A Comprehensive Survey on Three-Dimensional Mesh Watermarking

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***Abstract*—Three-dimensional meshes have been used more and more in industrial, medical and entertainment applications during the last decade. Many researchers, from both the academic and the industrial sectors, have become aware of their intellectual property protection and authentication problems arising with their increasing use. This paper gives a comprehensive survey on 3D mesh watermarking, which is considered an effective solution to the above two emerging problems. Our survey covers an introduction to the relevant state of the art, an attack-centric investigation, and a list of existing problems and potential solutions. First, the particular difficulties encountered while applying watermarking on 3D meshes are discussed. Then we give a presentation and an analysis of the existing algorithms by distinguishing them between fragile techniques and robust techniques. Since attacks play an important role in the design of 3D mesh watermarking algorithms, we also provide an attack-centric viewpoint of this state of the art. Finally, some future working directions are pointed out especially on the ways of devising robust and blind algorithms and on some new probably promising watermarking feature spaces.**

***Index Terms*—3D mesh, digital watermarking, copyright protection, authentication, attack, robustness.**

I. Introduction

Digital watermarking [1]–[3] has been considered a potential efficient solution for copyright protection of various multimedia contents. This technique carefully hides some secret information in the functional part of the cover content. Compared with cryptography, the digital watermarking technique is able to protect digital works (assets) after the transmission phase and the legal access. There exist different classifications of watermarking algorithms. We distinguish between *non-blind* and *blind* watermarking schemes depending on whether or not the original digital work is needed at extraction. Usually, one hopes to construct a *robust* watermark, which is able to go through common malicious attacks, for copyright protection purposes. However, sometimes the watermark is intentionally designed to be *fragile*, even to very slight modifications, in order to be used in authentication applications. Finally, researchers customarily classify watermarking algorithms into two categories, *spatial-domain-based* or *transform-domain-based*, according to the insertion space.

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Nowadays, 3D meshes [4] are widely used in virtual reality, medical imaging, video games and computer aided design. A mesh is a collection of polygonal facets targeting to constitute an appropriate approximation of a real 3D object. It has three different combinatorial elements: *vertices*, *edges*, and *facets*. From another viewpoint, a mesh can also be completely described by two kinds of information: the *geometry* information describes the 3D positions (coordinates) of all its vertices, while the *connectivity* information provides the adjacency relations between the different elements. Mathematically, a 3D polygonal mesh containing N vertices and M edges can be modeled as a signal $\mathcal{M} = \{G, C\}$, where

$$G = \{v_i\}_{i=1,2,...,N}, v_i = (x_i, y_i, z_i) \quad (1)$$

$$C = \{(v_{k_1}, v_{k_2})\}, 1 \le k_1 \le N, 1 \le k_2 \le N, k_1 \ne k_2 \quad (2)$$

Each vertex element v_i in G is numbered by an index i and is described by its three-dimensional coordinates (x_i, y_i, z_i); C has M elements and each element stands for an edge connecting two different vertices indexed by k_1 and k_2. Instead of a list of edges, users usually prefer a list of all the mesh facets with their respective component vertices in a certain cyclic order. Although this list contains redundant information, it can facilitate the geometrical and topological operations on a given mesh. Fig. 1 shows an example of a 3D mesh. As illustrated by the close-up, the *degree* of a facet is the number of its component edges, and the *valence* of a vertex is defined as the number of its incident edges. Their formal mathematical definitions are given at the end of this paragraph. Although there are many other 3D representations, such as cloud of points, parametric surface, implicit surface and voxels, 3D mesh has become the *de facto* standard for numerical representation of 3D objects due to its algebraic simplicity and usability. Furthermore, it is quite easy to convert other representations to 3D meshes, which are considered low-level, but effective models.

Definition 1 (Degree of a facet): A facet is a minimum cycle of edges on the mesh surface that does not contain any other edge cycles. Formally, a facet f_i can be defined as a sequence of vertices $\{v_{i_1}, v_{i_2}, ..., v_{i_J}\}$, where $v_{i_j} \in G, j = 1, 2..., J$. The degree of the facet f_i is defined as the number of its component edges, and it is easy to deduce that this number is simply J (also the number of its component vertices) in the above expressions. Furthermore, we often request that all the vertices forming a facet should be on exactly a same plane.

Definition 2 (Valence of a vertex and its 1-ring neighbors):

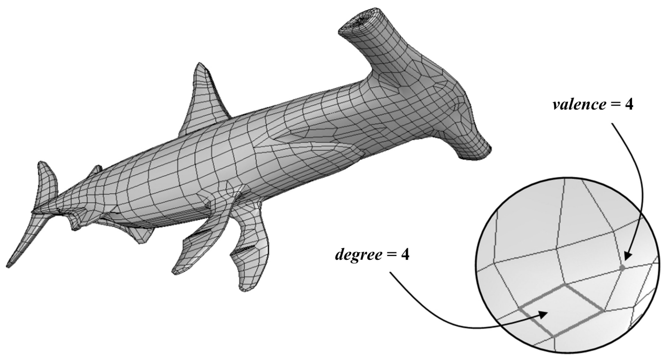

Fig. 1. Example of a 3D mesh and a close-up illustrating the *valence* of a *vertex* and the *degree* of a *facet*.

The valence of the vertex v_i is defined as:

$$valence(v_i) = \mathcal{N}(\{v_j | v_j \in G,\ v_j \neq v_i, and\ (v_i, v_j) \in C\}) \tag{3}$$

where $\mathcal{N}(.)$ is a function that returns the cardinality of a set, and all the elements of the set $\{v_j | v_j \in G,\ v_j \neq v_i, and\ (v_i, v_j) \in C\}$ form the 1-ring neighbors of the vertex v_i.

With the increasing capability of capturing, processing and visualizing 3D data, the intellectual property protection of 3D meshes has attracted more and more attention. Naturally, as a promising technique, watermarking appears to be a good candidate for solving this emerging problem. Fragile watermarks can be used to authenticate the origin and integrity of the received 3D mesh data at the user end. This paper, as the extended version of [5], reviews the nearly 10-year history of the research on 3D mesh watermarking since the publication of the first relevant algorithms in 1997 [6], and it provides some suggestions on the future working directions in this developing discipline. The remainder of this paper is organized as follows. Section II discusses the special difficulties encountered when watermarking 3D meshes and provides an overview of the most important techniques proposed in the literature. Attacks on watermarked meshes play an important role in the design of suitable watermarking algorithms. They are much more intractable than their counterparts on images. Therefore, section III is dedicated to analyzing various possible attacks and discussing the corresponding solutions in order to resist them. Some open questions and possible research directions are detailed in the last section.

II. 3D Mesh Watermarking Techniques

A. Difficulties and Classification

There still exist few watermarking methods for 3D meshes, in contrast with the relative maturity of the theory and practices of image, audio and video watermarking. This situation is mainly caused by the difficulties encountered while handling the arbitrary topology and irregular sampling of 3D meshes, as well as the complexity of the possible attacks on watermarked meshes.

We can consider an image as a matrix, and each pixel as an element of this matrix. This means that all of these pixels have an intrinsic order in the image, for example the order established by row or column scanning. This order is usually used to synchronize watermark bits (*i.e.* to know where the watermark bits are and in which order). On the contrary, there is no simple robust intrinsic ordering for mesh elements, which often constitute the watermark bit carriers (primitives). Some intuitive orders, such as the order of the vertices and facets in the mesh file, and the order of vertices obtained by ranking their projections on an axis of the objective Cartesian coordinate system, are easy to be altered. In addition, because of their irregular sampling, we still lack an effective spectral analysis tool for 3D meshes. This situation makes it difficult to apply existing successful spectral watermarking schemes, such as the one proposed in [7], on 3D meshes.

In addition to the above point, robust watermarks also have to face various intractable attacks. The reordering of vertices and facets do not have any impact on the shape of the mesh, while it can seriously desynchronize the watermarks that rely on this straightforward ordering. The similarity transformations, including translation, rotation, uniform scaling and their combination, are supposed to be common operations through which a robust watermark should survive. Even worse, the original watermark primitives can disappear after a mesh simplification or remeshing. Such tools are available in many software packages, and they can completely destroy the connectivity information of the watermarked mesh while well conserving its shape. Usually, the possible attacks can be classified into two groups: the geometric attacks that only modify the positions of the vertices, and the connectivity attacks that also change the connectivity aspect. Section III provides a detailed investigation on these attacks and discusses the existing solutions to make the watermarks robust against them.

Watermarking 3D meshes in computer aided design applications has other difficulties caused by design constraints. For example, the symmetry of the object has to be conserved and the geometric modifications have to be within a tolerance for future assembly. Under this situation, the watermarked mesh will no longer be evaluated only by the human visual system, which is quite subjective, but also by some strict objective metrics.

In the following, we introduce the existing 3D mesh watermarking algorithms by distinguishing them between fragile techniques and robust techniques. In each class, it seems convenient to subdivide the members into two subclasses, depending on whether the watermark is embedded in the spatial domain (by modifying the geometry or the connectivity) or in a transform domain (by modifying the coefficients obtained after a certain transformation).

B. Fragile Techniques

A fragile technique for authentication application often has to possess two features: it should be vulnerable to even very slight modifications of the watermarked asset; and it should be capable of locating, or even identifying the endured attacks. However, we often want the (semi-)fragile watermark to be robust against the so-called content-preserving operations including vertex/facet reordering in the mesh file and similarity transformations. In many authentication applications, these operations are not considered as malicious attacks, but as routine operations because they have theoretically not any influence on the mesh shape. In this subsection, we will also mention some high-capacity techniques used for annotation or covert communication applications.

1) Fragile Techniques in Spatial Domain: The spatial description of a 3D mesh includes a geometry aspect and a connectivity aspect. We begin with the techniques modifying the geometry.

- *Fragile Techniques in Spatial Domain Modifying the Geometry*

The algorithms that directly modify the individual vertex positions are often fragile techniques. Yeo and Yeung [8] proposed such a fragile algorithm that can be used for mesh authentication. The basic idea is to search for a new position for each vertex where two predefined hash functions have an identical value, in order to make all vertices valid for authentication. At the extraction phase, one simply examines the validity of each vertex and locates the possible attacks on the invalid vertices. The watermark embedding algorithm depends on a pre-established vertex order to prevent the causality problem. Formally, *causality problem* means that the insertion of the posterior watermark bits disturbs the synchronization of the anteriorly inserted bits, or directly changes the feature values of the watermarking primitives where the anterior bits are inserted; hence, the extracted bits can be different from the original ones, even in the absence of attacks. Here in the algorithm of Yeo and Yeung [8], the first hash function is dependent only on the position of the current vertex to be watermarked, but the second one is also dependent on the positions of its 1-ring neighbors. When considering the 1-ring neighbors for hash function calculation, the authors only take into account the previously watermarked ones, which are in front of the current vertex in the pre-established order. Without this order, the causality problem occurs, which in this case means that the watermarking of one vertex can impact the validities of its neighbors that have already been watermarked. Hence, the proposed scheme is fragile to vertex reordering.

Lin *et al.* [9] considered vertex reordering as an operation that even a fragile watermark should be able to resist because it is harmless to the mesh shape. Thus, they solved the causality problem by setting both hash functions dependent only on the coordinates of the current vertex. They also proposed a more controllable modification scheme with a better attack localization capability. Chou and Tseng [10] solved the causality problem by introducing the adjusting vertex method. In their watermarking algorithm, one of the two hash functions is dependent on the barycenter of the vertex 1-ring neighbors. However, nearly every watermarked vertex has an adjusting vertex selected from its neighbors. The position of this adjusting vertex is tuned in order to keep the neighbors' barycenter unchanged after watermark insertion. Another feature is that the peak distortion for each watermarked vertex is accurately controlled so that severe distortions, which are possible in [8], [9], are avoided.

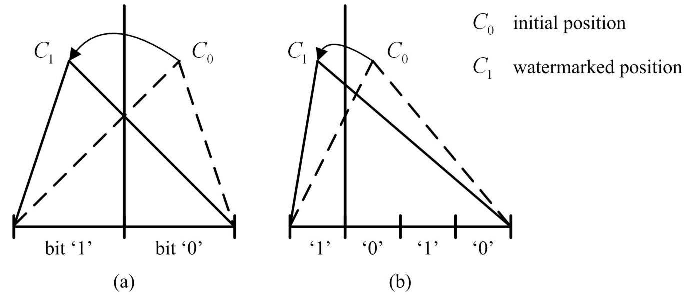

Fig. 2. Watermarking primitive in the algorithm of Cayre and Macq [11], the projection of a vertex is moved into the nearest correct interval: (a) the opposite edge is divided into two intervals; (b) the opposite edge is divided into four intervals. The inserted bits are both '1'.

The objective of a high-capacity watermark is simply to hide a large amount of secret information within the mesh object for applications such as content labeling and covert communication. High-capacity watermarks are often fragile (in sense that they are not robust), and some of them have the potential to be successful fragile watermarks with precise attack localization capability. These are the reasons why we present them here, in the "fragile techniques" section. Individual vertex coordinates are also used to construct such high-capacity approaches. Cayre and Macq [11] proposed a high-capacity blind data-hiding algorithm for triangular meshes. By choosing the projection of a vertex on its opposite edge in a triangle as the primitive (see Fig. 2), the theoretical capacity can attain 1 bit per vertex. The synchronizing mechanism relies on the choice of the first triangle according to a certain geometrical criterion (*e.g.* one of the triangles intersecting with the most significant principal axis of the mesh) and a further geometric spreading scheme that is guided by a secret key. A higher capacity, which is about 3 bits per vertex, is achieved in [12] by applying a multi-level embedding procedure. This procedure consists of modifying successively the parallel, vertical, and rotary positions of a vertex related to its opposite edge in a triangular facet. By quantizing the distance from a facet to the mesh center, Wu and Chueng [13] gave another scheme whose capacity can attain 1 bit per facet.

It is worth pointing out that for the fragile techniques used for authentication (integrity verification) [9], [10], the causality problem is well resolved, but they are not invariant to similarity transformations. On the contrary, most existing high-capacity methods [11]–[13] are invariant to these transformations, but it is difficult to use them for authentication due to the lack of a precise attack localization capability.

- *Fragile Techniques in Spatial Domain Modifying the Connectivity*

Presently, there are only a few 3D mesh watermarking techniques based on connectivity modification (neither fragile nor robust). Ohbuchi *et al.* [6] presented two such algorithms. In the first one, the local triangulation density is changed to insert a visible watermark. The second algorithm first cuts one band of triangular facets off the mesh and then glues it to the mesh with just one edge. This facet band can be a meaningful pattern or simply determined by a secret key. Both methods are visible and fragile. But the embedded watermarks do not spread all over the mesh, and this fact stops them from being useful fragile watermarks for integrity authentication due to the lack of attack localization capability.

2) Fragile Techniques in Transform Domain: Usually, researchers insert watermarks in a kind of spectral domain of the asset to improve the robustness or the imperceptibility, according to the spread spectrum communication principle. However, some other transformations, such as multiresolution analysis, are much more flexible.

3D mesh multiresolution analysis [14] is a useful tool to reach an acceptable trade-off between the mesh complexity and the capacity of the available resources. Such an analysis produces a very coarse mesh that represents the basic shape (low frequencies) and several detail bands at different resolution levels (medium and high frequencies). These methods permit realizing a synthesis process during which multiple representations with different complexities (*i.e.* resolutions) can be created.

The most interesting point of the multiresolution analysis for watermarking is its flexibility: inserting at different locations allows to meet different application demands. For example, insertion in the coarsest-level representation can ensure a good robustness, while embedding in the detail bands provides an excellent capacity. Under the same additive insertion intensity, insertion in the mesh low resolution component can be both more robust and more imperceptible because such an insertion makes the object expand or contract a little, while keeping its basic shape. The insertion in high resolution levels may permit constructing effective fragile watermarks capable of precisely locating the attacks.

Wavelets are a common tool for such a multiresolution analysis. The mathematical formulation of wavelet analysis and synthesis of 3D meshes was introduced by Lounsbery *et al.* [15]. Fig. 3 illustrates one iteration of the lazy wavelet decomposition mechanism. A group of four triangles is merged into one, and three of the six initial vertices are conserved in the lower resolution. The wavelet coefficients are calculated as the prediction errors for all the deleted vertices, and they are 3D vectors associated with each edge of the coarser-level mesh. One straightforward prediction is the midpoint of the two conserved vertices having been incident to the deleted vertex. Note that this kind of wavelet analysis is applicable only on semi-regular meshes. Fig. 4 shows the wavelet decomposition of a dense Rabbit mesh; the watermark can be inserted either in the coarsest-level mesh (robust watermark), or in the wavelet coefficients at different levels (high-capacity or fragile watermarks).

Cho *et al.* [16] proposed a fragile algorithm in the wavelet domain to authenticate semi-regular meshes. They first apply several wavelet decompositions on the original triangular mesh and then consider the facets in the obtained coarser mesh as authentication primitives. The basic idea is to slightly modify each facet so that the values of two predefined functions are the same, in order to make all these facets valid for authentication. Both function inputs are invariant to similarity transformations. However, it seems that two problems exist: first, the causality problem occurs because the modification of the current to-be-watermarked facet can influence the validities

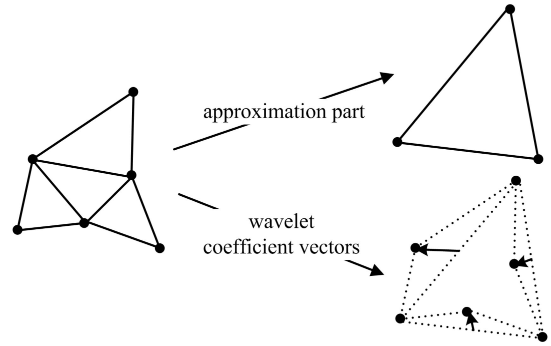

Fig. 3. Illustration of one iteration of the lazy wavelet decomposition mechanism of 3D semi-regular triangular meshes.

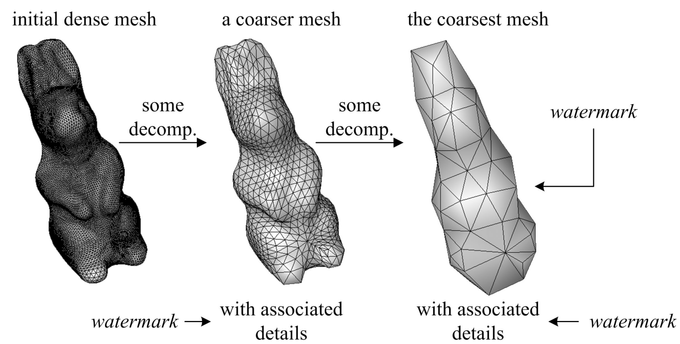

Fig. 4. 3D mesh watermarking techniques based on wavelet transform.

of its already watermarked neighboring facets (this problem is not mentioned by the authors); secondly, the watermark is inserted in a relatively coarse mesh obtained after several wavelet decompositions, which seems disadvantageous to provide precise attack localization capability. Recently, Wang *et al.* [17] have described a fragile watermarking technique for authenticating semi-regular meshes that is both robust to vertex/facet reordering and similarity transformations, and capable of precisely locating the endured attacks. In their method, after one wavelet decomposition, the norm and the orientation of each obtained wavelet coefficient vector are independently modified so that they both imply a same watermark symbol, serving for authentication. Based on wavelet transform, a high-capacity scheme is reported in [18], which relies on modification of the norm permutation of the wavelet coefficient vectors at a certain resolution level.

C. Robust Techniques

A robust technique should at least be able to resist the attacks that cause distortions smaller than a certain threshold beyond which the watermarked mesh is greatly degraded. However, we always hope to construct robust techniques as strong as possible while keeping the watermark imperceptible.

1) Robust Techniques in Spatial Domain: Between the geometry and the connectivity parts of a 3D mesh, nearly all the existing spatial robust algorithms take the former as primitive, which tends to be superior in both robustness and imperceptibility. The fragility to connectivity attacks of the algorithms modifying connectivity information prevents them from being (blind) robust watermarks. It is important to note that this section focuses more on watermarking primitives than on robustness, which will be explored in detail in the next section. Also note that some techniques presented in this subsection are not strictly robust, but they are neither fragile. These techniques can be considered as data hiding schemes that were proposed during early stage of the development of 3D mesh watermarking techniques.

As reported in the subsection concerning fragile techniques in spatial domain, inserting 1 bit in each vertex makes the algorithms very vulnerable. Therefore, some algorithms choose the positions of groups of vertices as watermarking primitives in order to try to strengthen the robustness. Yu *et al.* [19] gave a non-blind robust algorithm. Vertices are scrambled and divided into several groups using a selected secret key and in each of these groups one bit is inserted by modifying the lengths from its member vertices to the gravity center of the mesh. The modulation scheme is a simple additive method with an adaptive intensity obtained by a local geometrical analysis of the mesh. The extraction is also quite simple, since it is sufficient to regroup the vertices and to inverse the additive insertion model. However, a pre-processing step of registration and resampling is necessary to extract the watermark (to ensure a sufficient robustness and to recover the same grouping of the vertices at extraction as during the insertion), and this step makes the algorithm non-blind. One watermark bit is repeatedly inserted in each member vertex within a group; this redundant insertion and the weighting rule at the extraction are the main reasons for its good robustness. Meanwhile, their method is the first attempt in history to insert a watermark in a global and essentially geometric characteristic of a 3D mesh (here the lengths from vertices in a same group to the mesh center). In Benedens's "Vertex Flood Algorithm (VFA)" [20], after grouping vertices according to their distances to the center of a designated triangle, each group's range interval is then divided into $m = 2^n$ subintervals; the distances between all the member vertices in a same group and the chosen triangle center are then altered so that the new distances all fall into a certain subinterval that stands for the next n watermark bits.

Recently, researchers have attempted to embed watermarks in spherical coordinate systems by using certain kinds of histograms. This approach seems promising because some blind and robust techniques have been devised based on modification of these histograms. Zafeiriou *et al.* [21] first calculate the center and principal axes of the mesh object and afterwards convert the vertex coordinates into the registered spherical system (r, θ, φ), then they divide the vertices into several groups associated with different ranges of θ. The histogram of the prediction errors of vertex radial components is constructed for each group. The prediction is calculated from the vertex 1-ring neighbors by applying a local neighborhood operator. The authors assume a Gaussian distribution of these prediction errors in a group, and embed one watermark bit by modifying the left or right side distribution of the histogram. The basic idea is to alter the histogram one-side variance either on the left or on the right so as to indicate the bit '-1' or the bit '+1', respectively. Similarly, Cho *et al.* [22] construct the histogram of the distances between vertices and mesh gravity center, and then divide this histogram in bins associated with different ranges of this distance. They make the hypothesis of a uniform distribution in each bin. Finally, one bit is inserted by slightly altering either the mean value (see Fig. 5) or the variance of the distribution in each bin. Both algorithms proposed by Zafeiriou *et al.* and Cho *et al.* are robust to common geometric attacks and simplification. However, these methods can suffer from the causality problem because the key parameters during the histogram reconstruction, such as the gravity center in both methods and the principal axes in the method of Zafeiriou *et al.*, could have been changed after watermark embedding. Unfortunately, neither of these two papers has clearly discussed the impact of this problem on the algorithm's robustness. Nevertheless, the basic idea of their algorithms deserves deeper investigation because the statistical mesh shape features implied in these histograms are quite robust and can be excellent watermark carriers.

Furthermore, watermark embedding in the spherical coordinate system, especially in the radial component $r_i = \sqrt{x_i^2 + y_i^2 + z_i^2}$, has additional advantages. We may devise some similarity-transformation-invariant algorithms if the distance component is relative to the mesh center. Moreover, since the component r_i represents approximately the mesh shape, its modification is supposed to be more robust than a single x_i, y_i or z_i component modification. These are two other reasons why numerous researchers chose to insert watermark in the spherical coordinate system [21]–[23].

Facets have several interesting measures for watermarking. Ohbuchi *et al.* [24] chose the ratio between the height of a triangle and its opposite edge length as primitive to construct a watermarking technique that is intrinsically invariant to similarity transformations (Triangle Similarity Quadruple (TSQ) algorithm). Benedens [20] reported a blind algorithm in which the triangular facet height is quantized. In another method proposed by the same author [25], the Extended Gaussian Image (EGI) of a mesh is established by clustering facets according to their normal directions. Then, in each bin of the EGI, the average normal direction of the group of facets is modified to carry one watermark bit. Since these average normal directions approximately describe the mesh shape, this scheme is demonstrated to be relatively robust to simplification and remeshing. Kwon *et al.* [26] proposed a similar approach based on EGI. Both algorithms are semi-blind mainly because they need to recover the original mesh pose in the 3D space at extraction to achieve an invariant EGI. Instead of EGI, Lee *et al.* [27] adopted Complex EGI for watermarking. They construct the EGI in the same way, but associate each bin with a complex weight, which depends not only on the bin's total surface size but also on the proximity of the involved facets. In their algorithm, the bins with bigger complex weights are selected as carriers, and this selection is proven to be able to reinforce the robustness. One inconvenience of the facet-based algorithms is that the modification of the positions of the involved vertices is indirect and sometimes quite complicated, especially in the last three algorithms based on EGI or complex EGI. In general, the motivation to embed watermark in facets is mainly to reinforce the robustness, especially to similarity

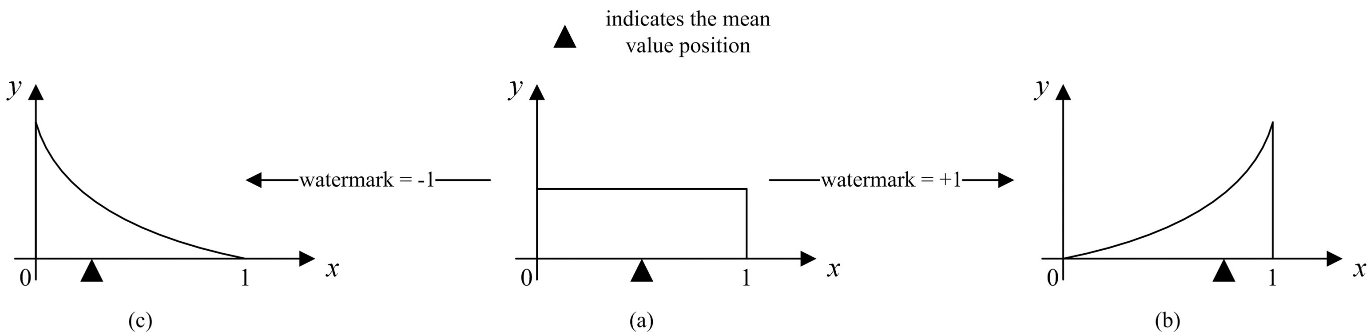

Fig. 5. Watermark embedding in the algorithm of Cho *et al.* [22] that modifies the mean value of the histogram in a bin: (a) the assumed uniform distribution in a bin; (b) the mean value is increased to embed a bit '+1'; (c) the mean value is decreased to embed a bit '-1'. The horizontal axis indicates the normalized distances from vertices to the mesh gravity center (normalized relative vertex norms), and the vertical axis represents the occurrence probability.

transformation and simplification. However, the final modification on vertices is indirect, and it is sometimes difficult to control the introduced distortion and the expected robustness.

There exist other spatial techniques that modify the geometry, which are not quite as robust but all have some particularity worth mentioning. Bors [28] reported a blind algorithm that is robust to similarity transformations. The primitive is the relative position of a vertex to its 1-ring neighbors. A two-state space division is established (*e.g.* inside or outside of an ellipsoid), and the vertex is assumed to be moved into the correct subspace according to the next watermark bit. Ohbuchi *et al.* [24] presented the "Tetrahedral Volume Ratio Embedding" algorithm that is invariant to affine transformation (note that it is different from similarity transformation in sense that it also includes shears). Song and Cho [29] provided an interesting means for easily using existing image watermarking techniques. A bounding cylinder is generated from the cover mesh, and then a regular sampling is carried out on the profile of this cylinder. For each sample, the authors calculate the horizontal geodesic distance from the sample to the mesh surface and take this value as the brightness of this sample pixel. A watermark can then be inserted in this pseudo-range image. The changes on horizontal geodesic distances after watermarking have to be reflected on the 3D mesh by modifying the positions of related vertices. At last, Bennour and Dugelay [30] proposed to insert watermarks in the 2D contours of a 3D mesh object.

To summarize, the main drawback of the robust techniques in spatial domain is their relatively weak robustness to connectivity attacks, except the histogram-based and EGI-based techniques. For blind schemes, the synchronization is a difficult problem, because both the attacks and the insertion process itself (causality problem) can desynchronize the watermark. However, these methods often have the advantage of high capacity, and are easy to implement.

2) Robust Techniques in Transform Domain: Most of the successful robust image watermarking algorithms are based on spectral analysis. A better imperceptibility can be gained due to the information spreading effect of the inserted watermark bits in all the spatial part of the cover content, and by taking advantage of the masking effect of the human visual system. A better robustness can be achieved if the watermark is inserted in the low and medium frequency parts. Unfortunately, for 3D meshes, there does not yet exist an efficient and robust spectral analysis tool. Moreover, the lack of a natural parameterization and the irregular sampling make spectral analysis even more difficult. Almost all the existing spectral analysis tools have their limitations. In addition to the algorithms that embed watermarks in the spectrum obtained by direct frequency analysis, here we also present the algorithms based on multiresolution analysis. The basic idea behind both of them is the same: modification of the data obtained after a certain mesh transformation.

- *Robust Techniques in Transform Domain Based on Direct Frequency Analysis*

Researchers have tried different types of frequency analysis, but all of them have their limitations or deficiencies.

For spectral analysis based on a Laplacian matrix, a matrix D of dimension $N \times N$ (N being the number of mesh vertices) is constructed based on mesh connectivity. The construction of this symmetric matrix is quite simple and implies the adjacency relations between vertices. If the vertices v_i and v_j are connected by an edge, then the elements d_{ij} and d_{ji} of the matrix D are set to -1; otherwise, they are set to 0. Each diagonal element d_{ii} is equal to the valence of the vertex v_i. The N-sized spectral vectors $O = (o_1, o_2, ..., o_N)$, $P = (p_1, p_2, ..., p_N)$, $Q = (q_1, q_2, ..., q_N)$ are calculated respectively as the projections of the three coordinate vectors $X = (x_1, x_2, ..., x_N)$, $Y = (y_1, y_2, ..., y_N)$, $Z = (z_1, z_2, ..., z_N)$ on the N normalized eigenvectors of this Laplacian matrix, which have been sorted in an ascending order according to their associated eigenvalues. Fig. 6 illustrates the spectrum amplitude of the simplified Bunny mesh (100 vertices). The i_{th} spectrum amplitude coefficient is calculated as $s_i = \sqrt{o_i^2 + p_i^2 + q_i^2}$. This mesh spectral analysis tool was originally introduced in graph theory, and then used by Karni and Gotsman [31] for mesh compression. Later, based on this analysis, Ohbuchi *et al.* [32] proposed a non-blind watermarking method (additive modulation of the low and medium frequency coefficients), while Cayre *et al.* [33] gave a blind one (quantization of the low and medium frequency coefficients).

There exist two serious problems with the Laplacian frequency analysis. First, the computation time increases rapidly with mesh complexity due to the diagonalization of the $N \times N$

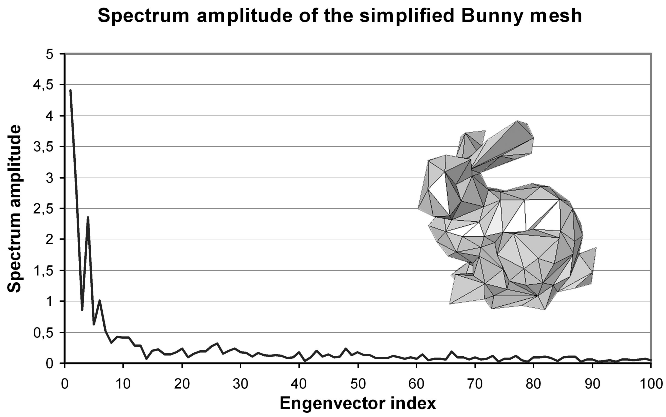

Fig. 6. The spectrum amplitude of the simplified Bunny mesh (100 vertices).

Laplacian matrix. This complexity problem forced the authors to cut the original mesh into several patches possessing fewer vertices. Secondly, the analysis procedure depends on the mesh connectivity information. To overcome this fragility, the authors proposed a pre-processing step of resampling at the extraction phase in order to recover exactly the same connectivity as in the cover mesh.

Wu and Kobbelt [34] reported another spectral algorithm that is based on radial basis functions. The construction of these basis functions is relative to the geometric information. This kind of analysis seems effective because it can provide a good approximation of the original mesh with just a very limited number of basis functions, effectively saving the calculation time. In spite of this improvement, the algorithm remains sensitive to various attacks and dependent on the vertex ordering. For this reason, the authors proposed to carry out registration and resampling before the real extraction. With the similar objective of solving the computational performance problem, Murotani and Sugihara [35] proposed to watermark the mesh singular spectral coefficients. In this method, the matrix to be diagonalized has a much lower dimension. However, the robustness problem still exists and the algorithm remains non-blind to ensure robustness to connectivity changes.

Although current 3D mesh spectral analysis tools are not efficient and robust enough, they provide the opportunity to make use of the existing mature spectral watermarking techniques of digital images.

- *Robust Techniques in Transform Domain Based on Multiresolution Analysis*

Based on the regular wavelet analysis tool presented in the subsection concerning fragile techniques in transform domain (subsection II.B.2), Kanai *et al.* [36] proposed a non-blind algorithm that modifies the ratio between a wavelet coefficient norm and the length of its support edge, which is invariant to similarity transformations. Uccheddu *et al.* [37] described a blind one-bit watermarking algorithm with the hypothesis of statistical independence between the wavelet coefficient norms and the inserted watermark bit string. However, their methods are not robust to connectivity attacks.

With a remeshing [38] step before wavelet decomposition, the regular wavelet analysis can be extended to irregular meshes. Jin *et al.* [39] used such a technique to insert a non-blind watermark into both the coarsest representation and the spherical wavelet [40] coefficients of an irregular mesh. However, this remeshing step seems not robust enough and can introduce noise into the watermark, which can cause an extraction error. Using a direct irregular mesh wavelet analysis tool without any assisting remeshing step [41], Kim *et al.* [42] devised a blind algorithm; but their method is fragile to connectivity attacks.

Other multiresolution analysis tools are also employed to develop 3D mesh watermarking algorithms. Hoppe [43] presented a multiresolution decomposition method based on iterative edge collapse operations. The dual reconstruction procedure is based on iterative vertex split operations. Praun *et al.* [44] applied these decomposition and reconstruction methods for watermarking. They picked out the vertex split steps of the reconstruction process that introduced the most significant geometric modifications. For each vertex to be split in these selected steps, they defined a zone containing all its incident facets in the coarser-level mesh. They then found the corresponding area in the original dense mesh and took this area as the watermark carrier. One bit was inserted in each area by deforming it using a modulation function. Actually, their watermarking technique lies between spatial and classical spectral methods. Here, the multiresolution analysis serves to find the salient spatial parts of the mesh, and the insertion in these parts is supposed to be more robust. Unfortunately, these iterative edge collapse operations are dependent on the mesh connectivity. Thus, this algorithm is non-blind mainly due to the connectivity recovery before extraction. At last, Yin *et al.* [45] embedded a robust, but non-blind watermark (connectivity recovery is also necessary) in the coarsest representation after a mesh multiresolution analysis based on the Burt-Adelson pyramid decomposition [46].

Nonetheless, just as for the current direct spectral analysis tools, the available multiresolution analysis schemes have either connectivity restrictions or robustness deficiencies (especially to connectivity attacks). For the majority of these techniques, registration and resampling are recommended to ensure a sufficient robustness; but these pre-processing steps inevitably make the algorithms non-blind.

Besides direct spectral analysis and multiresolution analysis, mesh parameterization [47] is also used for watermarking. Parameterization is a technique that transforms a 3D mesh into a bidimensional description, and thus probably enables the use of existing 2D image watermarking algorithms. Li *et al.* [48] converted the initial mesh into the spherical parameterization domain and watermarked its 2D spherical harmonic coefficients. This algorithm is a semi-blind one since it needs the spherical parameterization information of the original non-watermarked mesh at extraction to ensure sufficient robustness.

III. Attack-Centric Investigation

The attacks constitute a critical factor when designing 3D mesh watermarking algorithms. In this section, we carefully discuss three types of attacks and introduce the existing solutions in the literature.

A. Robustness to Geometric Attacks

This kind of attack only modifies the geometric part of the watermarked mesh. No matter what is the nature of the geometric change, the attack is reflected by a modification of vertex positions.

1) Similarity Transformations: Similarity transformation is considered to be a common operation rather than an attack, against which even a fragile watermark should be able to stand. It includes translation, rotation, uniform scaling and combinations of the above three operations. Generally speaking, there are three different strategies to build a watermark that is immune to these attacks.

The first solution is to use primitives that are invariant to similarity transformations. Ohbuchi *et al.* [6] provided a list of such primitives. The most utilized is the ratio between two measures of a triangle (height or edge length). Some primitives used in existing blind spatial techniques are also invariant to similarity transformations, such as the quantized position of the projection of a vertex on its opposite edge in a triangle [11], and the relative position of a vertex to a zone defined by its 1-ring neighbors [28]. These primitives are all some relative measures between several absolute and individual ones.

Not only the watermarking primitives, but also the synchronization schemes have to be insensitive to similarity transformation. Existing synchronization mechanisms often consist of (1) criteria for choosing the first primitive and (2) further spreading schemes. For example, in [11], the authors consider every triangle as a two-state object with one entry edge and two exit edges. They take the longest edge in a certain facet intersecting with the mesh's most significant principal axis as the first entry edge. The spreading scheme is determined by a secret key: if the next bit in this key is '0', then the first edge in the clockwise direction from the entry edge inside the current facet is chosen as the next entry edge and the next triangle is thus determined, and *vice versa*. In [28], the reference vertex is selected as the one with the smallest average incident edges length, and the vertices to be watermarked are ordered by their distances to this reference vertex. The causality problem arises in the second mechanism because after watermark insertion, the order of the vertices may have been changed. That is why the author introduces a post-processing step to rectify this order. Another option is the so-called indexing scheme. One example is given in [6]. A group of four triangles are combined together as a primitive. One of them is modified to indicate the existence of watermark bits in this macro-group. Two other triangles are used to hide the real watermark bits. The index of these bits in the entire watermark sequence is hidden in the last triangle. The advantage of this option is that the extraction failure of a certain bit (or certain bits) will not influence the extraction (with correct indices) of the posterior bits, but at the same time it decreases the capacity.

The invariance to similarity transformation can be also achieved in a wavelet domain by watermarking the ratio between the norm of a wavelet coefficient vector and its support edge length [16], [36]. Moreover, if we expect robustness even to affine transformations, the Nielson-Foley norm [49] can be a good primitive candidate. Benedens and Busch [50] quantize this norm, and Wagner [51] replaces some medium-important bits of this norm to insert watermarks.

The second solution is to watermark in an invariant space. One such space can be obtained by carrying out the following steps [52].

1) Translate the origin of the objective Cartesian coordinate system to the mesh gravity center.
2) Carry out a uniform scaling so that the whole mesh is bounded in a unit sphere or cube.
3) Calculate the principal axes of the mesh and reorientate the object so that they coincide with axes of the Cartesian coordinate system.

The watermark is then inserted in this new space. But the causality problem occurs because the variables used in the above steps, such as the gravity center and the principle axis orientations are probably changed after watermark insertion. There will possibly exist some extent of errors when reconstructing this space at extraction. If a precise extraction is demanded, this introduced error cannot be ignored. Therefore, at least some feature values of the insertion space have to be memorized, but this will make the technique semi-blind, or even non-blind. Note that not all watermark embedding schemes need all of the above three steps: which steps are needed depends on the nature of the watermarking primitive.

The third solution is to carry out the registration of the input mesh at extraction with the original non-watermarked one. Low-precision registration methods use singular spectral coefficients [35], eigenvectors of the vertex correlation matrix [53], inertial moments [32], and characteristic points [34] of the two meshes. High-precision methods often need user interactions to determine a good initial condition, and then the registration is realized by iteratively minimizing a sum of local errors [32], [45]. This solution will obviously make the algorithms non-blind, but provides a better robustness.

2) Signal Processing Attacks: A mesh can be considered as a signal in the three-dimensional space. There are counterparts of the traditional one-dimensional signal processing techniques for 3D meshes, such as random noise addition, smoothing, enhancement, and compression (usually realized by quantization). Fig. 7.b and Fig. 7.c illustrate two examples. Although these operations can be very harmful to the inserted watermark, they are really common manipulations in animation and special effect applications.

Random noise addition, smoothing and enhancement can be modeled in the spectral domain by a modification of the high-frequency part. Quantization can be thought as a certain form of noise, but its effect is somewhat complicated. In general, the transform-domain-based techniques that modify the low and medium frequency parts are more robust to these attacks. Note that for the additive watermarking schemes, which insert the watermark by modulating (*i.e.* perturbing) spectral coefficients obtained by direct frequency analysis, insertion in the low frequency part is both more robust and more imperceptible compared to insertion in the high frequency part if they have the same embedding intensity [54]. Different additive modulation schemes have been developed. Ohbuchi *et al.* [53] proposed to repeat the watermark insertion in the first half of

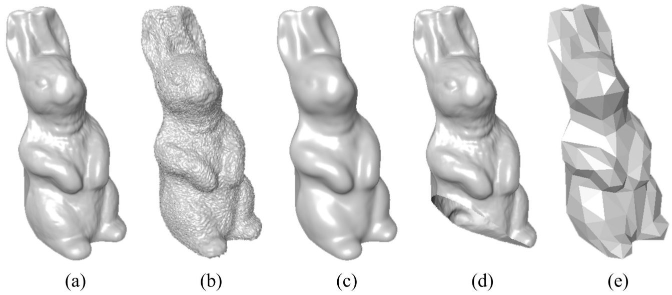

Fig. 7. Original mesh and four examples of attacked meshes: (a) original Rabbit mesh; (b) random noise addition; (c) smoothing; (d) cropping; (e) simplification.

the spectrum with constant intensity. Wu and Kobbelt [34] watermarked only the very low frequency coefficients and proposed an adaptive insertion intensity that is proportional to the amplitude of the coefficient. Lavoué *et al.* [55] gave another modulation scheme, in which the intensity is linear for the low and medium frequency coefficients and constant for the high frequency part.

Spatial techniques are less robust to signal processing attacks. One exception are the histogram-based techniques [21], [22]. Statistical mesh shape features used in these techniques tend to be preserved after such attacks because they represent global descriptors of groups of mesh combinatorial elements. Another efficient solution is to search for an adaptive insertion intensity based on local geometric analysis. This analysis can be based on the average length of the incident edges of a vertex [56], the geometric distortion introduced by a vertex split operation [44], the minimal incident edge length of a vertex [45], or the possible normal direction variance of the incident facets of a vertex after insertion [19]. The basic idea is to increase the watermarking intensity while ensuring visual quality. At last, redundant insertion [53] and use of error correction code [55] can sometimes significantly reinforce the robustness to these attacks.

3) Local Deformation Attacks: A local deformation is sometimes imperceptible if we do not have the original mesh for comparison, but it can seriously disturb the watermark, especially its synchronization.

One natural solution is to divide the mesh into several patches and repeat the watermark insertion in each patch. This decomposition can be based on curvature or semantic analysis, or simply on a discretization of the θ and/or φ domain in the spherical coordinate system. As mentioned previously, segmentation into patches may also decrease the insertion time for some transform-domain-based techniques. At extraction, one has to realize exactly the same decomposition. That is relatively simple and robust for non-blind techniques due to the availability of the cover mesh or the non-attacked stego-mesh, but designing a blind algorithm capable of resisting local deformation is a difficult task. The segmentation or discretization methods will probably fail at the extraction phase because the key parameters, such as curvature, mesh gravity center, or principal axes will certainly be disturbed after the watermark insertion itself or a local deformation attack. This situation forces the watermarkers to devise segmentation schemes robust to various attacks, including local deformations. Alface *et al.* [57] have made some efforts in this direction. They carried out a segmentation based on mesh feature points obtained by geodesic distance analysis, which is relatively robust to local deformation and cropping. However, the robustness of their blind algorithm still needs improvement. Another solution for resisting local deformation are the indexing mechanisms, as mentioned in subsection III.A.1. However, it is not easy to derive a blind indexing watermark that can withstand the connectivity attacks.

B. Robustness to Connectivity Attacks

This class of attacks includes cropping, remeshing, subdivision and simplification. Usually, they are quite difficult to handle.

Cropping is a special attack (see Fig. 7.d for an example), and some researchers prefer to treat it as a geometric attack because its consequence is quite similar to the one caused by local deformations. Watermark repetition in different patches and indexing schemes seem to be the most efficient ways in order to resist cropping.

With regard to the other connectivity attacks (Fig. 7.e illustrates an example of simplification), the algorithms that take the average normal directions of groups of facets as primitives [25], [27], or the histogram-based algorithms [21], [22], are less sensitive. These primitives approximately describe the mesh shape and thus are partly conserved after connectivity modification. Note that although the above histogram-based techniques are robust to mesh simplification, they remain vulnerable to non-uniform remeshing and subdivision. These attacks will seriously modify the distribution of these histograms and cause a failure of the watermark extraction. Other spatial techniques are less robust by reasons of both the geometric change of the primitives and the desynchronization problem. Constructing basis functions and calculating frequency coefficients in existing direct spectral analysis tools are either dependent on vertex order [34] or on mesh connectivity [32], [33]. Similarly, the existing multiresolution analysis tools often suffer from connectivity restrictions, or are not robust enough to connectivity changes. Hence, to attain sufficient robustness for these methods, the authors usually recommend performing connectivity restoration before extraction. This restoration procedure can be considered a resampling of the extraction input mesh (objective mesh) so as to obtain the same connectivity configuration as the cover mesh [19], [32], [45] or the non-attacked stego-mesh [34] (reference mesh). The task is to find, for each vertex in the reference mesh, a corresponding point on the surface of the objective mesh. This correspondence can be established by the nearest neighbor criterion [34], ray intersection [19], [32], or iterations targeting to minimize a particular cost function [45].

Two other possibilities to handle connectivity attacks are to find a robust transformation or parameterization domain that is not sensitive to connectivity change, or to insert watermarks in some robust mesh shape descriptors.

C. Robustness to Other Attacks

This group contains mainly two attacks: file attack and representation attack. The file attack simply consists in reordering the vertices and/or the facets in the mesh description file. In order to be invariant to this attack, one just needs to make the synchronization scheme independent of the combinatorial element orders implied in the mesh file. The representation conversion may be the most destructive attack to 3D mesh watermarks, because after such an attack, the mesh itself will no longer exist (for example, an approximation of a mesh with an NURBS model or with voxels). Until now, no researcher has mentioned robustness against this attack. In our opinion, the two ideas given at the end of the last subsection can also be potential solutions to resisting this serious attack.

IV. Discussion and Perspectives

Table I and II present a comparison of some typical algorithms of each class. The values in the column "Inserted bits" are the ones reported in the original papers. Most robustness performances are evaluated qualitatively by a sign ranging from '$--$', which means the least robust, to '$++$', which stands for the most robust. In these two tables, the algorithms are classified according to their watermarking primitives. The first three algorithms in the class "Spatial techniques on vertices" and the first algorithm in the class "Multiresolution analysis techniques" are fragile ones, and all other algorithms can be considered to be robust techniques. In the class "Other techniques", we list two other representative algorithms (one working in spatial domain, and the other one in transformation domain), which do not belong to any of the other four classes.

In the following, we list some hot topics and open problems in 3D mesh watermarking, and present some potential solutions.

A. Classic Problem: Trade-off between Capacity, Robustness, and Imperceptibility.

These measures are often contradictory. For example, high watermarking intensity provides better robustness, but normally degrades the visual quality of the watermarked mesh and risks making the watermark perceptible. Redundant insertion can considerably strengthen the robustness, but unavoidably decreases the capacity. Local adaptive geometric analysis seems favorable to find optimum watermarking parameters in order to achieve a sufficient compromise between these indicators. A valuable solution could lie in detecting rough (noised) regions where slight geometric distortions would be nearly invisible [28], [59], [60]. As observed in [28], these regions are characterized by the presence of many short edges, and they are somewhat equivalent to highly textured or detailed image areas, which are often used by image watermarking algorithms to obtain a better invisibility.

B. Algorithm Evaluation.

So far, the research community has lacked a widely used performance evaluation system of the existing algorithms. We at least need a standard attack benchmark and distortion measurement.

For the latter subject, Benedens *et al.* [61] first presented a study of different criteria to take into account in order to ensure imperceptibility of a watermark. They emphasize the importance of preserving the continuity and the symmetry of the surface. One of the most critical points is imperceptibility; indeed the visual distortion introduced by the watermark embedding has to be nearly invisible to a human eye. However, classical metrics based on geometric differences like the Hausdorff distance, available in many software packages [62], [63] do not match well with human visual perception. Hence, some authors have proposed perceptual distortion measures: Corsini *et al.* [64] introduced some perceptual metrics, based on global roughness variation, to measure the quality of a watermarked mesh. They argue that the presence of visual artefacts produced by the watermark is reflected by the amount of roughness introduced on the surface. They define two distinct roughness measures, which are matched with subjective experiments based on human evaluations. Similarly, based on curvature analysis in local windows of the mesh, Lavoué *et al.* [65] introduced a 3D perceptual metric following the concept of structural similarity. Finally, Alface *et al.* [66] presented two metrics for benchmarking 3D mesh watermarking schemes: one was based on a measure of distortion between several 2D views of the 3D objects, and the second was based on the distortion of energy calculated using 2D parameterization. These metrics however, do not incorporate a subjective experiment.

C. Construction of Robust and Blind Algorithms.

Robust and blind algorithms are very attractive because of their flexibility and reliability. In our opinion, this will require overcoming at least two difficulties. The first one is building a robust and secure synchronization mechanism, especially for spatial techniques. As mentioned before, the problem of desynchronization can be caused by both the causality problem during watermark insertion, and the attacks on the watermarked objects after insertion. Using certain robust aspects of the mesh to locate and index the watermarking primitives seems a good idea. Considering the example of watermarking semi-regular meshes, the wavelet coefficients of the coarsest-level mesh can be chosen as primitives and indexed by the lengths of their associated edges [18]. This ordering is experimentally very robust to geometric attacks and ensures a robust synchronization. Another advantage is that the causality problem is avoided: after we modify the norms of the wavelet coefficients to insert the watermark, their indices are not altered. One special difficulty in 3D mesh watermarking is that we often have to establish an ordering of the watermarking primitives according to their own properties. On the contrary, the locations and brightness (or color) of the pixels in an image are clearly separated, and even after a desynchronization attack, such as a rotation, it is not very difficult to recover the original order in a blind way.

The second difficulty is avoiding the registration and resampling pre-processing step, which succeeds in ensuring robustness, but inevitably makes the methods non-blind. Selecting

TABLE I
COMPARISON OF DIFFERENT 3D MESH WATERMARKING ALGORITHMS.

Categories	Algorithms	Clearly controllable intensity	Inserted bits	Blindness	Local adaptability
Spatial techniques on vertices	Yeo and Yeung [8]	No	1 bit/vertex	Yes	No
	Lin *et al.* [9]	Yes	1 bit/vertex	Yes	No
	Cayre and Macq [11]	Yes	1 bit/vertex	Yes	No
	Yu *et al.* [19]	Yes	≈50 bits	No	Yes
	VFA [20]	Yes	≈900 bits	Yes	No
	Zafeiriou *et al.* [21]	No	≈20 bits	Yes	No
	Cho *et al.* [22]	Yes	64 bits	Yes	No
	Bors [28]	No	≈0.2 bits/vertex	Yes	Yes
Spatial techniques on facets	TSQ [6], [24]	No	≈1.2 bits/facet	Yes	No
	Benedens [25]	Yes	≈30 bits	Semi	No
	Lee *et al.* [27]	Yes	≈50 bits	Semi	Yes
Direct spectral analysis techniques	Ohbuchi *et al.* [32]	Yes	32 bits	No	No
	Cayre *et al.* [33]	Yes	64 bits	Yes	No
	Wu and Kobbelt [34]	Yes	24 bits	No	No
	Alface and Macq [58]	Yes	64 bits	Yes	No
Multiresolution analysis techniques	Wang *et al.* [17]	Yes	≈1.5 bits/vertex	Yes	No
	Kanai *et al.* [36]	Yes	≈620 bytes	No	No
	Uccheddu *et al.* [37]	Yes	1 bit	Yes	No
	Praun *et al.* [44]	Yes	50 bits	No	Yes
	Yin *et al.* [45]	Yes	250 bits	No	Yes
Other techniques	Bennour and Dugelay [30]	Yes	≈500 bits	No	No
	Li *et al.* [48]	No	24 bits	Semi	No

TABLE II
CONTINUATION OF TABLE 1: ROBUSTNESS OF DIFFERENT ALGORITHMS TO VARIOUS ATTACKS.

Algorithms	Similarity transformation	Signal processing attacks	Local deformation and cropping	Connectivity attacks	Element reordering
Yeo and Yeung [8]	−−	Localization*	Localization*	Localization*	Fragile
Lin *et al.* [9]	−−	Localization*	Localization*	Localization*	Invariant
Cayre and Macq [11]	++	−	−−	−−	Invariant
Yu *et al.* [19]	Registration	+	−	Resampling	Invariant
VFA [20]	+	−	−	−	Invariant
Zafeiriou *et al.* [21]	+	+	−	+	Invariant
Cho *et al.* [22]	+	+	−	+	Invariant
Bors [28]	++	−	−	−−	Invariant
TSQ [6], [24]	++	−	+	−−	Invariant
Benedens [25]	Registration	+	−	+	Invariant
Lee *et al.* [27]	Registration	+	−	+	Invariant
Ohbuchi *et al.* [32]	Registration	++	++	Resampling	Resampling
Cayre *et al.* [33]	+	+	++	−−	Invariant
Wu and Kobbelt [34]	Registration	++	++	Resampling	Resampling
Alface and Macq [58]	+	+	++	+	Invariant
Wang *et al.* [17]	++	Localization*	Localization*	−−	Invariant
Kanai *et al.* [36]	+	−	−	−−	Invariant
Uccheddu *et al.* [37]	−	+	−	−	Invariant
Praun *et al.* [44]	Registration	++	++	Resampling	Resampling
Yin *et al.* [45]	Registration	+	−	Resampling	Resampling
Bennour and Dugelay [30]	Registration	+	+	−	Invariant
Li *et al.* [48]	+	+	+	Resampling	Invariant

*"Localization" means the capability of locating attacks for the fragile algorithms.

global and robust shape descriptors or transformations (*i.e.* geometric moments or spherical harmonic transformation) as primitives can be a good starting point. Some existing blind algorithms make use of a blind registration process at extraction. This process attempts to rebuild the same watermarking space as the one used for insertion. It often contains translation [21], [22], reorientation [21], and uniform scaling. In existing algorithms, this blind registration is based only on vertices that just represent a discrete sampling of the real continuous surface, and thus can provide inaccurate results. For example, the coordinates of the mesh gravity center are usually defined as the average coordinates of all the vertices, thus the result will be incorrectly displaced toward the mesh part where the sampling density is higher. This discrete calculation is also vulnerable to noise, smoothing, and of course connectivity changes. One solution is to compute the statistics, on which the blind registration depends, using points sampled on the surface of the mesh with uniform distribution (*i.e.* inside the facets), rather than on the vertex coordinates. Another solution is to process this blind registration in a more precise way, by using the analytic volume or surface moments. Tuzikov *et al.* [67] established the mathematical expression for the calculation of these continuous moments directly from the vertex coordinates. The values of these moments and the

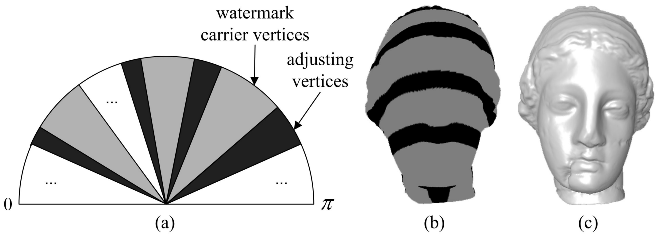

Fig. 8. (a) The θ domain is divided into several intervals with different ranges; (b) for the Venus head mesh, the vertices in gray zones are watermark carriers, and the vertices in black zones serve to process rectification after embedding; (c) the normally rendered Venus head mesh is also illustrated.

final blind registration result have proven to be much more robust than the discrete calculation [68]. Blind registration also suffers from the causality problem. To overcome this problem, one good solution is to separate the mesh elements into two groups: watermark carriers and adjusting elements [10]. After the watermark insertion in the former, the positions of the latter are modified in order to compensate for the influence of the watermark insertion on the blind registration. Fig. 8 illustrates such an example: the θ domain of the spherical coordinate system is discretized and all vertices are divided into two groups represented by gray and black zones, respectively; the vertices in the gray zones serve to embed the watermark, while the vertices in the black zones play the role of adjusting elements. However, this rectification scheme should be optimized in order to avoid visual distortions, especially on the borders of the zones.

D. Two Ideas toward Stronger Robustness.

Among all types of attacks, local deformation, cropping, simplification and remeshing are the most intractable ones, especially in the case of blind algorithms. In this subsection, we present two ideas that are possibly effective ways to achieving stronger robustness against these attacks.

1) Remeshing at Both Insertion and Extraction: One possibility to achieve robustness against hard connectivity attacks is to introduce a remeshing step at both the insertion and extraction sides. First, the possibly irregular cover mesh is remeshed to generate, for instance, a semi-regular mesh with a similar geometrical shape. This procedure is supposed to be composed of two steps: simplification, then subdivision and rectification (*i.e.* vertex displacements). Then, multiple watermarks can be inserted into this semi-regular mesh, which is later taken as the distribution version. During extraction, the input mesh is also remeshed and the watermark is extracted from the obtained semi-regular mesh. Here, the resistance to connectivity attacks is achieved by introducing a third party (a semi-regular mesh) with identical connectivity at both insertion and extraction, without transmitting any connectivity information (blindness is thus guaranteed). The key point lies in devising a remeshing scheme that is independent of and insensitive to connectivity changes. Additionally, this semi-regular mesh normally has a negligible geometric distortion compared to the original one and its simple connectivity makes it more adapted to compression [69]. Actually, Alface and Macq [58] have made some efforts in this area. They have devised a remeshing scheme based on mesh feature points, which are umbilical points obtained by curvature analysis, but the robustness of their method does not seem strong enough.

Combined with a mesh segmentation scheme based on shape analysis, the above watermarking scheme can also attain robustness against cropping and local deformation. A recent state of the art on 3D mesh segmentation can be found in [70]. However, the main problem lies in constructing a segmentation algorithm that produces similar results when the connectivity changes or when the shape is cropped. We can also envisage an indexing scheme on semi-regular meshes that resists cropping and local deformation considering that the remeshing step solves the difficulties caused by connectivity attacks.

2) Watermarking with Shape Descriptors: 3D object shape descriptors, usually used for indexing tasks, can be good watermark carrier candidates. Generally speaking, there exist four different groups of descriptors [68]: statistical, transform-based, structural, and multiview-based. The structural descriptors do not seem appropriate for use in watermarking because they are relatively high-level descriptors that are based on the structure or the semantic meaning of the 3D objects. The multiview-based descriptors are even less adapted.

The histograms used in [21], [22] are two statistical shape descriptors. Very satisfying in terms of robustness to ordinary simplification, they are well adapted to build blind schemes. However, one drawback is the lack of robustness to non-uniform simplification and remeshing. One possible solution, as mentioned before, is to carry out a uniform resampling of the vertices on the mesh surface before building the histogram. Another solution is to build a weighted histogram to decrease the contribution of elements from over-sampled areas. For example, the weight of a vertex in the algorithm of Cho *et al.* [22] could be proportional to the total surface of its incident facets. For the same purpose, a merging step could be introduced to merge vertices that are very close to each other, effectively considering them as only one vertex during the histogram construction.

The next breakpoint may be the transform-based descriptors, which mainly include geometric moments [71], 3D Fourier transformation [72], 3D Zernike moments [73], 3D angular radial transformation [74], and spherical harmonic transformation [75]. Some of them are particularly interesting because of their intrinsic invariance to rotation and robustness to various geometric and connectivity changes. For example, in the case of digital images, 2D moment invariants [76] and 2D Zernike moments [77] have already been used to build geometrically invariant, robust and blind watermarks. The transform-based descriptors usually decompose the object into different frequency-like components, which makes them suitable for spread spectrum watermarking approaches. Unfortunately, except for geometric moments, most of the above descriptors are defined on discretized voxel-based representations. To be able to apply voxel-based descriptors on 3D meshes, we have to first discretize the input mesh into voxels, then need a mesh generation technique like the well-known Marching Cubes algorithm [78] to transform the object back into mesh representation after watermark insertion. We think that the noise introduced by this last transformation could seriously disturb the inserted watermark and create visible artefacts on the mesh surface. Another option is to generalize the above descriptors to 3D meshes, which is difficult due to the irregular sampling and the presence of connectivity information. Furthermore, in order to facilitate the watermark insertion, these transformations have to be reversible (*i.e.* the mesh object can be reconstructed from the descriptors). If they are not reversible, as the geometric moments for example, then we have to realize a time-consuming iterative watermark insertion process, similar to what is done in [76] in the case of 2D images. Unfortunately, obtaining a reversible transform for 3D meshes is even more difficult.

E. Other Perspectives.

Other possible research topics include informed 3D mesh watermarking techniques, multiple mesh watermarking, 3D mesh digital fingerprints, content-based watermarking, and the interplay between compression and watermarking, or between subdivision and watermarking.

V. CONCLUSION

Three-dimensional mesh watermarking is an interesting and promising research area, with many potential practical applications. For example, an automobile constructor could insert watermarks into the car parts it has designed to protect its intellectual properties; a doctor could hide a patient's personal information in the 3D mesh model obtained after a scan, without impacting his diagnosis, to avoid mismatching the patient's personal information and his scan result; a mesh data receiver could authenticate the integrity and origin of the mesh model he/she has bought or obtained; even the texture of a mesh model, or the motion parameter of a mesh sequence could be inserted in the mesh description file via watermarking, just like hiding the audio signal of a video within the visual part of the video stream.

However, due to many difficulties stated in section II.A, such as the irregularity of the mesh description and the complexity of the possible attacks, research on 3D mesh watermarking is still in its infancy, even after ten years of studies of a large community. For fragile techniques of arbitrary meshes, constructing an algorithm capable of accurately locating the endured attacks and capable of surviving similarity transformations and vertex/facet reordering is a difficult task. For robust techniques, the causality problem, the desynchronization problem and the attacks (especially the connectivity attacks) are not easy to handle. In this paper, we have provided some working directions to devising robust and blind algorithms. Nearly all of them rely on a supposed efficient analysis or description tool of 3D meshes. They include robust mesh shape descriptors, robust mesh transformations, and remeshing algorithms insensitive to various attacks. Thus, in our opinion, the most important, but also the most difficult part of a 3D mesh watermarking system is the selection of a suitable feature space, in which the watermark signal is inserted. In order to achieve this target, the watermarkers probably should work closely with computer graphics and geometry processing experts.

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