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A Survey of the 3D Triangular Mesh Watermarking Techniques

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Abstract

Research efforts in digital watermarking have been mainly on audio, image and video data. Only recently, 3D watermarking has attracted the attention, due to the increasing proliferation of the 3D object scans and models, and the new trend of 3D imaging and communication witnessed in many areas, such as medicine, architecture and entertainment. In this paper, we present a compilation and description of the current state of the art in 3D triangular mesh watermarking. After a description of the different categories, paradigms, and methods develop so far, we provide a comparative study highlighting their merits and the shortcomings with respect to a set of standard criteria.

Keywords: 3D Watermarking; 3D Triangular Mesh; Robust Watermarking; Fragile Watermarking

Introduction

The recent advances of 3D shape acquisition and CAD technology and the widespread of 3D models across a variety of sectors spanning, Manufacturing, Medicine and Entertainment, raised concerns on their ownership protection, integrity verification, content tracing and last but not least about their usage for hiding information. 3D watermarking came as new technology for addressing these issues.

3D object models include parametric surfaces, cloud of 3D points, and polygonal mesh. This last is the most supported format. In this type of model, the surface is composed of a set of polygons stitched together to form the model shape. The mesh is encoded essentially of the polygons vertices's coordinates and the vertices connectivity within each polygon. But other topological information can also be derived such as the polygons connectivity or adjacency. Triangular mesh is the most commonly used mesh because of its simplicity and flexibility. Contrary to other polygons, triangle is the only polygon in which vertices are guaranteed to be coplanar.

3D triangular mesh watermarking is the process of embedding information into the mesh model. In addition the watermark term is employed in ownership protection, content labeling, authentication, and distribution channel tracing. The embedded data is also referred by the term payload in steganography applications, when the goal is to use the 3D mesh model as a medium for carrying secret information.

There are two major issues that make 3D triangular mesh models watermarking quite problematic com- pared to other media watermarking such as image and audio, namely: (1) 3D triangular mesh models lack an ordered structure that would allow a systematic analysis of model's surface, and (2) between the complexity and richness of 3D models in one hand, and the in- creasing number of meshes manipulation graphic tools in another hand, it becomes impossible to anticipate all attacks.

A variety of paradigms, methods and techniques have been developed to address the aforementioned challenges. This variety followed the same categorization found in its 2D counterpart. So 3D watermarking falls into two categories, namely, fragile and robust. Fragile watermarking, aims to inform about attempts for altering a model. Whereas robust watermarking is meant to endure and survive malicious mesh alterations, referred conventionally by the term attacks. These attacks can be categorized into geometric attacks that include geometric transformation, scaling, smoothing, topological attacks (mesh simplification, subdivision and remeshing). Other type of attacks targets the structure of the integrity of the model, such as cropping.

In fragile or robust watermarking, data embedding can be applied in the spatial or the spectral domain. In the former the data is embedded by altering locally or globally the geometry or the topology of the model surface. Whereas the latter involves the modification of a certain components of a spectral transform coefficients. Data embedding can also be qualified to be blind or non-blind, depending whether or not the original digital content is required to extract the embedded data

Watermarking methods can also be categorized as deterministic or statistical. Methods from the first category employ a set of constraints for embedding messages while the second category extract the message by using a statistical test and performing statistical changes in distributions of measurements from the object's mesh. This category was not mentioned in the previous surveys [1,2].

The rest of the paper will be organized as follows: In Watermarking Methods section, we will go through a detailed review of the current 3D watermarking works. Then in Comparative Study section we draw a comparative study. Finally, we terminate the paper with concluding remarks and future research directions.

Watermarking Methods

As mentioned previously, watermarking methods can be segmented into robust methods and fragile methods according to the application purposes. These can be also classified into different sub-categories depending on the nature of the model alterations.

Robust methods

A robust method is designed to protect the copyright. These methods can be classified into spatial methods and spectral methods.

Spatial methods: These methods act either on the geometry or the topology of the model. The geometry included the vertices, the facets and the normals. The topology encompasses connectivity features. The elementary entity carrying the watermark data is referred by the watermark primitive. Many methods operate on the triangular facet as a watermark primitive. Benedens [3] proposed a technique based on the Extended Gaussian Image. In the same context Kwon et al. [4] proposed a semi-blind technique that employed rather a local version of the EGI. The EGI has been augmented by an imaginary component by Lee et Kwon [5,6], and dubbed it, the CEGI. They claimed the same level of invisibility than Benedenss methods [3], in addition to its robustness against remeshing, simplification, cropping and noising.

Recently, Jing et al. [7] proposed a non-blind method using the average of normal to establish a new coordinates system. The signature is inserted into the selected vertices according to area of the two adjacent rings and in function of the curvature of the facets.

In another method, Benedens [8] proposed algorithm, dubbed vertex flood, whereby the distance to the center of mass of reference triangles is changed to encode the watermark bits. In a similar approach Yu et al. [9] inserted a bit by modifying the distance between a group of vertices and the center of mass of the mesh. The set of vertices are grouped according to a secret key. The method is non-blind and robust to simplification, noising as well as to some attack combination. However this method can produce a significant local geometry alteration as noticed by Zoran and Zeljka [10] whom proposed an improved variant in which the verticess displacement is moderated. Kuo et al. [11] introduced the moment-preserving method [12], in which groups of neighboring facets are selected and classified using some specific geometric moments in order to hold the embedded bits. Recently, Rolland-Neviere X et al. [13] generalized a framework for 3Dmesh watermarking. A method consists of modifying the vertex positions along the radial directions.

Other type of methods used particular special volumes for inserting data bits. Harte et al. [14] presented a blind watermarking scheme in which the embedded vertices are confined within ellipsoid or rectangular volumes. The embedding is performed by a vertex displacement function of their neighborhood and the bit to be inserted. Figure 1 depicts the insertion of 110 in three areas of the mesh using the method of Harte et al. [14]. He and Li [15] proposed to embed the watermark by modifying the location of vertices within their related space. Eshraghi and Samavati [16] followed this paradigm and suggested to displace the vertices in their tangent space.

Among the techniques that modify the geometry, there are also the statistical methods which extract the watermark using a statistical test. Some works performed data embedding using spherical coordinates (ρ,θ,ϕ) as was firstly proposed by Zafeiriou et al. [17]. In this work, he proposed the Principal Object Axis (POA) method whereby the major axis of the object is aligned with the z axis, and the data is embedded by moving the ρ component of the vertex the along the radial axis. This method is robust to similarity transforms. In a second method, dubbed

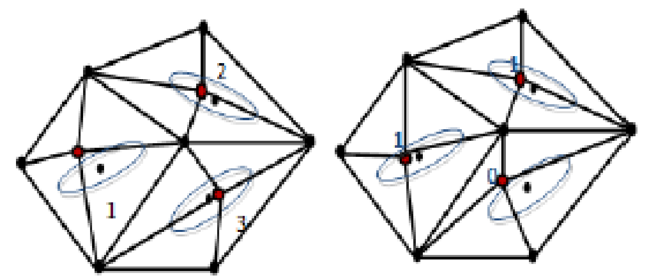

Figure 1: Mesh before and after insertion of the bits '110'

Sectional Principal Object Axis (SPOA), he restricted the displacements to set vertices having the coordinate θ within specific ranges in order to achieve robustness against mesh simplifications. A similar method was proposed by Kalivas et al. [18]. Another research [19] has explored the spherical coordinates system, where only the vertex norm of each point is modified. The embedding function is based on the Spread Transform Dither Modulation (STDM). The perceptual modulation controls the amount of quantization distortion, depends on both the roughness and the curvature at v_i. This method is not robust to reordering and simplification attacks.

Cho et al. [20] proposed a blind statistical method. In this work, either the mean or the variance of normalized distributions of vertex norms is changed according to the watermark code. This method show excellent robustness against most common mesh attacks, such as additive noise, smoothing and mesh simplification. However, these algorithms produce visible artifacts such as ripples on the 3D object surface. Al-face et al. [21] have applied locally the method of Cho et al. [20]. The algorithm consists of detecting robust shape feature points which are then used for embedding a watermark in a local neighborhood. Some optimizations however should be developed to improve the watermarking system.

Hu et al. [22] proposed a similar histogram-based method for watermarking 3D polygonal meshes by using quadratic programming. This method is more resistant to Gaussian noise, compared with Cho's method.

Luo and Bors [23] used the Quadratic Selective vertex placement scheme in order to find the best location of each vertex after modifying the statistics of the distances. In [24] they proposed a new statistical 3D water- marking method based on embedding into geodesic distance distribution calculated using the Fast Marching method (FMM). Nakazawa et al. [25] presented a new blind watermarking method. They firstly segmented the 3D triangular mesh using the mesh saliency based on the surface curvature. Then, they embedded the watermarks to the regions by statistically modulating the vertex norms. In the same context, Zhan et al. [26] proposed a blind watermarking algorithm based on vertex curvature. The watermark is embedded into vertex bins by modulating the mean fluctuation values of the bins. Generally this method has better robustness and better visual masking then Cho et al. [19].

Bors and Luo [27] proposed a new statistical approach to 3D watermarking by minimizing the 3D object surface distortion. They used the Levenberg Marquardt optimization method for vertices represented in spherical coordinates.

Topological methods proceed with data embedding by altering the connectivity and other topologic features of the mesh. Mao et al. [28] suggested subdividing triangles and inserting the data in the newly formed vertices. This method is robust to affine transformation. The triangle flood algorithm [8] of Benedend generates a unique path in the mesh, based on topological and geometric information, along which the data is inserted.

Spectral methods: Basically, spectral methods embed the data in certain coefficients of harmonic or multiscale transform. These methods have been developed to address attacks other than non-similarity transforms, such as simplification, remeshing, etc. Inspired by the Laplacian matrix-based mesh compression of Karni and Gotsman [29], several methods used the Laplacian coefficients for data embedding in different variants. Ohbuchi et al. [30] applied this paradigm to mesh model. They applied eigenvalue decomposition of a Laplacian matrix derived from mesh connectivity; they embed the watermark by modifying the coefficients amplitudes. Their method is robust to smoothing, moderate noise addition and cropping. So did Abdellah et al. [31], however, with a non-blind technique. These methods are robust to smoothing and some attack combination. Murotani and Segihara [32] methods embedded the watermark in the singular spectral coefficients, reducing thus the dimension of the matrix. The method is not robust to connectivity changes however.

Cayre et al. [33] developed the first blind method employing piece-wise Laplacian decomposition. The message is inserted repeatedly on the low and medium frequency to ensure robustness. Alface et al. [34] proposed to segment the 3D object patch in order to reduce embedding complexity by using the same process of Cayre [35]. This method also suffers from the problem of low strength. Recently, Yang and Ivrissimtzis [36] proposed blind watermarking algorithm by changing the Laplace coordinates.

Liu et al. [37] proposed the use of the Fourier-Like Manifold Harmonics Transform (MHT). This transform is invariant to the resolution and embedding, thus making it immune to mesh simplification and noise-addition. Wang et al. [38] proposed a robust and blind algorithm based on MHT. In contrast to the Lius method where only 5 bits are inserted, the method of Wang is capable to insert 16 bits. Another method based on MHT, Wang et al. [39] proposed a robust non blind watermarking algorithm for two-manifold mesh by combining manifold harmonic basis and elliptic curve digital signature algorithm. They segmented a 3D mesh into patches and embedded the watermark into the low frequency spectral coefficient of each patch. The algorithm improves the visual quality of the watermarked mesh.

Wu and Kobbelt [40] proposed a robust and fast spectral watermarking scheme for large meshes using a new orthogonal basis functions based on radial basis function. In order to enhance further the robustness against attacks, Praun et al. [41] developed a method based on the principles of spread-spectrum watermarking, previously employed in images, sound, and video. The spread-spectrum method [41] embeds the watermark at multiple scales into the perceptually salient features of the model. It has proven to be robust against a much broad range of attacks.

Multi-scale methods used mostly the wavelet trans- form (WT). Here data bits are inserted in the WT coefficients. Kanai et al. [42] non-blind method was among the first attempts in this category. They used the multi-resolution decomposition of Eck et al. [43].

Ucchedu et al. [44] presented a novel algorithm, whereby vertices at a given resolution-level and the related coefficients at the same level are used for bit insertion. Kim et al. [45] addressed multi-resolution watermarking of irregular mesh with the so-called irregular wavelet analysis scheme. Yin et al. [46] rather employed Burt-Adelson pyramid decomposition [47]. Hoppe et al. [48] proposed a mulit-resolution framework based on the edge-collapsing operator. Driven by the goal of achieving trade-off between imperceptibility and robustness, Motwani et al. [49] proposed WT-based watermarking using Fuzzy logic to set optimal amplitude of the watermark. Seoud et al. [50] introduced a robust watermarking method based on a spherical wavelet transformation. They applied the watermarking to 3D compressed model using a multilayer feed-forward neural network (MLFF).

Other authors such as [51-52] found advantages (increasing the capacity and enhancing the robustness) in using the spherical variants of the multi-resolution analysis such as [51] whom used spherical wavelet transform and, [52] whom adopted a spherical parameterization, and [53] who proposed the concept of Oblate Spheroidal Harmonics. Chen et al. [54] developed a non-blind watermarking method based on BNBW (biorthogonal non Uniform B-Spline Wavelets). The signature is inserted by modifying vectors of wavelet coefficients according to the bit of the signature.

Recently, Tamane et al. [55] have proposed a blind algorithm. This method inserted the optimization parameter and signature encoded by the transformation of Arnold, in the coe_cients of mid-band DCT after applying Haar transform on the 3D model. It is robust against attacks: rotation, translation, noise addition, cropping, smoothing. Xiaoqing F et al. [56] presented a new robust and blind 3D mesh watermarks algorithm. They embedded two kinds of watermarks into mesh model. The first one is inserted into DCT (Discrete Cosine Transform) frequency domain in some feature patches which are achieved using watershed segmentation. The second watermark is based on redundancy information of 3D model, such as vertex coordinates and vertex order. This algorithm cannot resist to simplification and re-meshing.

Fragile methods

Fragile watermarking is used for checking the authenticity and the integrity of 3D mesh model. In this context the watermark is meant to be sensitive to the least amount of mesh modifications as well as to indicate the locations of such modification in the mesh. As for robust watermarking, methods in the category can be segmented into spatial and spectral methods.

Spatial methods: Yeung and Yeo [57,58] pioneered the firrst fragile watermarking of 3D models for verification purposes by extending a 2D image watermarking to 3D. They proposed the idea of moving the vertices to new positions so that each vertex has the same value for two different and predefined hash functions. Attacks can then be revealed by the presence of vertices that do not comply with this condition. In this method the hash functions requires a predefined order of the vertices within the 1-ring neighborhood, otherwise the scheme become vulnerable to the causality problem.

Ohbuchi et al. [59] method embeds the data on a facet quadruples across the whole mesh. The quadruple facets must satisfy similarity conditions, dubbed, Triangle Similarity Quadruple (TSQ), used to recall them when the embedded information is retrieved. Each quadruple store quadruple of symbols composed of marker, subscript and two information data. These are embedded in the dimensionless features of the triangles (e.g. edge ratios), thus modifying the vertices' positions. To avoid the causality problem the facet quadruples should not be connected to each other. To set the insertion area, they used the Macro Primitive Embedding configuration (MEP). In Figure 2, we have example of MEP. This configuration consists of a central triangle that is used to store the key by changing the size $\{e_{14}/e_{24}, h_4/e_{12}\}$ and then change the V_1 V_2 V_3 peaks, one of his neighbors contains the index inserted into the pair $\{e_{02}/e_{01}, h_0/e_{12}\}$ and the other two remaining neighbors are used to record data values in pairs. The message is inserted in all the MEPs in the same way. To detect the message, simply find the MEPs and extract the index and the inserted data. The mesh can contain more MEPs in order to insert a lot of data as shown in the example of Figure 3.

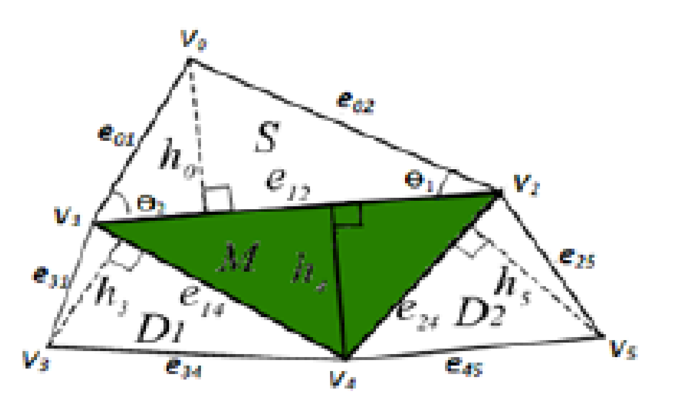

Figure 2: MEP (Macro Primitive Embedding). Vi are vertices, e_{ij} are the lengths of edges and hi are the heights of the triangles [60].

Lin et al. [60] approached the causality problem by proposing a rearrangement of the vertices harmless to the embedded watermark and making the two hash functions depending only of the position of the current vertex. Chou et al. [61] proposed a watermarking mechanism in which one of the hash functions is dependent of the mean of the 1-ring vertex neighborhood.

High capacity steganographic methods, where the integrity of the hidden data is a requirement, can be also classified as fragile. In these methods vertex are altered to embed data bits. The larger the number of bits, the higher will be the capacity of the method. Cayre and Macq [35] proposed a two-stage blind method where first the select a candidate stripe of triangles, then they perform bit embedding by projecting a triangle summit on the opposite edge segmented into two equal intervals. A facet is assigned the bit 0 or 1 depending on which segment the projection occurred as shown in Figure 4. The synchronization used some local (e.g. largest facet) or global (e.g. facet intersecting the largest principal axes) geometrical features.

In the same context, Werghi et al. [62] proposed a new method. They apply the method of Cayre and Macq [35] on a sequence of facets selected using the ORF structure [63] (Ordered Rings Facets).

Bors [64] proposed a blind watermarking method that locally embeds a string of bits on a set of vertices selected and ordered based on a certain distortion visibility criterion. The vertices associated to 0 (respectively 1) are shifted outside (respectively inside) a bounding volume. He proposed two variants, in the first the bounding volume is an ellipsoid defined by principal axes of the covariance matrix computed over the set 1- ring neighborhood. The second used abounded parallel planes. Here the vertex is moved along or opposite to the plane's normal depending of the bit value assigned to it. Wu and Chueng [65] developed an algorithm similar to the vertex Flood [8] by quantifying the distance between a facet and a center of mesh. Cheng and Wang [66] changed the position of the vertex in order to have a high capacity method. Huang et al. [67] proposed a new scheme fragile watermarking based on spherical coordinates.

Recently, Bata et al. [68] proposed a secure watermarking scheme based on LDPC codes. The proposed scheme consist on combining sparse quantized index modulation (QIM) for data hiding with run- length modulated low-density parity-check (LDPC) codes for recovering deleted watermark bits.

A fragile method acting on the mesh connectivity, dubbed Triangle Strip Peeling Symbol sequence (TSPS), was also introduced by Ohbuchi et al. [59]. The method consists in cutting out a stripe from the mesh except from one attaching edge that marks the start of the stripe. Figure 5 is an example of stripe. The stripe is formed by repeatedly appending adjacent facets trough a path encoded in the message data. The stripe can be shaped as a meaningful pattern that becomes visible when the mesh undergoes global connectivity alteration. However in this method the watermark cannot spread over the whole mesh, this reduces its capabilities for integrity authentication.

Spectral methods: In the frequency space, geometrical wavelet-transform has been an attractive tool. Here the watermark is inserted by altering the wavelet-transform coefficients computed at each facet or by altering the facets at given wavelet-transform resolution to equate predefined functions. Cho et al. [69] followed the latter paradigm by embedding the watermark data in facets of the lower resolution of the wavelet transform. This method suffers, however, from the causality transform. The method of Wang et al. [70] rather than alter the module and the orientation of the one-level WT coefficients to keep a same watermark symbol across the whole facets. This scheme has been also extended to multi-resolution levels [71].

Comparative Study

A watermarking algorithm should meet several requirements, on the top of them comes the robustness to as much as possible types of attacks and good watermark invisibility. We will discuss them in the following sections.

Distortion evaluation

Naturally, the watermarking process should verify a good visual imperceptibility of the watermark by reducing distortion effects caused by the watermark to the minimum. Mesh distortion is evaluated with the Metro method [72] which consists to calculate the Hausdorff Distance *HD* between the original mesh model and watermarked one. To measure the *HD* the following formula is used:

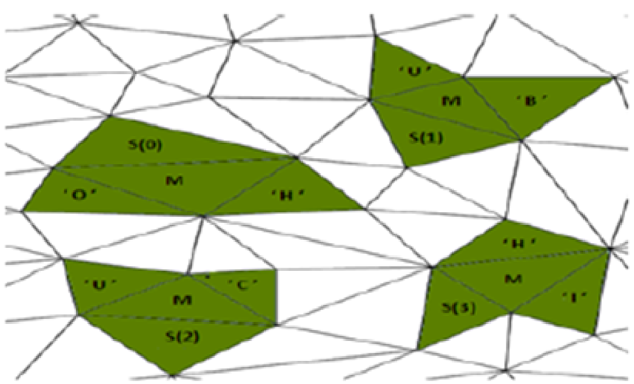

Figure 3: In this example, there are four MEPs in a mesh water marked with the word 'OHUBUCHI' (the MEPs are ordered S(0) to S(3)).

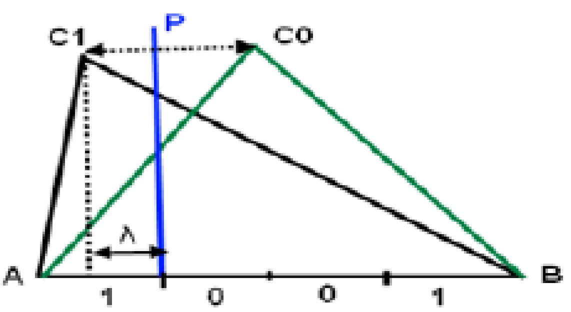

Figure 4: Watermarking primitive in the algorithm of Cayre and Macq [35].

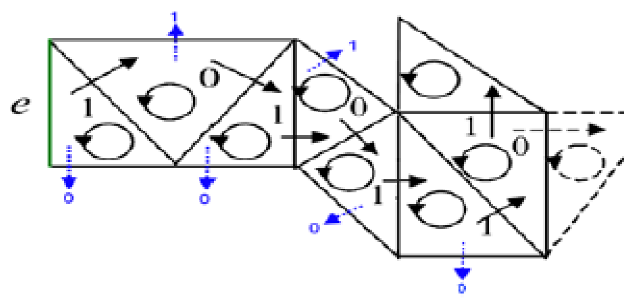

Figure 5: Construction of a triangle strip from the message '1010111'.

Methods		Robustness against Attacks							Type	Detection	Capacity
		Geometric			Connectivity						
		Similarity Transformations	*Smoothing (iteration)*	*Noise*	*Remeshing*	*Simplification*	*Subdivision*	*Cropping*			
Spatial	***Geometric***										
	Benedens [3]	no	yes	yes	yes	≤ 36%	yes	no	Robust	Semi blind	- 50 bits
	Jing et al. [5]	yes				≤ 5%			Robust	non blind	
	Yu et al. [8]	yes		≤ 0.6%		≤ 80%		yes	Robust	non blind	
	Kwon et al. [4]	yes		yes		≤ 30%		yes	Robust	Semi blind	50 bits
	Harte et al. [13]	yes	yes	yes		no		yes	Robust	Blind	20 bits
	Eshraghi and Samavati [15]	yes						yes	Robust	non blind	-
	Zafeiriou et al. [16]	yes		yes		≤ 40%		no	Robust	Blind	-
	Cho et al. [19]	yes	≤ 30	≤ 0.3%		≤ 90%	yes	no	Robust	Blind	64 bits
	Hu et al. [21]	yes		yes		yes		no	Robust	Blind	55 bits
	Lin et al. [61] Cayre and Macq [35]	no yes	yes	yes	no no	no	no	yes	Fragile Fragile	Blind Blind	512 ×512 -
	Bors [65]	yes		yes				yes	Fragile	Blind	32 bits
	Topologic										
	Mao et al. [27] TFA [28] TSPS [60]	yes yes yes		yes	no no	no no	yes	no yes	Robust Robust Fragile	Blind Semi blind Blind	- - -
Spectral	***Spectral***										
	Ohbuchi et al. [30	yes	yes	yes	yes	yes	no	yes	Robust	Non blind	16 bits 24 bits
	Abdallah et al. [22] Wu and Kobbelt [40]	yes	≤ 7	yes yes	yes	≤ 50%		yes yes	Robust Robust	Non blind Non blind	
				yes	yes	yes		yes	Robust	Blind	-
	Liu et al. [37]	yes	yes	yes		yes		no	Robust	Blind	5 bits
	Multiresolution										
	Kanai et al. [42]	yes	yes	yes	no	no	no	yes	Robust	Non blind	- 250 bits
	Uccheddu et al. [44]	yes		yes	no	no			Robust	Blind	
	Yin et al. [46]	yes		yes		yes	no	yes	Robust	Non blind	
	Chen et al. [54] Tamane et al. [56]	yes yes		≤ 0.3% ≤ 0.2%		≤ 70%		yes yes	Robust Robust	Non blind Blind	1200 bits
	Cho et al. [70]	yes		yes		yes		no	Fragile	Blind	- -
	Wang et al. [71]	yes		no	yes	no		no	Fragile	Blind	-

Table 1: Comparison of 3D mesh watermarking Methods

$$HD = max\{h(M_1), h(M_2)\} \quad (1)$$

Where $M_1 = (V,V')$ and $M_2 = (V', V)$, (V and V' rep resent respectively the original mesh and watermarked mesh).

$h(M_1)=\max\{\min(d(a,V'))\}$, a in V,

$h(M_2)=\max\{\min(d(b,V))\}$, b in V'.

Robustness measurement

The robustness indicates how resistant the watermarking scheme when the mesh object is subjected to attacks. The most common robustness measurements are the Bit Error Rate (BER) and the correlation between the inserted watermark bit and the extracted one. To validate the robustness of the algorithm, the correlation is introduced to measure the similarity between the extracted watermark sequence and the original watermark sequence:

$$Corr = \frac{\sum_{n=0}^{N-1}\left(\omega_n - \bar{\omega}\right)\left(\omega_n' - \bar{\omega}'\right)}{\sqrt{\sum_{n=0}^{N-1}\left(\omega_n - \bar{\omega}\right)^2 \times \sum_{n=0}^{N-1}\left(\omega_n' - \bar{\omega}'\right)^2}}$$

Where w^- is the average of the signature and the correlation corr in [-1, 1]. To evaluate the robustness of the algorithm against geometry attacks and connectivity attacks: rotation, translation, uniform scaling, noise, smoothing and simplification attacks are executed.

Discussion

Table 1 depicts a comparison of a group of representative works. The comparison assessed the robustness with respect to geometric attacks (similarity transforms, smoothing, and noising) and connectivity attacks (remeshing, simplification, subdivision, and cropping).

Based on the previously described state of the art and on Table 1, we notice that the principal issue of geometrical methods is that they cannot tolerate both geometrical and connectivity attacks, at least not with the same level of robustness. It is also noticed that most of them employ blind watermarking. And in general, the watermark insertion has little or no effect on the 3D model quality. As for the topological methods, handling causality problems and synchronization still seems not yet fully addressed. Most of the spectral methods have better robustness as compared to their geometric counterpart. Inserting the watermark and low frequency seems to produce a better imperceptibility. On the contrary, the computational efficiency is the main disadvantage of the transformed domain methods. Secondly, due to the obscure relationship between the geometry and the spectral coefficients, it is difficult to explicitly control the distortion. Even of wavelet method, it has disadvantage. It requires the mesh to be in a re- stricted connectivity scheme. For the irregular wavelet method, the connectivity must be identical with the original object in order to detect the watermark.

Watermarking methods can be also categorized as deterministic method [64] or statistical approach [19,20]. The methods from the first category employ a set of constraints for embedding messages while the second category extract the message by using a statistical test. Usually, deterministic methods allow a higher capacity of information embedding, making them suitable for steganography, but achieve lower robustness to attacks. On the other hand, the statistical methods are generally more robust but they achieve lower embedding capacity rates. Especially when the statistical features of an object are modified, it is not easy to control the distortion, at least without compromising the robustness.

Conclusion

The amount of research work produced in relatively short period in 3D triangular mesh watermarking reflects the importance and the impact of this new filed. Certainly the approaches, paradigms, and the techniques produced so far illustrate clear advances of the state of the art, yet major issues remain to be addresses. Probably on the top of them comes the difficulty of anticipating the different scenarios and the combinations of attacks that a model might go through. Also it seems that fully responding to the requirements that one would expect in terms of robustness, imperceptibility and blindness is hard to achieve, so rather a trade-off between these three criteria would be a more realistic objective. For robust watermark there is still work to do in defining the most appropriate primitives for a given type of attacks. For fragile watermarking, we believe that many of the current issues are inherited from the non-organized structured of the triangular mesh format.

Future watermark embedding schemes could concentrate on distortion control and the development of performance evaluation criteria. Moreover, future algorithms should be robust to various attacks.

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