Robust Watermarking Algorithm for 3D Multiresolution Meshes

Ikbel Sayahi, Akram Elkefi, Mohamed Koubaa and Chokri Ben Amar
National School of Engineers, Sfax University, Soukra Street, Sfax, Tunisia

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Abstract: Digital watermarking for 3D meshes is a means to copyright protection. In this paper, we propose a robust watermarking algorithm for 3D Meshes. We work on multiresolution, triangular and semi regular meshes having various sizes. Our algorithm is able to insert high amount of information in the field of multiresolution . For this reason, we apply a uniform scalling then a wavelet transform to the host mesh. Embedding step consist on modifying wavelet coefficients vector according to the bit to be inserted. These techniques do not generate a quality degradation of the mesh despite the important capacity adopted. Tests applied to various attacks have shown the robustness of our algorithm against rotation, translation, uniform scaling, Noise addition, smoothing, simplification and coordinate quantization. A comparison with literature revealed that we have a remarkable improvement over the published results.

1 INTRODUCTION

3D mesh is a new data type that has emerged from the 2000s. The idea was to use geometric modelization to build 3D objects presenting real scenes. Since their birth, 3D meshes have become increasingly used in several vital areas. Medicine, computer aided design, games, video and scientific simulations are examples. This wide range of applications and the birth of the networks of high speed broadband have encouraged the sharing and the transmission of this data category which causes a major security problem. The question was how to protect shared 3D meshes against fraudulent action. Digital watermarking has been one of the proposed answers. As it was the case for image, sound and video, watermarking 3D meshes consists of inserting indelible data into mesh without deteriorating the host object. During the last decade, many works have been proposed to secure 3D meshes. Therefore, a diversification in fields using during embedding information into meshes appears. Indeed, there are approaches that have chosen to work in the spatial field without transforming the mesh. We cite the work published in (Sharvari and Ratnadeep, 2012) and (Chao-Hung and al, 2013) as examples. Other works aimed to represent host meshes in transformed areas before embedding information. Among these used areas, we note the spectral domain as the case of works published in (Sharvari and Atnadeep, 2012). The multiresolution domain has also been present in recent works such as the approaches proposed in (Kai and al, 2007), (Zhiyong and al, 2013) and (Kai and al, 2010). Unfortunately, this diversification does not deny that watermarking 3D meshes is "still far from the level of maturity of other watermarking technologies for audio, video or image (Domenico and al, 2010)".

In this paper, we propose a robust and multiresolution domain watermarking algorithm. Our goal is to maximize the amount of information inserted while ensuring the preservation of the mesh quality. Treatments applied to watermarked mesh, should never prevent correct extraction of information.

2 RELATED WORKS

Since the release of the first 3D watermarking algorithm of in the last decade and until our days, 3D watermarking algorithm targeting 3D meshes have continued to appear. The aim is always to improve the following criteria: capacity, invisibility and robustness.

Although the goals are the same, the proposed watermarking algorithms are various. Some work has chosen to insert the information by modifying either the topological information such as the work in (Chao-Hung and al, 2013) or the geometric one (Xiangjiu and Zhanheng, 2012). In this case the mesh host will be treated in the spatial domain without un-

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dergoing any transformation. Insertion into a transformed domain and in particular the multiresolution one was an idea adopted in (Sharvari and Atnadeep, 2012) and (Sharvari and Ratnadeep, 2012) to improve the robustness criterion. These approaches proposed to modify wavelet coefficients during the insertion of information. Other approaches proposed like (Xiao and al, 2012) thought to insert information in the low frequency coefficients after transforming the mesh from the spatial domain to the frequency one.

Despite the variety of the proposed 3D watermarking algorithms and the efforts to innovate in this area, a perfect solution to the security problem of 3D meshes has not yet been reached for two reasons. The first is the complexity of handling 3D meshes compared with other types of data such as sound, image or video. The second reason was the difficulty of finding a compromise between robustness, visibility and capacity. These three criteria are closely related to a watermarking algorithm targeting 3D meshes because the change of one of these three impulses directly to the others remaining.

By definition invisibility means Inserting information in the mesh should never cause deterioration in the quality of the later.Capacity is the rate of information inserted to the mesh (number of bits in the case of binary information); As for robustness we can say that a watermarking Algorithm is said robust if extracting all inserted information is possible whatever the treatments applied to the watermarked mesh.Indeed, the increase of the amount of data to be inserted causes either a serious deterioration of the mesh quality or reduces the level of robustness.

The work presented in this paper falls into this context. We propose a new watermarking algorithm targeting multiresolution triangular meshes. Our goal is to maximize the rate of information inserted without affecting the quality of the host mesh while ensuring the robustness criterion. We must be able to extract all of information correctly regardless of the attacks that the watermarked mesh can undergo.

3 TECHNIQUES USED

To insert information into multi-resolution triangular meshes, we used the following techniques: Uniform scalling, Wavelet transform, Transformation to spherical system.

To prevent the watermark against similar transformation attacks, the host mesh undergoes a uniform scaling, said also ”Normalization”, in order to be included in a unit sphere (Kai and al, 2010).

To do this, we must first choose a scale having an arbitrary orientation. Next, we define n (nx, ny, nz) a unit vector whose direction is parallel to that of the chosen scale. Let K be the scale factor applying to plan passes through the origin and which is perpendicular to n (Zhiyong and al, 2013). For each vertex $V_i(x_i, y_i, z_i)$ we calculate the new coordinates $V_i^s(x_i^s, y_i^s, z_i^s)$ using formula 1.

$$V_i^s = V_i \times S \tag{1}$$

S is defined in formulas 2, 3, 4 and 5 as follows:

$$S = [S_1, S_2, S_3] \tag{2}$$

$$S_1 = \begin{pmatrix} n_x^2(K-1)+1 \\ n_x n_y(K-1) \\ n_x n_z(K-1) \end{pmatrix} \tag{3}$$

$$S_2 = \begin{pmatrix} n_x n_y(K-1) \\ n_y^2(K-1)+1 \\ n_y n_z(K-1) \end{pmatrix} \tag{4}$$

$$S_3 = \begin{pmatrix} n_x n_z(K-1) \\ n_y n_z(K-1) \\ n_z^2(K-1)+1 \end{pmatrix} \tag{5}$$

3.1 Wavelet Transform

Multiresolution analysis has become a center of interest for researchers in our day. To transform the mesh from spatial domain to multiresolution one, a wavelet transform should be applied. Only semi-regular mesh can be used. The main idea is then to decompose a mesh M_i in two sets: a low resolution mesh M_{i-1} grosser and a set of details D_{i-1} (see figure1): the analysis phase. All these details and meshes of different resolution level are then used to reconstruct the original mesh: synthesis phase. All details obtained

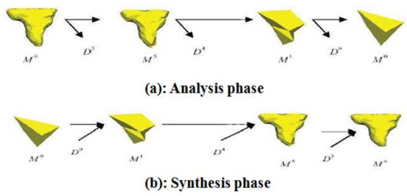

Figure 1: Wavelet Transform.

during analysis phase are assembled into a single vector called wavelet coefficient vector (CWV).

$$CWV = \begin{pmatrix} D_1 \\ \vdots \\ D_i \end{pmatrix} = \begin{pmatrix} d_1^x & d_1^y & d_1^z \\ \vdots & \vdots & \vdots \\ d_i^x & d_i^y & d_i^z \end{pmatrix} \tag{6}$$

Especially, this vector will be modified during insertion following bits to be inserted. The choice of multiresolution field is argued by the fact that insertion of information is done at different levels of resolution which eliminates the interaction between them (Kai and al, 2007).

To apply a wavelet transform to a triangular mesh, we need the use of 4 butterfly filters (Elkefi and al, 2004): 3 filters for prediction and one filter for update (Figure 2).

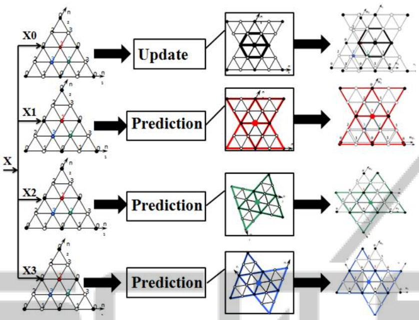

Figure 2: Butterfly filters.

The signal present at the input of the lifting scheme is divided into four channels. On each channel, the corresponding filter is applied. The prediction of a point is a weighted sum of a neighborhood available at time t.

3.2 Transformation to Spherical System

To embed information into meshes, we choose to transform the Cartesian coordinates (x, y and z) of each wavelet coefficient into the spherical coordinate system (ρ, θ, ψ). This passage is carried out by formulas 7:

$$\rho = \sqrt{x^2 + y^2 + z^2}$$
$$\theta = \arccos(\frac{z}{\rho})$$
$$\psi = \begin{cases} \arccos \frac{x}{\sqrt{x^2+y^2}} \\ 2 \times \Pi - \arccos \frac{x}{\sqrt{x^2+y^2}} \end{cases} \quad (7)$$

This passage allows obtaining the component , which represents the module of the wavelet coefficient. During insertion, the value of this component will undergo a modification according to the bit to be inserted. Therefore, we are changing the module of coefficients instead of changing the Cartesian components of these coefficients. This improves the criterion of invisibility.

To recalculate the wavelet coefficients, the application of inverse transformation is necessary after embedding. To ensure this passage, we use formulas 8:

$$x = \rho \times \sin\theta \times \cos\psi$$
$$y = \rho \times \sin\theta \times \sin\psi \quad (8)$$
$$z = \rho \times \cos\theta$$

4 OVERVIEW OF OUR APPROACH

Our watermarking algorithm aim is to embed data into triangular meshes in order to place a copyright protection or an indexing system.

After a dissemination step, during which many processing (said also Attacks) may be applied to the mesh, we carry out an extraction step. Our goal is to extract data correctly despite all these processing ie, to confirm the robustness criterion (see Figure 3).

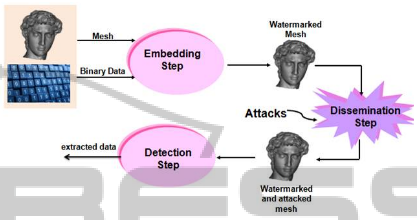

Figure 3: General structure of a watermarking algorithm.

4.1 Embedding Step

During this step, there will be the insertion of information in the host mesh. To do it, we should follow the instructions presented in Figure 5.

Having a 3D mesh, an acquisition step begins then a uniform scalling will be applied. The next step is called ”mesh pretreatment”. It aims at transforming the mesh from the spatial domain to the multiresolution one. This transformation results from the application of a wavelet transform. The present step ends with the extraction of the wavelet coefficient vector.

Using this vector, embedding watermark can occur. Watermark is a binary sequence generated using a pseudo random generator. The present step includes 3 parts: The first one is Transforming the wavelet coefficients into spherical system. The second is Embedding and recalculating Cartesian representation of wavelet coefficients. The last one is Inversing wavelets transform to rebuild the mesh.

The spherical coordinate transformation allows us to obtain the component ρ presenting the modulus of the wavelet coefficient. This component will be changed every time following bits of information to insert. This modification follows formula 9:

$$\acute{\rho}_i = \rho_i + \beta \times bit_i \quad (9)$$

β is called watermarking strength. When the β value increases, our watermarking treatment becomes more robust and more visible. β value is determined experimentally (see the Results section).

After the dissemination step during which the host mesh can undergo various treatments, the extraction

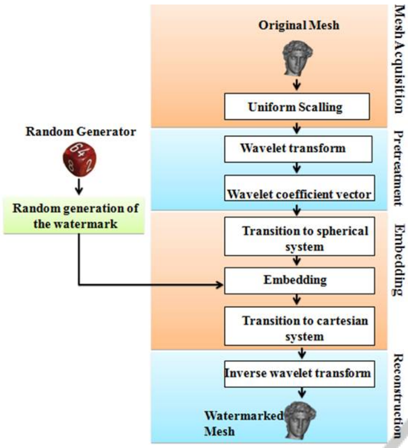

Figure 4: Insertion step.

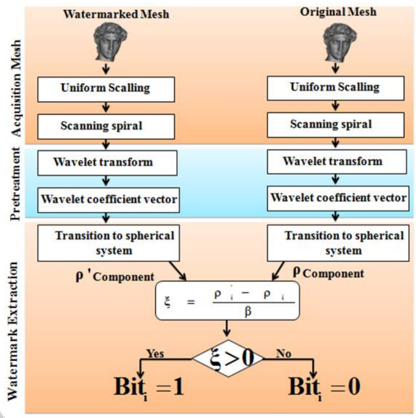

Figure 5: Extraction step.

phase begins. Unfortunately, a correct retrieval of information in the watermarked mesh is no longer certain. This is due to the treatments applied to the mesh. The latters can easily alter and even destroy watermarked information. To resolve this problem we propose an extraction scheme shown in figure 5.

4.2 Extraction Step

Extraction has the same steps as insertion. The watermarked mesh and the original one undergo uniform scaling then a wavelet transform. At the end of this step, we will obtain two vectors of wavelet coefficients. The first contains the watermarked vector and the other the original one. At this level, the extraction of embedded bits becomes possible.

To extract information, we have to calculate the wavelet coefficient vectors corresponding to the original and watermarked meshes. A transformation to the spherical system of these two vectors is necessary to apply formula 10:

$$\xi = \frac{\acute{\rho}_i - \rho_i}{\beta} \tag{10}$$

To tweak the inserted bit correctly, we need to discuss according to the value of ξ as follow in formula 11:

$$bit_i = \begin{cases} 1 & if \quad \xi > 0 \\ 0 & Otherwise \end{cases} \tag{11}$$

5 RESULTS

For evaluating our watermarking algorithm, two criteria must be taken into consideration. The first is the visibility criterion. Insertion of information in the host mesh must never cause visual deterioration of the latter. The second is the robustness criterion. A watermarking algorithm is said robust if the extraction of inserted information is correct whatever the treatments applied to the host mesh are.

5.1 Data Used For Tests

To test our approach, we use areal, semi-regular and multiresolution meshes stored in files. Dat. In this category of files, 3D object is represented at different levels of details. It is in fact composed of a coarse mesh and more information to refine the coarse mesh to its finest levels version. Very few are the watermarking works manipulating files with this extension. This is due to the sensitivity of meshes having this structure. In this work, we watermarked multiresolution meshes of various sizes (Feline.dat with 258,046 Vertex, Horse.dat with112642 vertex and venus.dat with 40962 vertex). These objects are characterized by containing forms having very sensitive details. The latters are easily influenced by any treatment which threatens the invisibility criterion.

5.2 Invisibility Criterion

Inserting a watermark in a host mesh should never cause detectable visual degradation. This suggests that the conservation of mesh quality after watermarking is a primary criterion in the evaluation of a watermarking algorithm.

To conclude on the influence of our algorithm on the mesh quality, we calculate the difference between the original mesh and the watermarked one. To find these differences, we resorted to calculate the Mean Square Error (MSQE or MSE) (Frederic and Marc, 2006). The main idea of this comparison is to calculate the distance between the two meshes. It represents the distance between a point x from the first mesh and a surface from the second one (Cline and Frdric, 2011).

$$d(M,\hat{M}) = (\frac{1}{area(M)} \int_{x \in M} d(x,\hat{M})dx)^{\frac{1}{2}} \quad (12)$$

The MSQE is then calculated using formula (13).

$$MSQE = max(d(M,\hat{M}), d(\hat{M},M)) \quad (13)$$

Another comparison tool we can also use is the PSNR (Peak Signal to Noise Ratio) measured in decibels (dB). This parameter calculates the ratio between the signal dynamics and the error of the watermarking.

$$PSNR = 20 \times log_{10}(\frac{Bounding\ Box}{MSQE}) \quad (14)$$

Using these two tools, we have applied many tests in order to study the influence of our approach on the visual appearance of processed meshes. First, our goal is to find the compromise between watermarking strength (i.e β value) and the visibility criterion (see table 1). Note that when the value of β increases, the watermarking robustness enhances but the mesh undergoes more visual degradation. The results presented show that with a β value equal to 0.00001, we could get good values of MSQE and PSNR. We will use this value in the remaining tests.

Table 1: MSE and PSNR according to β values.

β values	MSQE	PSNR
0.1	3×10^{-2}	34.34
0.01	2×10^{-3}	57.76
0.001	4×10^{-4}	71.84
0.0001	2.2×10^{-5}	97
0.00001	4.2×10^{-6}	111.42

As it is presented in table2, our approach has an important capacity compared to recently published work. PSNR and MSQE values prove that our approach retains almost the same visual appearance of the original mesh.

5.3 Robustness Criterion

Evaluating the robustness criterion needs the application of treatments at the host mesh. We call these treatments ”attacks”. According to (Kai and al, 2010), attacks which threaten a perfect extraction of information from a watermarked mesh can be classified into two types. The first one is said ”Geometry attacks”. They are intended to change coordinates of vertices in the mesh without hitting the topological data (connectivity). As an example we cite: Similarity transformation, Noise addition, smoothing and coordinate quantization. The second one is Connectivity attacks. their goal is to modify the connections between vertices without changing their positions. Only the topological information is targeted by this category of attacks. Simplification and cropping are examples. To test our approach we had to program some attacks treating the multiresolution files based on the algorithms explained in (Kai and al, 2010). After the application of each of these attacks, we calculate the correlation between the information inserted I1 and that extracted I2 using the formula 15:

Table 2: Compromise between capacity, visibility and correlation: comparison with literature.

Approach	Capacity	MSQE	PSNR
Our Approach	250000	2.2×10^{-6}	111.4
(*Sharvari and Ratnadeep*, 2012)	–	–	68.78
(*Sharvari and Atnadeep*, 2012)	–	–	92
(*Kai and al* ,2007)	4000	0	–
(*Zhiyong and al*,2013)	38198	–	81,97
(*Xiao and Qing*,2012)	765	0.0001	–
(*Kai andal* ,2008)	324	0.006	–
(*Cline and Frdric*, 2011)	104551	5×10^{-6}	–
(*Jen − Tse and al*, 2014)	32	–	–

$$C = \frac{(\sum_{i=1}^{n} I1_i - \bar{I1}) \times (\sum_{i=1}^{n} I2_i - \bar{I2})}{\sqrt{\sum_{i=1}^{n} (I1_i - \bar{I1})^2} \times \sqrt{\sum_{i=1}^{n} (I2_i - \bar{I2})^2}} \quad (15)$$

n refer to information size. The extraction of the information is correct, when the correlation value is close to 1.

5.3.1 Similarity Transformation Attack

It includes 3 attacks: translation, rotation and uniform scalling (see figure 6). These types of attacks never alter the form of the mesh.

Table 3 shows that our algorithm is robust against translation, rotation and uniform scalling.

Our algorithm is able to extract all the information even with the application of similar transformations attacks. This is justified by the correlation values shown in table3.

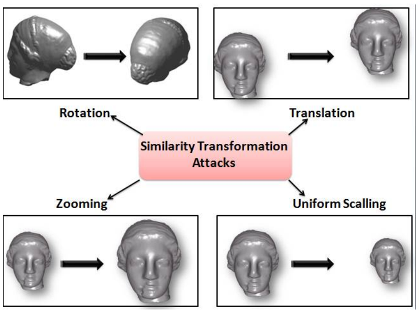

Figure 6: Similarity Transformation Attacks.

Table 3: Robustness against similarity transformation attacks.

	Translation	Rotation	Uniform Scaling
C	1	1	1

5.3.2 Noise Addition Attack

The main idea is to modify the coordinates of the vertices using a pseudo-random generator. This modification follows formula 16:

$$\begin{aligned} \acute{x_i} &= x_i + \alpha \times \bar{d} \\ \acute{y_i} &= y_i + \alpha \times \bar{d} \\ \acute{z_i} &= z_i + \alpha \times \bar{d} \end{aligned} \quad (16)$$

With d presents the distance from the center of gravity of the mesh and α is a pseudo random number. This noise can change the coordinates of the vertex by changing their Cartesian coordinates. This change will be a multiplication of these coordinates by the random factor α.

Points of the mesh will be then redistributed randomly in space which threatens inserted information (see figure 8).

As shown in Table 4, our approach has allowed us to extract correctly the information inserted even by applying random noise to the watermarked mesh. Extraction was acceptable with an intensity noise less than 10^{-3}. P presented in table5 define the proportion of Vertex Affected by Noise. By setting the noise level and varying the proportion of vertex affected by noise, we obtained correlation values near to 1. Algorithm published in (Xiao and Qing, 2012) under the same conditions gave lowest correlation values.

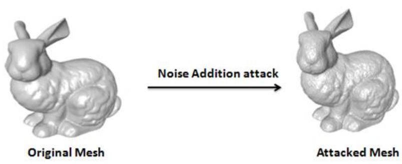

Figure 7: Noise addition Attack.

Table 4: Correlation depending on noise level.

Noise	0,1	10^{-3}	10^{-5}	10^{-6}
C	0,002	0,6	0,88	1
(*Roland Hu and al*, 2014)	0,12	0.3	0.4	–

Table 5: Correlation depending on Proportion of Vertex Affected by Noise.

P	10%	30%	50%	75%	100%
C	0,92	0,88	0,86	0,83	0,71
(*Xiao and Qing*, 2012)	0,84	0,48	0,41	0,30	0,10

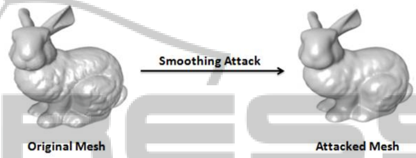

Figure 8: Smoothing Attack.

5.3.3 Smoothing Attack

To apply a smoothing attack to a mesh, formulas 17 should be used:

$$\begin{aligned} \acute{x_i} &= x_i + dFactor \times \bar{d_x} \\ \acute{y_i} &= y_i + dFactor \times \bar{d_y} \\ \acute{z_i} &= z_i + dFactor \times \bar{d_z} \end{aligned} \quad (17)$$

DFactor is a parameter manually initialized. As for d_x, d_y and d_z, they should be calculated as it seen in formula 18.

$$\begin{aligned} d_x &= \frac{\sum_{i=1}^{vertexNumber} \sum_{j=1}^{vertexNumber} x_j - x_i}{VertexNumber} \\ d_y &= \frac{\sum_{i=1}^{vertexNumber} \sum_{j=1}^{vertexNumber} y_j - y_i}{VertexNumber} \\ d_z &= \frac{\sum_{i=1}^{vertexNumber} \sum_{j=1}^{vertexNumber} z_j - z_i}{VertexNumber} \end{aligned} \quad (18)$$

Smoothing attack creates a distortion in the mesh. DFactor parameter measures the degree of this deformation of the mesh. The result of the application of this attack is a mesh whose surface is smoother than the original one (see figure 9). Smoothing attack treatment is usually applied to the mesh just after his construction. Table 6 shows that we can extract the infor-

Table 6: Correlation depending on Proportion of deformation (smoothing level).

dFactor	10^{-10}	10^{-9}	10^{-8}	10^{-7}
C	1	0,94	0,63	0,15
(*Roland Hu and al*, 2014)	0.43	0.31	0.18	–

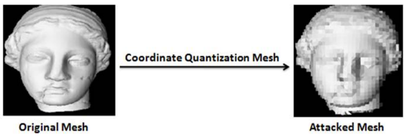

Figure 9: Coordinate Quantization Attack.

mation correctly only for a deformation factor lower than 10^{-8}. Beyond this range, the value of correlation deteriorates which reflects that a loss of information took place.

5.3.4 Coordinate Quantization Attack

This attacks aims at quantifying vertex coordination (see figure 9) using two factors previously calculated according to the maximum and minimum values along x, y and z. Let x_{max}, x_{min}, y_{max}, y_{min}, z_{max} and z_{min} these values. Ql refer to the quantification level which is initialized manually.

$$\begin{aligned} Step_x &= \frac{x_{max}-x_{min}}{Ql} \\ Step_y &= \frac{y_{max}-y_{min}}{Ql} \\ Step_z &= \frac{z_{max}-z_{min}}{Ql} \end{aligned} \quad (19)$$

$$\begin{aligned} Factor_x &= \left\lfloor \frac{x-x_{min}}{Step_x} \right\rfloor \times Step_x - x_{min} \\ Factor_y &= \left\lfloor \frac{y-y_{min}}{Step_y} \right\rfloor \times Step_y - y_{min} \\ Factor_z &= \left\lfloor \frac{z-z_{min}}{Step_z} \right\rfloor \times Step_z - z_{min} \end{aligned} \quad (20)$$

Having the two previous factors we can quantify vertex coordinates. For an eventual x_i, the quantization occurs following formula 21.

$$\acute{x_i} = \begin{cases} Factor_x \quad if \quad Factor_x > 0,5 \times Step_x \\ \quad Factor_x + Step_x \quad Otherxise \end{cases} \quad (21)$$

As it is shown in table 7, correlation values obtained by testing the approach with different quantization level show very well the robustness of our approach against the attack quantization coordinates.

Table 7: Correlation depending on quantizication level.

Quantization	100	196	225	289	361
C	0,01	0,2	0,5	0,9	1

5.3.5 Simplification Attack

The main idea is to present the mesh with a number of triangles less than the number in the original representation (see Figure 10). The results we have presented in Table 8 show very well that our watermarking algorithm is not sensitive to simplification. In fact, whatever the simplification degree is operated, the correlation is always 1.

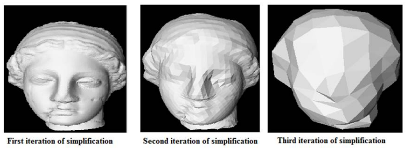

Figure 10: Simplification Attack.

Table 8: Correlation depending on simplification degree.

N.iteration	1	2	3	4	5	6
C	1	1	1	1	1	1
(*Roland Hu and al*, 2014)	0.15	0.31	0.46	–	–	–

6 CONCLUSIONS

In this paper, we present a new watermarking approach for 3D multiresolution meshes. Our algorithm consists in transforming the host mesh into the multiresolution area by applying a wavelet transform. Each wavelet coefficient resulting from this transformation will be represented in the spherical coordinate system to be then modified depending on the message to be inserted. Once all the information is inserted, the coefficients will be represented again in the Cartesian coordinate system to arrive to apply an inverse wavelet transform. The watermarked mesh is then obtained.

The results presented show clearly that our algorithm protects the mesh quality even with the insertion of a large amount of information compared to approaches existing in literature. The application of various attacks (noise addition, coordinate quantization, smoothing, simplification, translation, rotation and uniform scalling) to a watermarked mesh did not prevent correct retrieval of inserted information. All the results presented in this paper and the comparative study with recent works show that our algorithm has an improvement in terms of visibility, capacity and robustness.

To extend this work, we aim at minimizing the amount of memory used during execution, making this algorithm "blind" and testing it against the compression attack.

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