3D Watermarking Technology: Visual Quality Aspects

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Abstract. In these last years the applications involving 3D data are quickly increasing in number and many efforts to obtain 3D models by direct acquisition or modeling have been deployed. Additionally, the computer graphics power reached by personal computers and Internet have incremented the diffusion of this new media. For these reasons, the interest in developing techniques to provide IPR protection of 3D models is increasing. Watermarking technology has been successfully used for this purpose for other kinds of media such as images and video, but, a lot of work is again necessary to reach robustness and industrial applicability for 3D watermarking algorithms. In this paper we treat a specific aspect of 3D watermarking technology: the visual quality of the watermarked models. In particular, after a panoramic on 3D watermarking technology we present some ideas about this issue and we propose a method based on multiresolution analysis to improve this aspect in future watermarking algorithms.

1. Introduction

Today, the computer graphics capabilities of standard personal computers are becoming so high that applications requiring an extensive use of graphics are growing very fast in several fields, like that of Cultural Heritage (archaeological site reproduction, virtual museums), entertainment (games, animations, special effects) and Internet (enhanced user navigation, e-commerce, virtual reality). This process is causing a large diffusion of 3D models more and more complex and detailed. For this reason the computer graphics research community, in the last years, has put a lot of effort in the developing of tools and algorithms to build a framework to easily perform digital processing[1] on this new media. So, it is now possible to edit, render and compress 3D models of high complexity in an efficient way. But up to now only a limited attention has been paid to the issue of the IPR protection of this kind of multimedia data. In fact, while a lot of techniques and methods exist to embed copyright information in image, audio and video data, only few algorithms to hide confidential information (for IPR, authentication and so on) into a 3D model has been developed. One of the reason is that in 3D watermarking the robustness problem is more complex than for images or video, because of the different nature of the data; in fact a lot of diverse and difficult-to-prevent attacks are possibles. For these motivations, 3D watermarking has not reached yet the level of watermarking technology for image or video, that is now mature for the applications.

During the developing of 3D watermarking algorithms we have studied in depth the problem of the degradation of the model due to watermarking process, i.e. the visual quality of the watermarked models. In this paper, after introducing some concepts and issues related to 3D watermarking technology, we want to treat the aspect of visual quality of the watermarked models proposing a solution based on multiresolution analysis to improve this aspect in future 3D watermarking algorithms.

2. 3D Watermarking Technology

In digital watermarking, a digital code, or watermark, is embedded into a digital media, so that a given piece of information is indissolubly tied to it. This information can be used to prove ownership, identify a misappropriating person, trace the model dissemination through the network, and so on. The main goal of 3D watermarking is the production of a stego-model, i.e. a 3D model containing some hidden data.

A watermarking algorithm is called *blind*, if it does not require the original data to recover the embedded information (on the contrary, the algorithm is called *non-blind*); *readable*, if the algorithm is capable to read the watermark without knowing it in advance, *detectable* if it is able to establish if a certain watermark is present or not in the watermarked data.

Watermarking technology can be used to embedd public or private information. A *private watermark* may contain information to prove ownership of the digital media in dispute. *Public watermark* usually replaces header or other user-defined information. This last type of watermark requires high capacitiy, i.e. the watermarking system has to be capable to embedd a lot of bits in the digital data. On the contrary, the first type of watermark has strong robustness requirements but less constrains about capacity; in fact malicious users, the *attackers*, could want to do a misappropriate use of the digital media eliminating the watermark by modifiying it or a part of it. So, a private watermark has to resist to these modifications, that are called *attacks*.

An easy way to develop a 3D watermarking technique is to extend an image watermarking algorithm to 3D, since image watermarking is an already mature research field. However, the nature of the data itself make complicated this extension. In fact, an image is a bidimensional, regularly sampled collection of values, while a mesh is a collection of 3D space points (not regularly sampled) with intrisic curvatures and a particular topology. So there is more than one degree of freedom of difference between mesh and images: it is not a simple 2D to 3D extension!

2.1 Tridimensional Models and Representations

One of the characteristic of 3D models that 3D watermarking technology has to take in account is the fact that a model can be represented in different way. For example, by a collection of parametric curves (e.g. NURBS), by a set of implicit surfaces, or by polygonal meshes. In the following we assume *triangular mesh* representation, i.e. a mesh composed only by triangles. This is a common assumption because meshes can be seen as the lowest common denominator of other representations because it is very simple to convert other representation to mesh.

2.2 Embedding Features

The features used to embed the information depend on the media to watermark. For example, in image watermarking the information can be hidden by changing the value of a subset of image pixels, or of the coefficients of some mathematical transformation (e.g. the Fourier Transform). A mesh can provide more features to manipulate such as vertex positions, connections between vertices (topology) and other surface properties like texture or vertex colors. This characteristic apparently allows a lot of possibilities for watermark embedding, but we have to take into account that most of the model information is encoded by vertices. For this reason we are interested in the features related to the geometry of the model, i.e. *geometric* and *topological features*. The main *geometric feature* of a mesh are its vertices. One possible way to embed the watermark is to modify the position or the normals of vertices. Both this entities are altered by perturbing the coordinates of the mesh vertices. *Topological features* are related to the connectivity of the mesh vertices. Usually, a set of connected vertices is selected by using some proper geometric feature. Then, the connections of this set are altered to encode one or more bits. In the following, when we are talking about generic 3D watermarking algorithms, we assume that these algorithms embed the information in the model by perturbing mesh vertices.

2.3 Attacks on a 3D model

One of the main problems in 3D watermarking is that a lot of complex attacks can be carried out on a mesh. Additionally, due to the more complex nature of the data itself, an attack carried out on 3D data is more complicated to prevent than one on image or video data. In fact, as previously noticed, a mesh is not a collection of regularly sampled values, such as audio, images or video, but a collection of unorganized points in 3D space with intrisic curvatures and a particular topology defined by the connections between vertices. It is difficult to imagine all possible attacks on a polygonal mesh, some of these are:

- *Traslation/Rotation/Uniform Scaling.* These geometric transformations are very used in computer graphics to position a 3D model inside a scene.
- *Noise.* For noise attack we intend the random perturbation of mesh vertices.
- *Re-triangulation.* This attack concerns the changes between the connections of the mesh vertices.
- *Mesh smoothing.* A smoothing of the surface represented by a polygonal mesh can be obtained by mesh filtering. One of the most popular mesh filter is Taubin filter[2] that acts as a low-pass filter on the mesh attenuating the roughness of the surface that it represented.
- *Polygonal simplification.* This operation is often used to transmit a low-level version of the model or to optimize a model eliminating most of the non-salient faces.
- *Cropping.* An attacker can discard the part of the model that he does not need. For example the hand of a statue.
- *Remeshing.* This operation can be described as a geometric resampling of the shape of the mesh followed by a re-definition of the connections between vertices.

2.4 Previous Work on 3D watermarking

In the last years some algorithms to embed data into 3D polygonal models have been developed. Ohbuchi et al. Have been proposed [9] some different algorithms called Triangle Similarity Quadruple (TSQ), Tetrahedral Volume Ratio (TVR), Triangle Strip Peeling Sequence (TSPS) and Macro Density Pattern (MDP). Recently Ohbuchi et al. have developed another interesting technique based on frequency analysis of the mesh [10] that has good robustness properties. Other relatively recent algorithms has been developed by Olivier Benedens [11,12,13]. One of the most interesting of them is the Normal Bin Encoding (NBE)[12] algorithm that uses faces normal to embed the watermark. Face normals are directly related to the shape of the models, so this algorithm is very robust against attack like simplification. This algorithm is blind but its robustness against other attacks different from simplification are not clear. One of the most robust algorithm for mesh watermarking has been developed by Praun, Hoppe and Finkelstein [14]. The main idea of this algorithms is to build basis functions on salient features of the mesh in order to obtain a displacement of the mesh vertices. The salient features of the mesh are obtained by a multiresolution analysis performed with a progressive mesh encoding of the original mesh. This techniques is robust against many of the previously described attacks thanks to a initial registration/resampling phase that needs the original model to be performed. So, the main limitation of this algorithm is that it is not blind. Kanai et al. have developed another algorithm based on multiresolution analysis [15]. This algorithm uses wavelet decomposition of meshes to embed the watermark. In particular the watermark bits are encoded in the wavelet coefficients. This method is robust against additive noise, cropping and affine transformation. Even this technique is not blind.

3. Visual Quality of 3D Watermarked Models and Our Investigations

An important issue related to 3D watermarking concerns the perception of the watermark by the user. This crucial point has been deeply studied in image watermarking where a lot of work to make the watermark invisible to human eye has been done [3,4,5]. For many reasons this aspect radically changes when we treat 3D watermarking. For example, in interactive applications, the user can see the 3D model from every point of view he likes, so, if the user has an original version of the model a visual comparison with the watermarked one will point out the geometric deformation introduced by the watermarking algorithm. On the contrary, if the user does not know anything of the original model, even high deformations could not be noticeable. For example, consider an human head. If the watermarking algorithm strongly deforms facial features, for an observer it is impossible to say if the head he is seeing is watermarked or not.

Neverthless, in some applications (e.g. Cultural Heritage preservation) the watermarked model and the original one must be very close each other from a geometrical point of view, despite the perceptibility of the watermark. One way to give an objective measure of the degradation introduced on the model by a watermarking algorithm it is to use some metric (e.g. Hausdorff distance) to quantify the geometric difference between the surface of the original model and the waternarked one. In this paper we present a method to measure the difference between a model and its watermarked version from a subjective point of view, in order to evaluate the perceptibility of the watermark. To achieve this goal we have realized a software to test if a user is able to distinguish between two version of the same model; the original and the watermarked one. More details about this test and the relative results will be given in the next section.

During our studies to develop 3D watermarking algorithm we have investigated a multiresolution-based approach in order to improve both robustness of the watermarking algorithm and visual quality of the watermarked model. The framework of our algorithm[16] is sketched in figure 1. The solution we have investigated consist on applying the watermarking algorithm on a coarse version of the input model and re-obtain the watermarked model at the original resolution by re-adding the details extracted during the multiresolution analysis process.

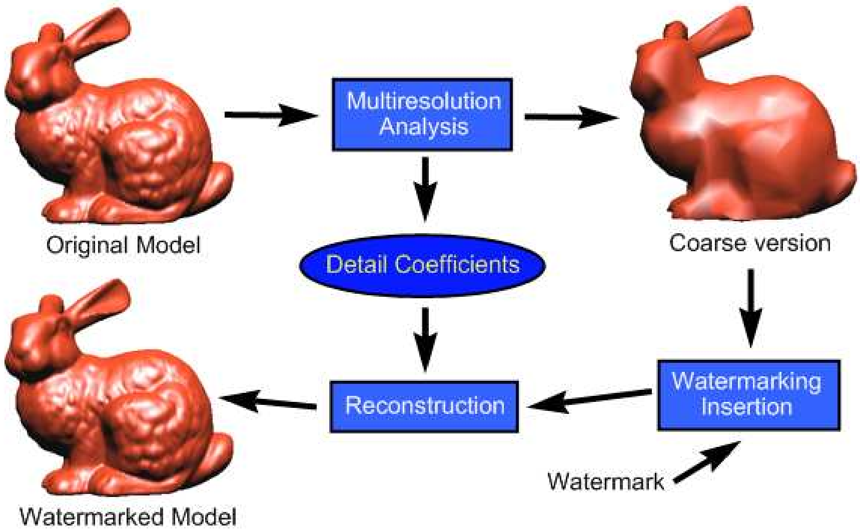


Figure 1: A multiresolution framework for 3D watermarking algorithms.

Our approach provides a *class of 3D watermarking algorithms*, in fact the information in the coarse version can be embedded by different watermarking algorithms. Additionally, several kind of mesh multiresolution analysis tools[6,7,8] can be used.

4. Experimental Results

As previously exposed, the purpose of this experimental results is to measure the degradation of a 3D model watermarked by a generic vertices-perturbation watermarking algorithm, and to show that an approach based on multiresolution analysis can be used to improve the imperceptibily of the watermark to human eye.

4.1 Subjective Test to Measure Watermark Perceptibility

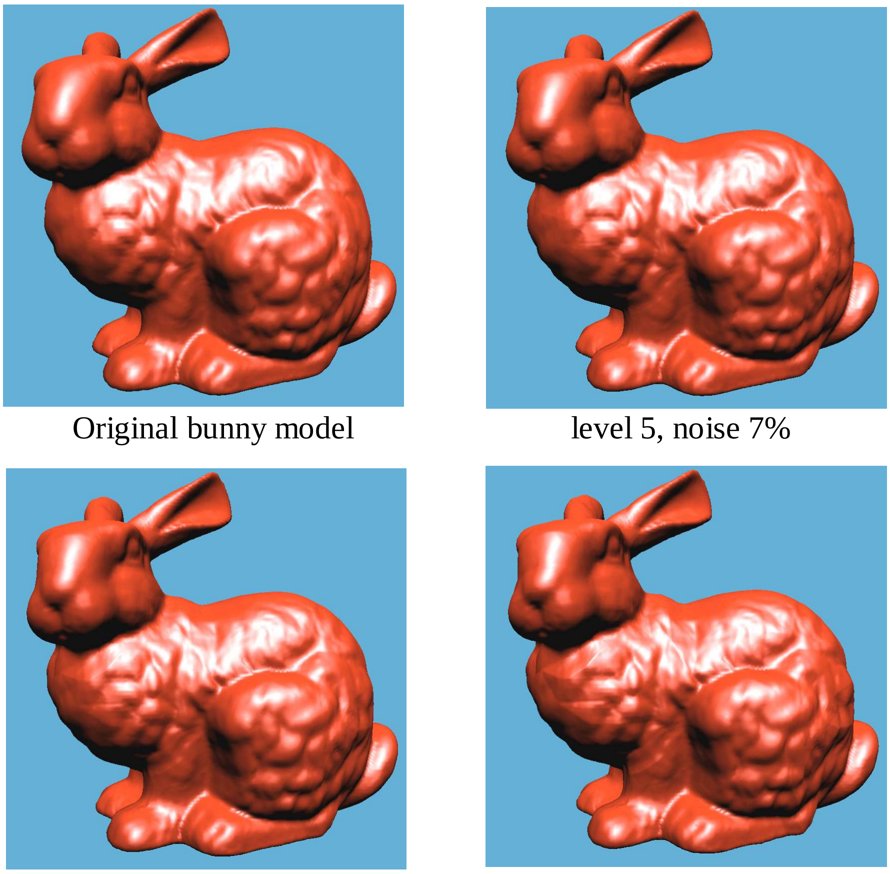
The test to measure the perception of the watermark consists to show to a user three models denominated model A, model B and model C. The user has to recognize if model C is equal to the A or B. This test is repeated several times in order to establish (with a certain degree of confidence) if the user is able to distinguish between the original and the watermarked model. To improve the efficency of the test the models are presented in a random way, i.e. model C will randomly set to be the original or the watermarked one, while A and B are, respectively, the watermarked and the original. In this way the correspondence is unknown to the observer. In order to simulate real use of 3D model the software allow user-interaction i.e. the user can rotate, translate and zoom all three models before making his choice.

4.2 Generation of watermarked models

The models used for this test have been generated in the following way. Referring to the framework of figure 1, an input model has been decomposed by wavelet analysis [7]. The vertices of the obtained low-resolution mesh have been perturbed by 3D noise, in order to simulate a generic watermarking algorithm based on vertices perturbation. Then, the details coefficients (wavelet coefficients in this case) are used to reconstruct the model obtaining the watermarked high-resolution version. Figure 3 show some of the generated models for different amount of noise. The amount of noise is measured as the percentange of the largest side of the OBB (Object Bounding Box) containing the model. For *level* we intend the level of resolution of the coarse version. More specifically, wavelet decomposition generate different levels of resolution. Table 1 reports, for each level of resolution of the model, the number of its faces and the maximum ammissible amount of noise (determined by repeating the test for different users) before that the watermark is perceived by a user.

Table 1: Data relatives to the wavelet decomposition of the bunny model.

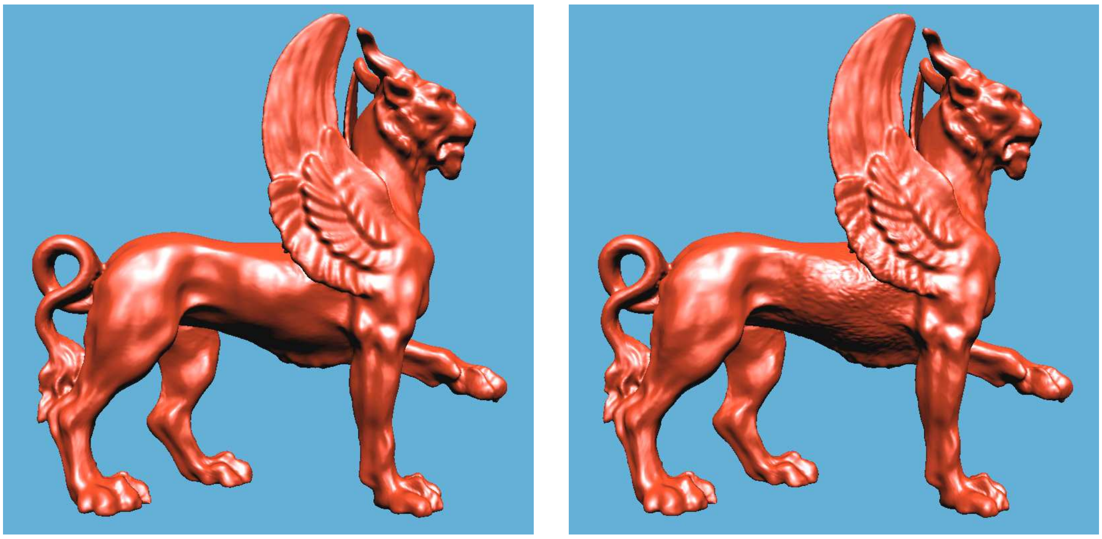
Level of Resolution	Number Of faces	Maximum amount of noise
Level 1 (original model)	313,950	Not available
Level 2	78,430	1%
Level 3	19,550	2%
Level 4	4,830	4%
Level 5	1,150	12%



Original bunny model — level 5, noise 7%

level 5, noise 12% — level 5, noise 20%

Figure 3: Some of the models used for perceptibility watermark test.



Original Feline model level 2, noise 2%

Figure 4: Different properties of the surface results in different visual effects.

4.3 Results and considerations

Figure 3 and 4, and table 1, summarize the experimental results. In practice, as show in table 1, the multiresolution analysis is a very efficient way to hide vertices perturbation. Additionally, thanks to the knowledge of the maximum amount of imperceptible noise; it is possible to set the maximum power that a watermarking system can use to insert the watermark.

Another interesting considerations that emerge is that the properties of the surface results in different visual effects. In particular, the smoothness of the surface influence the visibility of the watermark. In fact, as show in Figure 4, the rough regions naturally hide the watermark. So, future watermarking algorithms based on vertices perturbation should take into account this fact, weithing the watermark insertion in order to avoid smooth regions. This is a well-known problem in image watermarking, where perceptual mask have been developed in order to improve the watermark imperceptibility [3,4,5].

5. Conclusions

In this paper a panoramic on 3D watermarking technology has been presented focusing on visual quality of 3D watermarked models. In particular, a way to evaluate the visual quality of a watermarked model has been presented and a solution, based on multiresolution analysis, to improve this aspect in future watermarking algorithms has been proposed.

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References

[1] P. Schroder and W. Sweldens, "Digital Geometry Processing". In *Sixth Annual Symposium on Frontiers of Engineering*, pp. 41-44, 2001.

[2] G. Taubin, "A Signal Processing Approach to Fair Surface Design", *ACM SIGGRAPH 95 Conference Proceedings (aug. 1995)*, pag. 351-358, 1995.

[3] C. I. Podilchuk and W. Zeng, "Image-adaptive watermarking using visual models", *IEEE Journal Sel. Areas Commun.*, vol. 16, no. 4, pp. 525-539, May 1998.

[4] R. B. Wolfgang, C. I. Podilchuk and E. J. Delp, "Perceptual watermark for digital images and video", Proc. *IEEE*, vol. 87, no.7, pp. 1108-1126, July 1999.

[5] F. Bartolini, M. Barni, V. Cappellini and A. Piva, "Mask building for perceptually hiding frequency embedded watermarks". In Proc. *ICIP98 Int. Conf. Image processing*, Chicago, IL, Oct. 1998, vol. I, pp. 450-454.

[6] A. W. F. Lee, W. Sweldens, P. Schroder, L. Cowsar, and D. Dobkin, "MAPS: Multiresolution Adaptive Parameterization of Surfaces". In Proceedings of *SIGGRAPH 1998*, pp. 95-104.

[7] M. Eck, T. DeRose, T. Duchamp, H. Hoppe, M. Lounsbery and W. Sweldens, "Multiresolution Analysis of Arbitrary Meshes", *Computer Graphics (SIGGRAPH 96 Proceedings)*, pag. 325-334, 1995.

[8] M. Lounsbery, T. DeRose, J. Warren, "Multiresolution Analysis for Surface of Arbitrary Topological Type", *Transaction on Graphics (SIGGRAPH 95 Proceedings)*, Annual Conference Series, 1995.

[9] R. Ohbuchi, H. Masuda and M. Aono, "Watermarking Three-Dimensional Polygonal Models", *ACM Multimedia 97*, ACM Press, pag. 261-272, 1997.

[10] R. Ohbuchi, S. Takahashi, T. Miyazawa and A. Mukaiyama, "Watermarking 3D Polygonal Meshes in the mesh spectral domain", in *Proceedings of Graphics Interface 2001*, B. Watson and J. W. Buchanana, eds., pp.9-18, 2001.

[11] O. Benedens, "Two High Capacity Methods for Embedding Public Watermarks into 3D Polygonal Models", *Proc. Multimedia and Security (Orlando, Florida, U.S.A., 1999)*, pag.95-99, 1999.

[12] O. Benedens, "Watermarking of 3D Polygonal Based Models with Robustness against Mesh Simplification", Proc. *SPIE Security and Watermarking of Multimedia (1999)*, pag. 329-340, 1999.

[13] O. Benedens, C. Busch, "Towards Blind Detection of Robust Watermarks in Polygonal Models", Proc. *EUROGRAPHICS 2000, Computer Graphics Forum*, Volume 19, No. 3, pag. C199-C208, Blackwell 2000.

[14] E. Praun, H. Hoppe and A. Finkelstein, "Robust mesh watermarking", in *Proc. SIGGRAPH 1999*, pp. 49-56, August 1999.

[15] S. Kanai, H. Date, and T. Kishinami, "Digital Watermarking for 3D Polygons using Multiresolution Wavelet Decomposition", *Proceeding of the Sixth IFIP WG 5.2 International Workshop on Geometric Modeling: Fundamentals and Applications (GEO-6)*, pp. 296-307, Tokyo, Japan, December 1998.

[16] M. Barni, F. Bartolini, V. Cappellini, M. Corsini and A. Garzelli, "Digital watermarking of 3D meshes", in Mathematics of Data/Image Coding, Compression, and Encryption VI, with Applications, SPIE Proc. Vol. 5208, Schmalz Eds., 3-8 August 2003, San Diego, CA, USA.