State of the art: Compression of 3D meshes

Zeineb ABDERRAHIM* BOUHLEL Mohamed Salim*

*UR-SETIT, ISBS, 3038
Sfax, Tunisia

***Abstract*— The three-dimensional mesh compression has increasingly been a vital subject matter for years and has had a rich state of the art. Therefore, it is selected to be the cornerstone of this article. As a matter of fact, we began with the mono-resolution compression methods; then, we moved to the progressive methods and, at last, to the methods based on multi-resolution analysis. Now, we can distinguish between those which focus on the semi-regular mesh and those which are adapted to the irregular topological structure of the mesh.**

Keywords-component; compression; mesh; 3D object;coding; geometry; connectivity; progressive

I. Introduction

The technological developments of acquisition, computer graphics and vision have altogether paved the way to the existence of a three-dimensional modeling of this world. The major goal, in fact, is to model an object with a geometrical description by using the geometric primitives (such as points, polygons, volumes, etc.). In this perspective, the mesh plays a key role in the representation of 3D objects. Thanks to their simplicity and effectiveness, whether surface or volume, a representation adapted for transmission can be constructed.

Despite the increase in computer-storage space and network-transmission speed, the complexity of 3D meshes has quickly increased to represent objects with more details. Therefore, to visualize these detailed and complex 3D objects, it is indispensable to possess effective compression techniques in order to reduce the storage size and transmission time on the network.

Subsequently, compression has become a pertinent tool not only to allow for a compact storage of these massive meshes, but also for their rapid transmission in applications at a limited bandwidth. For this reason, many compression techniques have been proposed over the last fifteen years [1] [2].

We can classify the compression algorithms of 3D meshes into two large categories. The first category gathers the mono-resolution compression techniques, which are also known as non-progressive techniques, allowing lossless compression and requiring full decoding before visualizing the object. The second class is the progressive compression techniques that allow compression and transmission of progressive levels of resolution.

In this article, we go through the main works carried out in the field of compression of triangular progressive mono-resolution meshes and the methods based on multi-resolution analysis that are applicable either to semi-regular meshes or to irregular topological structures.

II. Mono-resolution compression

The mono-resolution compression techniques are the techniques that were first proposed. They are meant to encode the mesh with a minimum number of bits by removing the existing redundancy in the original representation of connectivity. The global form of the original model of the mono-resolution technique is available at the end of the transmission.

Among the mono-resolution compression techniques are those which are listed below:

- Band of generalized triangle introduced by Deering in 1995 [3],
- Topological surgery proposed by Taubin and Rossignac in 1998 [4],
- Valence based approaches proposed by Touma and Gotsman 1998 [5],
- Edgebreaker and extensions proposed by Rosignac in 1999 [2].

A. Coding by band of triangle

Deering, who first introduced the concept of "geometric compression", proposed coding by band of generalized triangle in 1995 [3]. The band of generalized triangle may be depicted by a sequence of symbols L (left) and R (right) depending on the way the vertices are connected together. For instance, the current vertex creates a new triangle connected to the previous one by its left or right part

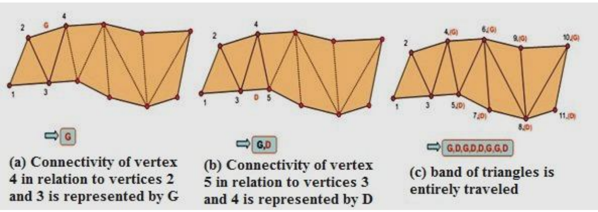

Figure 1. Coding by bands of generalized triangle

The author also uses a buffer memory to reduce the size of coding because of the appearance of the same vertex in the sequence. The compression of the position and the attributes of the vertices are fulfilled by a direct linear prediction. This technique requires an adequate division of the mesh in order to achieve an efficient compression.

Indeed, various studies stem from this approach [6] trying to ensure a coding cost per face constant with the number of faces. Still, when referring to the mesh division in bands of triangles, Rossignac [2] proposed an algorithm named “edgebreaker” ensuring a maximum coding cost of 2 bits per face but this time using an alphabet of 5 codes instead of a binary stream to describe the bands of the triangles. Yet, this method is useful only for too irregular meshes.

B. *The coding by valence*

Touma and Gotsman [2] propose a coding by valence algorithm defined for the oriented manifold mesh. The valence of the vertices can efficiently be encoded by entropic coding. Thus, for a regular mesh, the topological cost tends towards zero (0.2 bpv). The geometry is encoded by prediction using the parallelogram rule.

Afterwards, this approach was upgraded by Alliez and Derbrun in 2001 [7]. They proved that the upper bound of their encoder is 3.24 bits per vertex for large irregular meshes. More recently, Isenburg also proposed an alternative [8], the polygonal surface meshes based on ASCII encoding.

C. *Geometry coding*

The approaches based on the vertices repeatedly enumerate the vertices indicating their valence (that is to say the number of neighboring vertices) [5] [9] [7]. In fact, they spring from an algorithm of conquest.

Geometry is encoded independently of connectivity. To encode the geometry, we use a quantification of the vertex coordinates then a prediction of the position of the vertices by relying on the strong correlation that exists between a vertex and its neighbors. And, finally, we encode the estimation error between the predicted position and the actual position. The most used prediction techniques are:

- The differential prediction;
- The linear prediction;
- The prediction by the parallelogram rule.

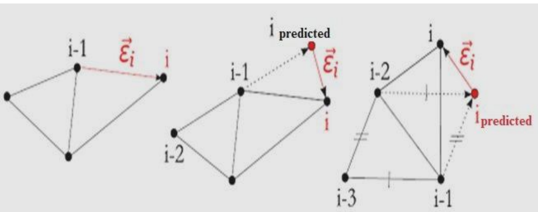

Figure 2. The differential prediction (left), the linear prediction (middle), the prediction by the parallelogram rule (right).

III. PROGRESSIVE COMPRESSION

To ensure the scalability of the transmission as well as the visualization of the 3D data, it is essential to develop methods of progressive compression based on multi-resolution representations with several levels of detail [10].

The progressive compression methods encode the mesh hierarchically. They are based on a coarse mesh (basic) and a refinement of information gradually transmitted to obtain different levels of resolution. Unlike the mono-resolution methods, they offer the possibility of accessing the intermediate reconstructions of a 3D object during its transmission *“Fig. 3”*. Indeed, decoding and transmission may stop at any time.

Figure 3. Progressive transmission of 3D object

However, the main challenge of these approaches is the optimization of the flow-distortion compromise so as to obtain an approximation of the final mesh that can be as faithful as possible throughout the refinement process.

Generally speaking, these approaches are more efficient than those in mono-resolutions in terms of coding efficiency and compression ratios. So, we can get better compression ratios by accepting some losses, but the geometric shape is slightly altered. Among the main progressive methods we can mention.

A. *Progressive compression method based on simplification*

1) Progressive Meshes: The first algorithm of the representation of progressive meshes was introduced by Hoppe [11], [12]. This progressive representation, which is based on the simplification of successive meshes by contractions of edges "edge collapse" while encoding, removes a vertex at once. The reverse is the reconstruction "vertex split" which is achieved by separating the vertices while decoding. Contractions of edges are chosen so that the approximations remain close to the original mesh by using a given geometric criterion.

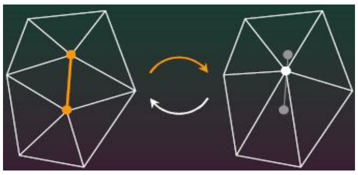

Figure 4. Separation of vertices (white arrow) and contraction of edges (red arrow)

This approach can generate a delicate granularity per vertex and define a metric to choose an edge among the candidates during the contraction by using an energy function related to the geometry in order to obtain a better approximation [13]. The total cost is non-linear (n.log (n)); it is reserved for meshes of low complexity.

2) Coding by removal of vertex: Cohen-Or and al propose a simplification algorithm based on the technique of coloring the patches and successive withdrawals of the vertices followed by a deterministic retriangulation **[**14**]**.

This method, indeed, consists in repeatedly removing the vertices independently, then re-triangulating the formed patches and encoding the triangles of a patch by alternation of 2 or 4-colors in a way that the decoder, based on the colors, can detect the vertices during the reconstruction. Thus, connectivity is progressively encoded at an average cost of 6 bits per vertex.

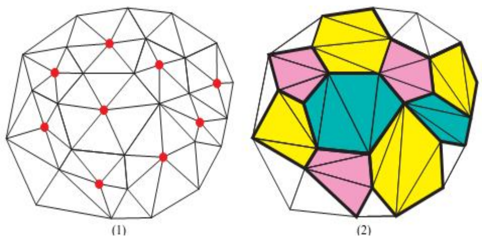

Figure 5. (1) The original mesh with an arbitrary triangulation and (2) after removal of the mesh vertices and triangulation.

3) Encoding by deterministic retriangulation (valence based): The previous algorithm was recently improved by Alliez and Desbrun who introduced the technique of progressive mesh encoding [15] where the connectivity of the mesh is reconstructed by transmitting only the valence of the vertices with some additional codes called null-patch [16].

As a result, there is a better conservation of the regularity of the mesh during the decimation. This is reinforced by re-triangulation under the constraint of keeping the vertex degrees around 6. This approach compresses the connectivity of the mesh at an average of 3.69 bits per vertex.

4) Encoding by decomposition of geometric tree: Unlike the previous approaches, Gandoin and Devillers [17] [18] suggest a compression algorithm guided by geometry rather than connectivity and founded on the kd-tree subdivision. Its principle, first, is to encode the total number of points on an arbitrary number of bits. Second, we move to recurringly subdivide the current cell into two half-cells and encode the number of vertices of the mesh contained in one of them on an optimal number of bits by using an arithmetic encoder until they have no more divisible cells in the list.

The main objective in their approach is to achieve continuity between the coarse approximations to the more detailed approximations of the object. Connectivity is encoded by encoding all the changes in the cell subdivision.

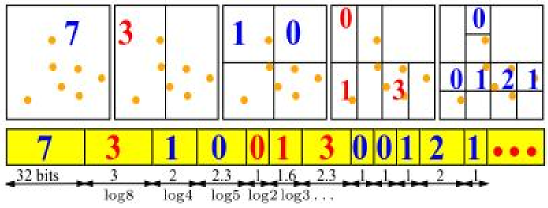

Figure 6. Encoding technique of geometric information [18].

This method is improved by Peng and Kuo [19] by replacing the Kd-tree with the Oc-tree data structure. The Oc-tree cells are refined in order of priority, where the subdivisions of cells with the best improvement of distortion are executed first. These approaches provide sound results for lossless compression, but this is limited to triangular models and can induce artifacts of blocks. That may reduce the flow-distortion performance to low rates. Cai and al. [20] introduced the first progressive compression method adapted for large meshes. This method might have most of the existing methods based on Oc-trees.

B. Progressive compression method based on spectral analysis

In this context, we, first, point out the spectral approach introduced by Karni and Gotsman [21] who proposed a spectral decomposition by projecting the mesh geometry on a set of eigenvectors from the diagonalization of the discrete laplacian operator.

These methods provide good approximations of meshes even with few transmitted coefficients. They are generally effective for low-flow compression of models with smooth geometry. They result in average coding costs of about 4.5 bits / vertex and a reconstruction compatible with efficient access optimized to the data for an efficient product.

The main inadequacy of the spectral compression is related to the computational complexity of the decompression process which is cubic with the number of vertices [10]. These methods offer a progressive geometry but connectivity remains unchanged during the transmission. In fact, most works are oriented towards multi-resolution analysis which is becoming more and more important. It is, accordingly, an alternative that has both geometric and topological scalability.

C. Progressive compression method based on multi-resolution analysis

The multi-resolution analysis is extended to meshes by the pioneering works of Schröder and al who introduced the lifting scheme in 1995, and, then in 1997, Lounsbery and al established the link between the wavelets and the subdivision surface. This method involves applying a technique of quaternary subdivision of recurring surfaces to a single basic mesh. The subdivision consists in adding an extra vertex to the middle of each edge forming the triangle. Then, we move these new added vertices so as to get the most faithful approximation to the mesh to be coded on each level of detail.

The objective of the multi-resolution analysis of surfaces is to make a reversible decomposition of a mesh by using two applied filters in cascade.

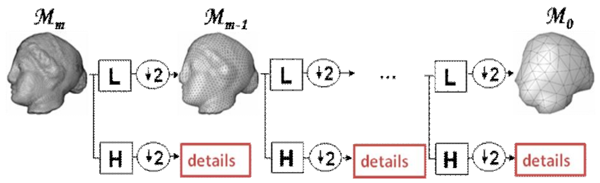

Figure 7. The multi-resolution analysis with low-pass filter (letter L) and high-pass (letter H)

There are two main methods of multi-resolution analysis used for the mesh compression. The main difference lies in the mesh structure in question: it is used either in re-meshing in order to make more regular structure or in directly considering the irregular structure of the mesh.

1) Compression methods based on remeshing: The pioneer progressive compression method of semi-regular meshes was proposed by Khodakovsky and al. [22] in 2000. It resides in remeshing an arbitrary mesh M into a semi-regular mesh by using the algorithm MAPS (Adaptive Multi resolution Parameterization of Surfaces) [23]. After this step of remeshing, Khodakovsky and al choose to apply a mesh transformed into a semi-regular wavelet based on the loop interpolating filter. This method reduces the reconstruction error of about a factor of four to comparable rates.

A recent method has been proposed by Payan and al [24] which is a compression algorithm with loss for dense triangular meshes incorporating a binary allocation. This method is based on a step of remeshing by using a normal remesher and a mesh transformed into a non-lifted Butterfly wavelet. Regardless the desired compression ratio, the used binary allocation helps us to control the visual quality of the reconstructed mesh when encoding the geometry to optimize the flow-distortion compromise [25].

In 2009 Roudet and al [26] proposed a new approach of progressive compression of semi-regular surface meshes based on a method of adaptive wavelet decomposition. The approach initially applies a step of remeshing to the input mesh. Then, it applies global wavelet decomposition and segmentation based on the frequency variation of the wavelet coefficients on the surface. The advantage of the frequency based segmentation is that it allows for distinguishing the homogeneous regions of the surface. The resulting partitions are, then, independently decomposed and encoded by the zero tree encoder (*"Fig. 8"*).

Since the topology information is completely eliminated, these methods are totally progressive and lead to high compression rates. However, these methods suffer from a number of restrictions related to the associated remeshing processes [10].

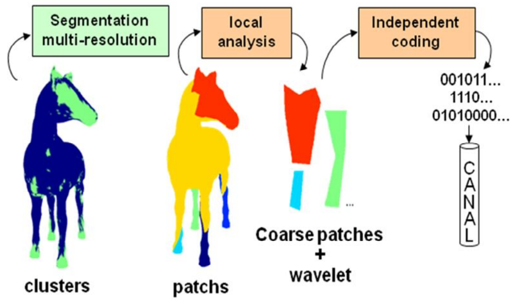

Figure 8. Independent encoding of each partition

2) Irregular compression methods: Among the progressive compression techniques of the irregular mesh, we may refer to the ones listed below:

- The approach of Bonneau and al in 1996 [27] and 1998 [28];
- The approach of Roy and al in 2003 [29] and 2005 [30];
- The approach of Valette and al in 2004 [15] and 2009 [32].

Bonneau and al [28] come up with a new multi-resolution analysis method based on non-overlapping spaces and use wavelets called BLaC-wavelets" (Blending of Linear and Constant) allowing for the extension of the wavelets of Haar. In this method, the scaling functions are replaced by an approximation scaling function. We also use an approximate refinement function which is used to define the link between the levels of successive resolutions and which is applied to develop a multi-resolution analysis framework for an irregular triangular mesh of a planar or spherical domain [27].

Equally important, Roy and al [29] [30] suggest a multi-resolution analysis approach for irregular meshes with multiple attributes which can encode, besides the geometric aspect, that of the attributes with the second generation wavelet of the lifting diagrams. The used decomposition method is based on incremental mesh decimation, precisely the one introduced by Hoppe [11] and led to the construction of a sequence of resolution levels. This method is effective for applications such as filtering, sound effects and adaptive simplification.

Valette and al [16] proposed a new approach of decomposition in wavelets that can be applied to irregular triangular 3D meshes. The very approach, indeed, is able to be directly adapted to the topological structure of irregular meshes by offering new irregular subdivision schemes (*"Fig. 9"*). The purpose of this approach is to overcome the difficulty of the connectivity subdivision, which is imposed by Lounsbery's method, and to keep the geometry and connectivity of the approximations as close as possible to the original mesh. Also, to avoid the re-meshing step, no additional calculations are needed for this step [31]. The connectivity coding cost is around 2 bits / vertex.

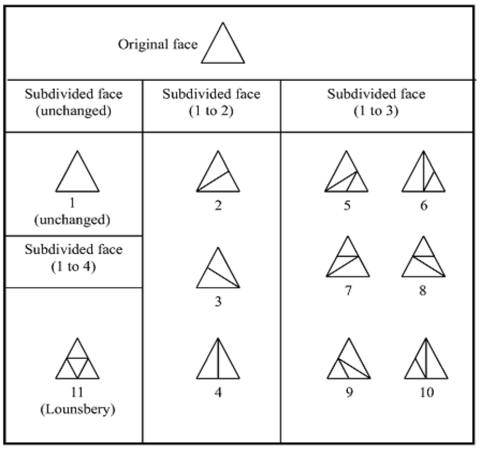

Figure 9. List of cases of irregular subdivision wavemesh [16]

In 2009, Valette and al [32] proposed a new algorithm for lossless progressive compression of the mesh based on a metric "Incremental Parametric Refinement" abbreviated as "IPR", where the connectivity is uncontrolled in a first step, which gives visually pleasant meshes at each resolution level by saving the connectivity information compared to the previous approaches. The coordinates of the vertices are quantified and transmitted, in a gradual way, by using a quantification progressive method adapted to each vertex. This adaptive quantification proves its effectiveness in improving the flow distortion compromise, particularly at low flow.

More recently, [33] [34] presents a new method of optimizing the flow-distortion which rests on the adaptation of the precision of quantification of the geometry as well as the color for each intermediate mesh. The used adaptation is performed to each iteration and consists in choosing, among the operation of decimation and the operation of reducing the precision of quantification, an operation that improves the flow-distortion ratio.

Table 1. Represents the compression ratios of the various methods applied to the various meshes of the reference by using a quantification of 10 or 12 bits.

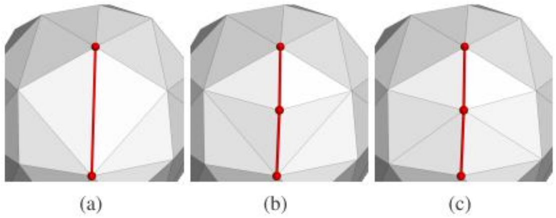

Figure 10. The refinement scheme proposed by IPR: (a) Selection of the longest edge (red) for refinement. (b) It is divided into two and creation of two new triangles. (c) Retriangulation to satisfy the property of local Delaunay [32].

IV. CONCLUSION

The 3D objects are omnipresent in our daily lives thanks to their large use in various fields and to the development of computer graphics. They are generally represented in the form of a triangular surface mesh. This mesh has different properties in respect of multimedia objects and requires a large amount of information to be stored in order to obtain a precise representation. This requires a technical compression to allow for the storage, transmission and visualization of three-dimensional objects.

Indeed, in this article, we achieved a state of the art of the existing compression methods of 3D objects. The first compression techniques are mono-resolution techniques. Subsequently, many mono-resolution methods have been extended to the progressive compression. In this context, unlike the techniques applicable to irregular meshes, there are recent methods that completely change the original mesh connectivity on behalf of the semi-regular topological representations: the geometric compression methods.

REFERENCES

[1] P. Jingliang, K. Chang-Su, and C.-C. Jay Kuo, "Technologies for 3d mesh compression : A survey",Journal of Visual Communication and Image Representation, pp. 688–733 , December 2005.

[2] J. Rossignac, Edgebreaker, "Connectivity compression for triangle meshes", IEEE Transactions on Visualization and Computer Graphics, Vol. 5, No. 1, 1999.

[3] M. Deering, "Geometry compression", Proceedings of ACM SIGGRAPH, 1995.

[4] G. Itaubin, J. Rossignac,"Geometric compression through topological surgery", ACM, Transaction on Graphics, April 1998.

[5] C.Touma and C.Gotsman, "Triangle mesh compression", pp. 26–34, Graphics Interface,1998.

[6] G. Taubin and J. Rossignac, "Geometric compression Through Topological Surgery", ACM Transaction on graphics, Vol. 17, No. 2, April 1998, pp. 84-115.

[7] P. Alliez and M. Desbrun, "Valence-Driven Connectivity Encoding for 3D Meshes", EUROGRAPHICS 2001, Volume 20, No. 3, 2001, 10p.

[8] M. Isenburg and J. Sonoeyink, "Coding with ascii : compact, yet text-based 3D content", First International Symposium on 3D Data Processing Visualisation and Transmission, pp.609-616, 2002.

[9] M. Isenburg and J. Snoeyink, "Mesh Collapse Compression", Proceedings of ACM Symposium on Computational Geometry, 1999, pp. 419-420.

TABLE I. COMPARISON OF COMPRESSION RATIO IN BITS PER VERTEX

Model	S	Q	TG98[5]	AD01[15]	GD02[18]	VP04[16]	PK05[19]	IPR09[32]	LE11[33]
Fandisk	6475	10	**10.3**	17.4	-	13.5	13.3	12.4	16.1
Venusbody	11362	10	-	14.1	-	**11.4**	-	-	12.0
Horse	19851	12	17.5	20.9	20.3	19.8	**16.6**	18.2	20.6
Torus	36450	12	4.6	5.8	-	6.3	11.8	13.6	**5.7**
Rabbit	67039	12	**12.4**	17.6	-	15.6	14.8	**13.6**	16.4
Fertility	241607	12	-	-	-	14.7	**12.7**	13.9	-

[10] K. Mamou, T. Zaharia and F. Prêteux, "Compression progressive de maillages 3D par approximation B-Spline", Proceedings CORESA'2005, France ,2005.

[11] H. Hoppe, "Progressive meshes," in ACM Siggraph 96 Conference Proceedings, 1996, pp. 99–108.

[12] H. Hoppe, "Efficient implementation of progressive meshes" ,Computer & Graphics, vol. 22, 1998.

[13] H. Hoppe, T. DeRose, T. Duchamp, J. McDonald and W. Stuetzle, "Mesh Optimization", Proceedings of ACM SIGGRAPH, 1993, pp.19-26.

[14] D. Cohen-Or, D. Levin, and O. Remez, "Progressive compression of arbitrary triangular meshes," in IEEE Visualization 99, 1999, pp. 67–72.

[15] P. Alliez and M. Desbrun, "Progressive encoding for lossless transmission of 3d meshes," in ACM Siggraph Conference Proceedings, 2001, pp. 198–205.

[16] S. Valette and P. Rémy, "Wavelet-Based Progressive Compression Scheme for Triangle Meshes: Wavemesh", Ieee transactions on visualization and computer graphics, march /april 2004,vol. 10.

[17] O.Devillers and PM.Gandoin, "Comression interactive de maillage triangulaire arbitraires".Rapport de recherche ,INRIA Sophia Antipolis,2001,28p.

[18] O.Devillers and PM.Gandoin, "Progressive Lossless Compression Of Arbitrary Simplicial", ACM Transactions on Graphics 2002, Siggraph'2002 ,p. 21:372-379.

[19] J.Peng, C.Kuo -C. J.: "Geometry-guided progressive lossless 3d mesh coding with octree (ot) decomposition". ACM Trans. Graph. 24, 3 (2005), 609–616. 2, 3, 4, 8, 9 .

[20] K. Cai, Y. Liu, W. Wang, H. Sun, E. WU, " Progressive out-of-core compression based on multi-level adaptive octree", In ACM international Conference on VR-CIA (2006), ACM Press, New York, pp.83–89.

[21] Z. Karni and C. Gotsman, "Spectral Compression of Mesh Geometry", ACM Siggraph Conference Proceedings, pp. 279–286,2000.

[22] A. Khodakovsky, P. Schröder, W. Sweldens, "Progressive Geometry compression", International Conference on Computer Graphics and Interactive Techniques, SIGGRAPH 2000, 2000, pp. 271-278.

[23] A. W. F. Lee, W. Sweldens, P. Schröder, L. Cowsar and D. Dobkin, "MAPS : Multiresolution Adaptive Parametrization on Surfaces", International Conference on Computer Graphics and Interactive Techniques, SIGGRAPH'98, Orlando, Florida, USA, July 1998.

[24] F. Payan and M. Antonini, "An efficient bit allocation for compressing normal meshes with an error-driven quantization", Computer Aided Geometric Design, 2005, vol.22,no 5, p.466–486.

[25] F. Payan, "Optimisation de compromis débit- distorsion pour la compression géométrique de maillages surfaciques triangulaires" ,Thèse de doctorat, STIC de Nice_Sophia Antipolis, 2004.160p.

[26] C. Roudet, F. Dupont and A. Baskurt, "Semi-regular 3d mesh progressive compression and transmission based on an adaptative wavelet decomposistion". Proceedings of SPIE, Wavelet Applications in Industrial Processing VI, January 2009, Vol. 7248.

[27] G.-P. Bonneau, S. Hahmann, G.M. Nielson, "BLaCWavelets: A Multiresolution Analysis With Non Nested Spaces", IEEE Proceedings Visualization'96,1996, pp. 43-48.

[28] G.-P. Bonneau, "Multiresolution analysis on irregular surface meshes", IEEE transactions Visualization and Computer Graphics, Volume 4, Number 4, October-December, 1998, pp. 365-378.

[29] M. Roy, S. Foufou, A. Koschan, F. Truchetet and M. Abidi, "Multiresolution Analysis for Irregular Meshes", Proceeding of SPIE in industrial processing, October 2003, vol. 5266,p.249-259.

[30] M. Roy, S. Foufou, A. Koschan, F. Truchetet and M. Abidi, "Multiresolution Analysis For Meshes With Apparences Attributes", IEEE International Conference on Image Processing (ICIP'05), Genoa, Italy, September 2005.

[31] S. Valette, "Modèles de maillages déformables2D et multirésolution surfaciques 3D sur une base d'ondelettes ", Thèse de doctorat, INSA Lyon, 2002.161p.

[32] S. Valette, R. Prost, R. Chaine, "Progressive Lossless Mesh Compression Via Incremental Parametric Refinement", Computer Graphics Forum28, 5(July 2009),1301–1310.

[33] Ho. Lee, "Compression progressive et tatouage conjoint de maillages surfaciques avec attributs de couleur", thése doctorat, Université Claude Bernard ,Lyon 1 21juin 2011,160p.

[34] Ho. Lee, G. Lavoue, F. Dupont, "Rate-distortion optimization for progressive compression of 3D mesh with color attributes", The Visual Computer 28(2): 137-153 (2012).