among the set of triangle labels (C, R and L).

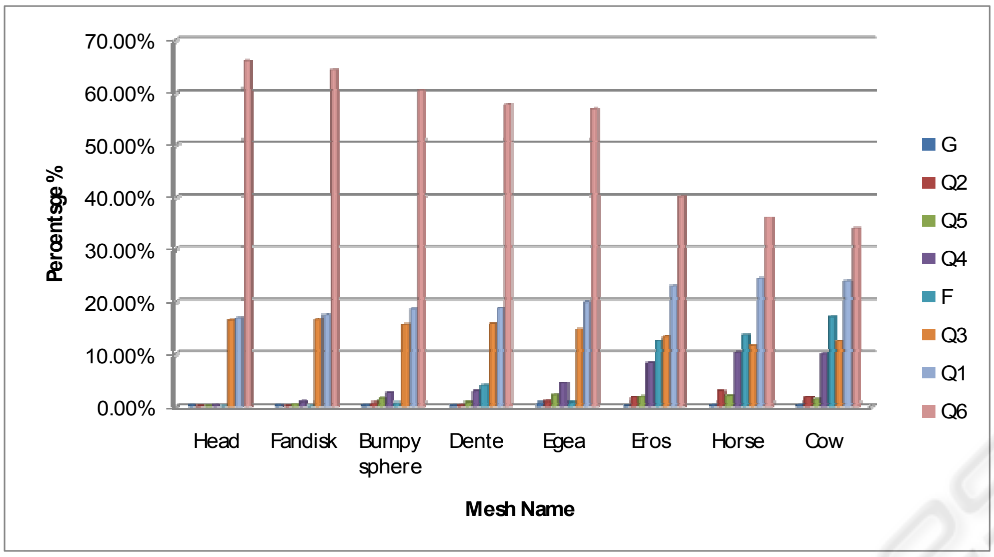
Based on this study a variable length binary code is given for the labels (Q_6: 0, Q_1: 10, Q_3: 110, F: 1110, Q_4: 11110, Q_5: 111110, Q_2: 1111110, G: 1111111) of quad meshes and (Q_6: 0, Q_1: 10, Q_3: 110, F: 1110, Q_4: 11110, R: 111110, Q_2: 1111110, Q_5: 11111110, G: 1111111110, C: 1111111110, L: 1111111111) of tri-quad meshes. This code is based on Huffman coding (Huffman, 1952) and leads to the optimal compression ratio that can be achieved.

Table 2: Compression results of quad meshes.

File name	Connectivity size		Compression ratio	
	Unencoded	Encoded	bpq	bpv
Head	2.49 MB	18.44 KB	1.53	1.53
Fandisk	1.81 KB	13.92 KB	1.58	1.58
Bumpy sphere	866 KB	7.3 KB	1.74	1.74
Dente	3.51 MB	30 KB	1.86	1.86
Egea	1.23 KB	11.58 KB	1.9	1.9
Eros	4.16 MB	50.94 KB	2.7	2.7
Horse	3.13 MB	42.93 KB	2.9	2.9
Cow	643 KB	9.8 KB	3.1	3.1
Average			2.17	2.17

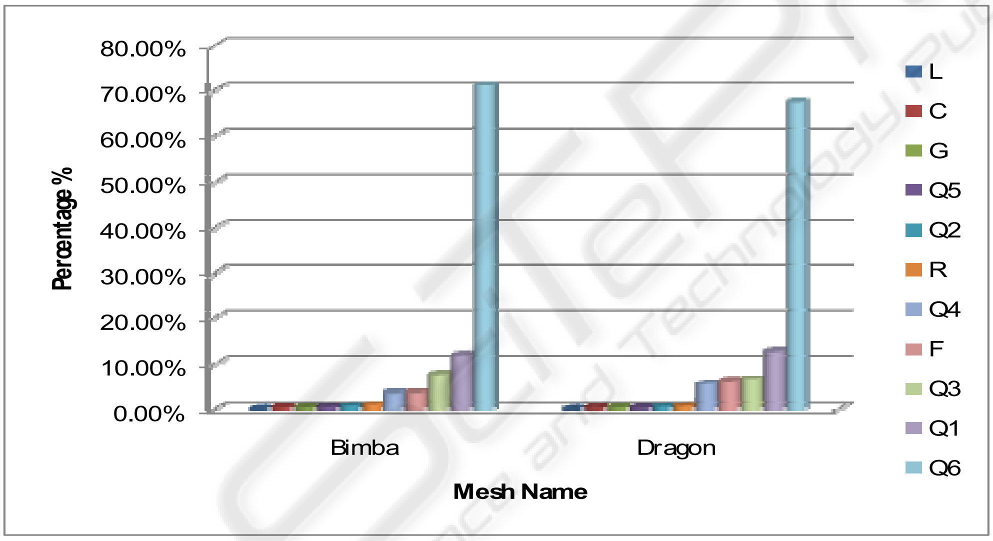
Table 3: Compression results of triangle-quad meshes.

File name	Connectivity size		Compression ratio	
	Unencoded	Encoded	bpp	bpv
Bimba	386 KB	511 KB	1.76	1.77
Dragon	3.35 MB	3.741 KB	1.92	1.93
Average			1.84	1.85



	Average Percentage
G	0.26%
Q2	1.00%
Q5	1.21%
Q4	4.9%
F	5.99%
Q3	14.6%
Q1	20.36%
Q6	51.81%

(a)



L	0.06%
C	0.36%
G	0.38%
Q5	0.41%
Q2	0.67%
R	0.86%
Q4	4.27%
F	4.63%
Q3	6.93%
Q1	12.15%
Q6	69.28%

(b)

Figure 5: Frequency percentage each file consumes from the encoding data file.

Table 2 and 3 list the results of the bit rates of compression ratio per polygon (bpp) and per vertex (bpv) for quad meshes and the hybrid triangle-quad meshes respectively. The results in both tables are arranged in ascending order according to the compression ratio which varies from the smallest bit rate of 1.53 (Head example) to the largest bit rate of 3.1 (Cow example) for quad meshes.

This variation in results can be estimated by referring to figure 5a which shows the degradation in the percentage of Q_6 labels whose bit code length is the least. This degradation is consumed in other labels having larger bit code lengths. Another parameter that affects the compression ratio is the shape characteristics of the models (Khattab, Abd El-Latif, Abdel Wahab and Tolba, 2007). The largest percentage of split cases during mesh traversal, the largest percentage of F and G labels added to the encoding file which finally results in much increase of bit rates per polygon for these meshes.

According to the binary code associated to each label, an average compression ratio of 2.17 bit per quad and per vertex is achieved for quad meshes and 1.84 bit per polygon and 1.85 bit per vertex for triangle-quad meshes. This result is more efficient compared to the late results obtained by Kronrod and Gotsman (Kronrod and Gotsman, 2000) and its enhancements of (Mukhopadhyay and Jing, 2003 and Kosicki and Mukhopadhyay, 2004) directly and without applying any complex or arithmetic coding.

5 CONCLUSIONS

In this paper, we present an efficient face-based connectivity encoding technique for compressing non-triangular meshes. The presented technique extends the previous work done by the authors in their first contribution (Khattab, Abd El-Latif, Abdel Wahab and Tolba, 2007) for compressing triangular meshes to the special class of pure quad and hybrid triangle-quad meshes. The presented technique reduced the interaction types introduced by Kronrod and Gotsman (Kronrod and Gotsman, 2000) from thirteen to six by elimination of the interaction types that causes the boundary to be split. This approach saves for the encoding technique its simplicity and efficiency. This reduction of interaction types improved the compression ratio over the state-of-the-art face-based techniques for compressing non-triangular meshes. It is believed that applying entropy or arithmetic coding to the achieved results will lead to further increase in compression ratio. The future work is to apply this efficient non-split encoding technique for meshes with arbitrary topology such as boundary and holes. The work in this direction is under progress and the initial results are promising.

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