From 3D Mesh Data Hiding to 3D Shape Blind and Robust Watermarking: A Survey

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Abstract. The need for secure communication of high value 3D virtual objects is becoming very important as a consequence of an increasing activity in simulation, entertainment, industrial design and cultural heritage. Secure communications of intangibles rely on cryptography and on watermarking of the transmitted objects to protect them against modifications (authentication watermarks) and redistributions (tracing forensic watermarks). While watermarking of image, audio and video is reaching maturity, 3D watermarking is still a technology in its infancy. Up to now, 3D watermarking has mainly focused on triangle meshes which are the most used digital representations of the shape of a 3D model. We show in this paper how recent signal processing techniques applied to meshes pave the way towards blind and robust watermarking of 3D shapes. We propose a survey of existing techniques and discuss their robustness, imperceptibility, capacity and security constraints.

1 Introduction

Over the last decennium, the digital rights management (DRM) problem of protecting data from theft and misuse has been addressed for many information types, including software code, digital images, videos and audio files. Demand for ways to similarly protect 3D graphical models is significantly growing. Scanned cultural heritage sculptures and artifacts, collaborative designed industrial models, graphical models used for online commerce or entertainment are examples of highly valuable contents that developers and owners are reluctant to distribute without control over piracy and reuse. This is the reason why there is an increasing need for watermarking of 3D models.

However, due to the very particular specificities of 3D objects, 3D watermarking is far from the maturity of watermarking algorithms dedicated to regularly sampled signals such as audio, image and video watermarking. 3D watermarking must cope with several challenging issues such as the non-euclidian nature of 3D meshes representing shapes as well as their usually irregular sampling which make difficult the extension of signal processing well-known tools. Other issues are related to the lack of adapted perceptive quality assessment tools, the variety of 3D attacks and the absence of consensus on 3D watermarking schemes

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requirements. It turns out that protecting a given 3D shape is very challenging knowing it can be represented with the same approximation error by many different meshes.

This survey first illustrates these specific problems and then presents a detailed overview of existing 3D mesh or 3D shape watermarking schemes. Section 2 introduces basic definitions and Sect. 3 presents an overview on 3D watermarking applications and 3D watermarking schemes requirements. Emphasis is put on the wide variety of 3D attacks and the challenges they pose for watermarking schemes. This section also focuses on watermark (and attack) imperceptibility assessing. Then Sect. 4 proposes a survey of existing watermarking schemes by highlighting their respective contributions and limitations. These schemes are classified by their embedding domain, distinguishing spatial, transform, attribute and compression domains. We present the intuition and main ideas of each referenced watermarking scheme and, where possible, we discuss their optimality in terms of robustness, capacity, imperceptibility and security. Section 5 concludes this survey by highlighting future research trends and remaining open issues.

2 Basic Definitions

3D virtual objects approximate a surface in the three-dimensional space. These objects can be represented by different structures such as *polygonal (or triangle) meshes*, *parametric surfaces* (such as Non-Uniform Rational B-Splines (NURBS), Bézier splines, Catmull-Rom splines...), *point-sampled surfaces*, *implicit surfaces*, *voxel-based representations* etc. However, the triangle is the basic geometric primitive for standard graphics rendering hardware and for many simulation algorithms. This fact partially explains why much of the work in the area of 3D watermarking deals with 3D triangle meshes. Although some schemes have been proposed to watermark NURBS (e.g. [36,31]) and point-sampled surfaces (e.g. [16]), we restrict this survey to 3D mesh watermarking schemes.

A 3D triangle mesh M can be seen as the embedding in the 3D space of geometric primitives: *vertices*, *edges* and *faces* (V, E, F). The set of these primitives are often referred to as the *connectivity* of the mesh. The embedding of vertices in the 3D space is named *geometry* and is represented by the set of the vertex coordinates (x, y, z). The vertices are also commonly referred to as *points* or *nodes*. Their number is noted n and ranges from 10^3 to 10^9.

Another important notion is the *topology* of a 3D mesh. This word is frequently used with different meanings in papers related to Computer Graphics and specifically to 3D watermarking. Indeed, topology can be referred to as:

- a synonym of connectivity [11].
- a description of the local geometric configuration of a face or vertex neighborhood [35].
- the mathematical study of the properties (genus, Euler characteristic, ...) of geometric solids or figures that are not changed by homeomorphisms [55].

These definitions are very different even though connectivity properties depend on the shape topology. In order to avoid confusions, we distinguish these different meanings by respectively naming them connectivity, local geometric configuration and shape topology [55].

3 3D Watermarking Applications and Requirements

This section presents the application context of 3D watermarking as well as the requirements of such applications. Readers not acquainted with watermarking vocabulary may find an excellent introduction in [17].

3.1 3D Watermarking Applications

3D watermarking applications may be classified following the general consensus on digital media watermarking [33]:

- Intellectual Property Rights (IPR) protection applications: This class of applications includes *copyright protection*, *fingerprinting*, *usage control* and *forensic*. For these applications, watermarking schemes are used to robustly convey information about content ownership and IPR.
- Content verification applications: The goal of the watermarking scheme in this case is to indicate whether the content has undergone any alteration and, in certain cases, to determine the type and location of such alteration. These applications are *authentication* and *integrity checking*.
- Data Hiding applications: In this class of applications, watermarks aim at conveying hidden information which is related or not to the content. Content-related information is mainly used for functionality enhancement purposes or for adding value to the content. Other kinds of hidden information are more related to steganography purposes.

The requirements of these three classes of application contexts are obviously very different. They are often described in terms of capacity, robustness, imperceptibility and security [17]. These watermarking scheme features are the topic of the following subsections.

3.2 Robustness and Attacks

Robustness concerns the ability of the embedded watermark to resist against a given class of usual or malicious manipulations of the content. These manipulations are often called *attacks*. General watermarking attacks can be classified in four categories following the analysis of Voloshynovskiy et al. [49]: removal attacks, geometrical attacks, cryptographic attacks, and protocol attacks. Such a classification has not been proposed yet for 3D watermarking attacks. In this survey, we follow the classification used by most authors of 3D watermarking papers.

- Similarity and affine transforms: *Rotation*, *uniform scaling* and *translation* (RST) transforms are mesh geometry modifications which are considered as common mesh manipulations. They are often referred to as *similarity transforms* and may be seen as the minimal requirement for a 3D watermarking scheme. *Non-uniform scaling*, *shear*, *projective distortions* are examples of more general *affine transforms* which are usually considered as intentional degradations of the mesh shape [4].
- Noising and de-noising: *Noising* attacks are usually performed by white gaussian noise addition on vertex coordinates. *De-noising* is usually performed by *Laplacian smoothing* [45]. This filter iteratively places each point in the barycenter of its point neighborhood. Other filters, described later in this paper, include curvature flow and transform domain smoothing.
- Connectivity attacks: Connectivity attacks modify the mesh adjacency information without modifying geometry. Among these attacks, *vertex reordering* is a manipulation which may desynchronize hidden data without any geometry or topology modification. Indeed, on the contrary of audio and image, the order of 3D mesh samples has no physical meaning. This attack has also been classified as a *distortion-less attack* in [18]. *Re-triangulation* is another connectivity attack which modifies triangles by edge flips.
- Sampling (or re-sampling) attacks: Sampling attacks are here referred to as attacks which modify the mesh geometry and connectivity but leaving its shape topology unchanged. These attacks are very common in practice and the most varied and challenging for a robust watermarking scheme [9]. In fact, a watermark aiming at protecting the 3D model shape should be robust to any modification of the sampling that preserves the shape visual perception. Sampling modifications include mesh *simplification* (removal of points and faces commonly used for a faster rendering [23]), mesh *refinement* (addition of points and faces usually by subdivision) and *remeshing* (local or global point density and connectivity changes)[2].
- Topological attacks: *Topological* attacks are complex attacks which may change the topological features of the mesh shape [55] (topological thus refers to shape topology). *Cropping* is the most well-known attack of this class. Most cropping attacks significantly degrade the shape but some of them preserve important parts of the shape that should also be protected (for example the head of the Michelangelo's David statue). Other possible attacks include imperceptible cuts and hole filling [55].
- Compression attacks: Since there is still no widely used mesh *compression* standard [1], the usual way to test the robustness of a watermarking scheme against compression algorithms consists in testing *point coordinates quantization*. This test also covers the truncation of vertex coordinates mantissas in effect of *format conversion* attacks.
- Geometrical deformations:These attacks are usually not handled in the literature with exception to [20] which proposes *bending* invariant signatures. Other complex geometrical transforms include mesh *editing*, mesh *morphing* and *local deformations* (for example addition of imperceptible small *bumps* [9]).

This list is of course not exhaustive but illustrates the relative wider variety of attacks a 3D watermarking scheme may undergo when compared with audio, image and video watermarking. It is obvious that neither watermarking nor attacks should affect the content so that the consecutive distortions become perceptible.

3.3 Imperceptibility

Assessing whether two shapes are differently perceived when rendered on a 2D screen is a difficult yet necessary task to evaluate imperceptibility. Most metrics used for benchmarking 3D watermarking schemes have been developed in the field of mesh simplification [23]. These are the *Hausdorff distance*, the *Root Mean Square Error* (RMSE) (a.k.a. *Vertex Signal-to-Noise Ratio* (VSNR)) and the *Geometric Laplacian Distortion Metric*. The Hausdorff distance is based on a point to surface distance [14], the RMSE and VSNR are based on mean point-to-point Euclidian distances [15] and the Geometric Laplacian proposed by Karni et al. [28] can be seen as the mean between point-to-point distances and a local smoothness evaluation. However, these metrics give poor estimations of the perception of the mesh shape since the human eye is much more sensitive to perturbations of a surface smoothness by random additive noise than to the smoothing of an already smooth surface yet producing the same metric error (Fig. 1).

(a) **(b)** **(C)**

Fig. 1. Perception and usual 3D metrics. (a) the Stanford *head model*, (b) the same model after 430 iterations of Laplacian smoothing, (c) the same model after a noise addition of .17 percent. Comparing (a) with (b) and (a) with (c) with the RMSE metric leads to the same score of approximately .0001 while the perceived distortion is much more important for model (c).

As previously mentioned, many different meshes (with different connectivities and point densities) can represent the same continuous shape with very similar approximation errors (Fig. 2). Moreover, some lossy compression algorithms actually perform a complete remeshing of the shape as a preprocessing step [1]. Subsequently these different meshes are all representations of the same content. A robust watermark embedded to protect such content should therefore be retrieved on any remeshed version of this model producing the same perceived content through rendering.

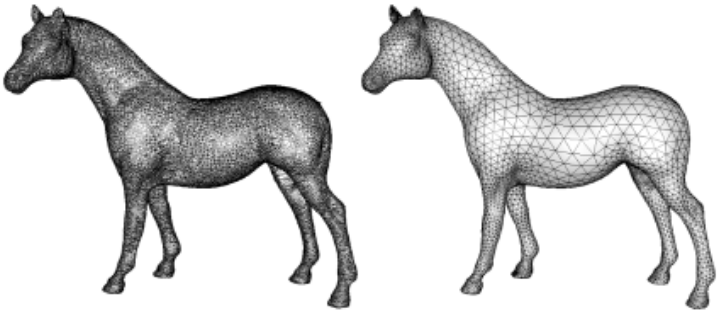

Fig. 2. The same shape (*horse model*) represented by two different triangle meshes (data courtesy of Alliez and Gotsman [1]). The perception of both shapes are identical under usual rendering conditions. Point density variations and connectivity differences are smoothed and interpolated by usual shaders [21]. Both meshes therefore represent the same content.

The first attempts to model watermark or distortion perceptibility have focused on geometry curvature and geometry symmetries. For revealing the presence of a watermark, Benedens [8] has proposed to use the strategy of Zhou and Pang who present mean curvature diagrams and other curvature measures as metrics and visualization tools [59]. In 2003, Benedens has also shown that watermark embeddings which respect *reflective and axial symmetries* as well as *surface continuity* are less perceptible and more robust [9]. Surface discontinuity artifacts are generally smoothed by common interpolative shaders (Gouraud, Phong, ... [21]). These artifacts can be seen as high-frequency perturbations of the surface [28]. Moreover, some shape regions should be avoided for embedding such as sharp features (very common for CAD models) and curvature-constant regions (e.g. planar, spherical, cylindrical, ...).

Linking approximation errors with the human perception has first been explored for 3D watermarking by Corsini et al. [15], who propose a roughness-based metric to evaluate differences between original and watermarked versions of 3D meshes. This metric has been sucessfully validated through psycho-visual experiments inspired by ITU-T norms.

Similarly, Rondao Alface et al. [42] have proposed to compare rendered 2D images with a mutual information criterion (image-based metric). Psycho-visual experiments have also been run for 3D watermarking attacks such as noise addition, simplification and smoothing. Touch perception through haptic devices has also been explored to test the transparency of 3D watermarking algorithms by Prattichizzo et al. [40].

In conclusion, most watermarking schemes and attacks are cnstrained to be imperceptible. However, there is still a lack of standard tools enabling to assess such imperceptibility.

3.4 Capacity, Content and Security

Principles and intuition of 3D watermarking security do not differ much from the general watermarking case. Capacity however deserves some more observations. Indeed capacity is more difficult to estimate depending on the content aimed at by the application. For authentication and data hiding applications, the *mesh* representation is the content to protect. In these cases, capacity directly depends on the number of points or faces in the mesh. For the applications related to IPR protection, the content is the *shape* approximated by the mesh. The watermarking capacity related to the shape certainly depends on the curvature variations of the surface but the attempts to model it are at their very beginning (shape analysis based on information theory [38]).

3.5 3D Watermarking Schemes Requirements

As mentioned before, there is still no widely accepted consensus on 3D watermarking schemes requirements. Focusing on specificities related to 3D (requirements of general watermarking applications can be found in [17]), we present here a synthesis of the basic requirements proposed by authors of keystone 3D watermarking schemes [4,7,9,35,37,39,11,16,53]. These requirements depend on the target type of 3D model (CAD models, smooth digitalized models, non-manifold meshes ...) and on the application context. Alliez et al. have shown in [1] their review of recent advances of 3D mesh compression that there is still no compression algorithm that suits well for any kind of 3D mesh. These remarks also stand for 3D watermarking. Smooth models and meshes with sharp features or discontinuities show for example very different rate-distortion properties. The number of points of a mesh also influences the performances of algorithms which currently lack of scalability. Authors usually distinguish small meshes ($n < 10^4$), large meshes ($10^4 < n < 10^6$) and very large meshes ($n > 10^6$).

The context of application obviously determines the requirements of the watermarking scheme. Blind detection or retrieval should be preferred to informed detection whenever the availability of the original model implies a risk of misuse or theft [17]. Copyright protection thus demands blind detection (some side-information can however be tolerated). Integrity and authentication also require blind detection when the integrity of the original itself cannot be trusted. Moreover, using informed detection or retrieval necessitates the development of efficient database 3D shape retrieval algorithms to compare the original with the suspect mesh [8]. Blind detection (or retrieval) however involves many more challenges than informed detection and still leads to poor robustness results in practice.

Robustness requirements are the most difficult to determine. Integrity and authentication (as well as augmented contents) watermarking schemes should resist against RST transforms, lossless format conversion and vertex re-ordering and be fragile against all other attacks. Cayre et al. [13] however also propose cropping as an attack to which these schemes should be robust.

For copyright protection applications, robustness is required for all attacks preserving the visual perception of the shape. In practice, most papers proposing

copyright protection 3D watermarking schemes only test RST transforms, vertex re-ordering, noise addition, compression, simplification, smoothing, cropping and subdivision. It is considered that the visual shape is the content to protect. Other kinds of properties of the mesh shape can also be important to protect such as touch perception (roughness and haptic textures properties) and functional imperceptibility. The latter concerns for example industrial CAD models which are virtually designed and then manufactured to be part of a complex system. Attacks and watermarks should not modify the design properties of such models.

In conclusion, each proposed watermarking scheme should carefully describe the target application and subsequent requirements.

4 3D Watermarking Schemes

In this survey, we describe most well-known and recent contributions to 3D watermarking. We classify them by the domain of embedding: spatial, transform, compression and attribute domains. This classification is further subdivided in function of the targeted application.

4.1 Spatial Domain

The 3D watermarking schemes which embed data in the spatial domain may be classified in two main categories : *Connectivity-driven* watermarking schemes and *Geometry-driven* watermarking schemes.

4.1.1 Connectivity-Driven Watermarking Schemes

We refer as *connectivity-driven* watermarking algorithms to those which make an explicit use of the mesh connectivity (some authors also refer to *topological features*, where topology must be understood as connectivity) to embed data in the spatial domain. These schemes are typically based on a public or secret traversal of all (or a subset of) the mesh triangles. The original model is usually not needed at the detection or decoding stage, they are therefore *blind* schemes. For each triangle satisfying an admissibility function, slight modifications are introduced in local invariants by changing the adjacent point positions. As a consequence, these schemes are sensitive to noise addition. However, well-designed embeddings may interestingly resist against some local connectivity modifications. Three main different strategies (a.k.a. *arrangements* [35], see Fig. 3) enable to re-synchronize the embedded data even after re-triangulation or cropping:

- Global arrangement: canonical traversal of all the connectivity graph.
- Local arrangement: canonical traversal of subsets of the connectivity graph.
- Subscript arrangement: explicit embedding of the localization of the information. This implies to hide both the data bit and its subscript as well.

If subscript arrangements need to embed more information than the local or global arrangements, they are usually more robust [11].

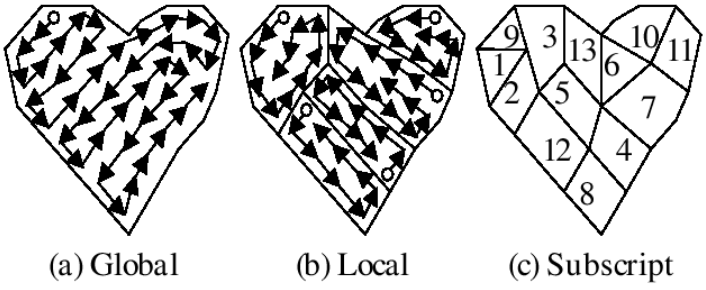

Fig. 3. Embedding strategies of connectivity-driven schemes: (a) global arrangement, (b) local arrangement, (c) indexed arrangement (data courtesy of Ohbuchi et al. [35])

Among this class of watermarking schemes, Ohbuchi et al. [35] have proposed four different watermarking algorithms in the first work published on 3D watermarking. These schemes are respectively named *Triangle Similarity Quadruple* (TSQ), *Tetrahedral Volume Ratio* (TVR), *Triangle Strip Peeling Sequence* (TSPS) and *Macro Density Pattern* (MDP). These schemes have inspired most connectivity-driven schemes developed so far. We classify these schemes by the application they target.

4.1.1.1 Data Hiding. Based on the fact that similar triangles may be defined by two quantities which are invariant to rotation, uniform scaling and translation (RST transforms), TSQ modifies ratios between triangle edge lengths or triangle height and basis lengths. A simple traversal of the mesh triangles is proposed to compute Macro-Embedding-Primitives (MEP). A MEP is defined by a marker M, a subscript S and two data values D_1 and D_2 (see Fig.4). Decoding is simply achieved by traversing each triangle of the mesh, identifying the MEPs thanks to the marker triangle. Then the subscript enables to re-arrange the encoded data D_1 and D_2. This scheme is invariant to RST transforms and to cropping thanks to the subscript arrangement. As security is not dealt with, this scheme can only be used for data hiding applications.

The invariant used by TVR is the ratio between an initial tetrahedron volume and the volume of tetrahedron given by an edge and the its two incident triangles. These ratios are slightly modified to embed the watermark and are invariant to *affine transforms*. Based on a local or global arrangement, TVR is a blind readable watermarking scheme. This scheme can only be applied on 2-manifold meshes (each edge has at most two incident faces). Benedens has extended this scheme to more general meshes without constraints of topology (*Affine Independent Embedding* AIE [8]). These schemes are however no more robust against cropping when compared to the TSQ scheme. These schemes can however hide f bits in a triangle mesh of f triangles which is much more than TSQ.

The third scheme, TSPS, encodes data in triangle strips given the orientation of the triangles. Based on a local arrangement, it presents the same robustness

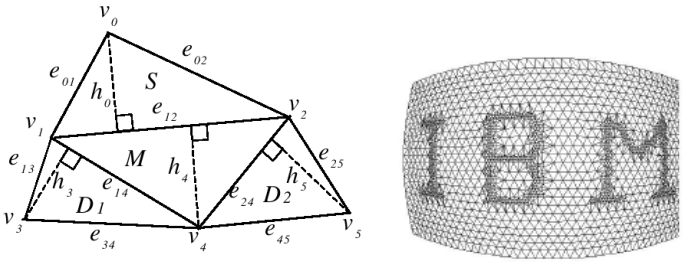

Fig. 4. On the left, Macro Embedding Primitive. For each MEP, the marker M is encoded by modifying the point coordinates of the triangle v_1, v_2, v_3 so that dimension-less ratios $l_{14}/l_{24}, h_0/l_{12}$ (l_{ij} stands for the length between vertices v_i and v_j) are set to specified values which will enable to retrieve marker triangles at the decoding stage. Then, the subscript is similarly encoded by modifying v_0 and subsequently $l_{02}/l_{01}, h_0/l_{12}$. Finally, data symbols D_1 and D_2 are encoded in $l_{13}/l_{34}, h_3/l_{14}$ and $l_{45}/l_{34}, h_5/l_{24}$ respectively. On the right, Macro Density Pattern example (data courtesy of Ohbuchi et al. [35]).

properties than the TSQ scheme. The capacity is difficult to estimate as the triangle strips generally do not transverse all the faces of the mesh. If it is not competitive with TSQ or TVR, this scheme is the basis of the best steganographic schemes presented in the sequel.

Finally, Ohbuchi's MDP is a visual watermarking method which embeds a meshed logo in the host model by changing the local density of points (see Fig.4). The logo is invisible with most common shading algorithms [21] but turns visible when the edges of the mesh are rendered. However, visible watermarking of 3D meshes has not many applications so far.

Focusing on the improvement of the mesh traversal simplicity and speed, O. Benedens has proposed another connectivity-driven scheme: the *Triangle Flood Algorithm* (TFA) [4]. This scheme uses connectivity and geometric information to generate a unique traversal of all the mesh triangles. Point positions are modified to embed the watermark by altering the height of the triangles and also to enable the regeneration of the traversal. This schemes exactly embeds $f - 1$ bits where f stands for the number of triangles.

4.1.1.2 Steganography. Cayre and Macq [11] have proposed a blind substitutive scheme which encodes a bit in a triangle strip starting from the triangle presenting the maximal area. This triangle strip is determined by the bits of a secret key, and determines the location of the encoded data in the 3D mesh. This scheme can be seen as an extension of TSPS with security properties which make it suitable for steganography purposes. It is indeed not possible to locate the embedded data without the knowledge of the secret key. For these reasons, this spatial substitutive scheme can also be considered as an extension of Quantized Index Modulation (QIM) schemes to 3D models.

Still considering steganography, Wang and Cheng [54] have improved the capacity of the precedent approach. First, they resolve the initial triangle for embedding by Principal Component Analysis (PCA). Next, an efficient triangular mesh traversal method is used to generate a sequence list of triangles, which will contain the hidden message. Finally, they embed three fixed bits per vertex for all vertices relying on three independent degrees of freedom. As a result, they exploit larger capacity in the 3D space. However, this capacity gain has been reached at some expense of the proved security features of the scheme of Cayre and Macq [11].

4.1.1.3 Authentication. Recently, Cayre et al. [13] have extended their previous scheme by using a global optimal traversal of the mesh and an indexed embedding. The authors specify the requirements of a 3D watermarking scheme for the authentication application context. They show their scheme withstands the attacks they consider in such context : RST transforms and cropping. For the cropping attack, the minimum watermark segment (MWS) is computed. They also propose a careful study of the capacity and security (in bits) of the embedding, the class of robustness and the probability of false alarm. The analysis of such features of a 3D watermarking scheme is difficult to perform for all other connectivity-driven watermarking schemes.

In conclusion, connectivity-driven algorithms are characterized by their relative fragility and their *blind decoding* capabilities. The embedded watermark does generally not resist against noise addition or global imperceptible re-triangulations (with exception to MDP). They are suitable for annotation and related applications only, with exception to more recent works which deal with the security issue [11,54] and [13]. These have been successfully designed respectively for steganographic and authentication purposes. Copyright or copy protection cannot be provided by this class of schemes as they do not resist against re-sampling.

4.1.2 Geometry-Driven Watermarking Schemes

This section presents the 3D watermarking schemes which embed data in the geometry. These schemes modify the point positions and/or the point (or face) normals. Point normals are estimations of the local continuous surface normal and are tied to the local shape of the mesh. On one hand, while surface sampling determines point positions, its influence on point normals is negligible if the point density is sufficient to accurately represent the surface. On the other hand, noise addition affects much more point normals and curvature estimations than point positions.

Notice some schemes need the orientation of face normals to be consistent and cannot be applied to non-orientable surfaces such as a Möbius strip. Point normals are usually estimated by a weighted sum of the adjacent faces normals or adjacent point positions. This means that a modification of the connectivity may affect the neighborhood of a point and have an impact on the point normal measure. However, attacks which modify point normals generally have a visual impact on the rendering of the mesh [21] and should therefore not be dealt with by a watermarking scheme.

4.1.2.1 Data Hiding. The *Vertex Flood Algorithm* (VFA) [5] embeds information in point positions. Designed for public watermarking, its high capacity is its main feature. Given a point p in the mesh, all points are clustered in subsets (S_k) accordingly with their distance to p. This point is the barycenter of a reference triangle R whose edges are the closest to a predefined edge length ratio :

$$S_k = \{p_i \in V | k \leq \frac{\|p_i - p\|}{W} < k+1\}, 0 \leq k \leq \lfloor \frac{d_{MAX}}{W} \rfloor \ , \tag{1}$$

where d_{MAX} is the maximal distance allowed from p, and W is the width of each set. Each non-empty subset is subdivided in $m+2$ intervals in order to encode m bits. The distance of each point in a subset is modified so that it is placed on the middle of one of the $m+2$ intervals. The first and last intervals are not used for encoding in order to prevent modifications of point distances which would affect the other subsets. Decoding does not need the original mesh and is simply achieved by reading point positions the subintervals in each subset S_k. As the scheme of Harte et al., VFA only resists against RST transforms. Compared to connectivity-driven watermarking schemes, this scheme can achieve higher capacity, only limited by the point sampling rate and the point position quantization precision.

4.1.2.2 Authentication. Yeo et al. [51] have developed an authentication algorithm by modifying point positions so that each mesh point verifies the following equation:

$$K(I(p)) = W(L(p)) \ , \tag{2}$$

where $K(.)$ is the verification key, $I(p)$ is an index value depending on point coordinates, $W(.)$ is the watermark represented by a binary matrix and $L(p)$ gives the location in the watermark matrix. $I(p)$ has been designed to be dependent on the neighborhood of point p. This interesting feature allows the detection of cropping attacks. Compared to connectivity-driven schemes also targeting authentication, the computational cost of this method is higher and the security features have not been deeply analyzed.

4.1.2.3 Informed Copyright Protection. Informed or blind schemes dedicated to copyright protection are often referred to as *robust watermarking schemes*. The schemes should resist to all known manipulations and attacks which do not produce a visible distortion on the 3D mesh. Schemes that resist to remeshing and re-sampling are often referred as *3D shape watermarking schemes*.

The *Normal Bin Encoding* (NBE) scheme [4] embeds data in point normals. Thanks to the curvature sampling properties pointed out before, this scheme resists against simplifications of the mesh. Point normals are subdivided in *bins*. Each bin is defined by a normal n_B named the *center normal* of the bin and an angle ϕ_R called bin radius. If the angle between a point normal n_i is less than ϕ_R then n_i belongs to such bin. Each bin encodes one bit of information by using different features such as the mean of the bin normals, the bin mean angle difference and the ratio of normals inside a threshold region determined by an

angle ϕ_K (with $\phi_K < \phi_R$). Point positions are modified so that the target value is assigned to the chosen bin feature. The decoding is simply achieved by computing the bins and their features but needs the original model for preprocessing purposes. This scheme has been improved later [8] and provides interesting imperceptibility and robustness features. The main drawback is the scalability of this technique which cannot efficiently handle meshes with more than 10^5 points.

Yu et al. [53] have proposed an informed robust scheme based on the histogram of the distances from the points of the surface to its center of gravity. This distance histogram is subdivided in bins and the points are iteratively displaced so that the mean or the variance of the histogram bin lies on the left or right of the bin middle to respectively encode a 0 or a 1. A scrambling of the vertices defined by a secret key is also proposed to secure the embedding of the watermark. The informed detection of the watermark necessitates the registration and resampling of the original and watermarked versions of the 3D model. The robustness features of this scheme cover noising and denoising attacks, cropping and resampling. Unlike NBE, this scheme has good scalability properties.

Focusing on imperceptibility criterions such as symmetry and continuity preservation, Benedens [7] has proposed a copyright protection watermarking scheme based on a *sculpting approach*. It uses Free Form Deformations (FFD) at distinct locations of the mesh (the so-called feature points) to embed a watermark. The basic steps performed by the embedding part of the algorithm consist in a first selection procedure of feature points and the displacement of these points along the surface normal (inwards or outwards depending on the watermark value) by a FFD. These two operations are ruled by secret keys. The detector is based on the assumption that random copies of the original model have features that are independently randomly distributed (i.e. independently randomly pointing inwards and outwards the surface following the same distribution). This algorithm presents very good imperceptibility and robustness results against noise addition, smoothing, cropping, affine transforms and a relatively good robustness against re-sampling. The latter strongly depends on the detector properties and registration optimality. Comparing the schemes of Yu et al. [53] and this scheme should be done by using the same fine registration and re-sampling process. It appears that the sculpting approach provides better imperceptibility results and comparable robustness features.

4.1.2.4 Blind Copyright Protection. Unlike informed robust watermarking schemes, these schemes cannot survive combined remeshing and cropping attacks so far. They also generally provide less robustness to geometric attacks. However, blind detection is a nice property that is usually required for a copyright protection application scenario. M. Wagner [50] has proposed a scheme which embeds data in the point normals of the mesh. These normal vectors are estimated by the *Laplacian operator* (a.k.a. *umbrella operator*) applied on the point neighborhood:

$$n_i = \frac{1}{d_{p_i}} \sum_{p_j \in N(p_i)} (p_j - p_i) \ , \tag{3}$$

where d_{p_i} is the number of point neighbors of p_i and $N(p_i)$ is the neighborhood of p_i. The watermark is a continuous function $f(p)$ defined on the unit sphere. Normal vectors n_i and the watermark function are converted in integers k_i and w_i respectively:

$$k_i = \lfloor \frac{c}{d} \|n_i\| \rfloor \tag{4}$$

$$w_i = \lfloor 2^b f\left(\frac{n_i}{\|n_i\|}\right) \rfloor \ , \tag{5}$$

where d is the mean length of these normal vectors, c is a parameter given by a secret key, and b is the number of bits needed to encode each w_i. The embedding proceeds by replacing b bits of k_i by those of w_i resulting in k'_i. Then the modified normals n'_i are re-computed by $n'_i = \frac{k'_i d}{c} \frac{n_i}{\|n_i\|}$. The watermarked coordinates of each point p'_i are obtained by solving the following system of $L+1$ linear equations:

$$n'_i = \frac{1}{d_{p'_i}} \sum_{p'_j \in N(p'_i)} (p'_j - p'_i) \ . \tag{6}$$

However, it is not possible to build a surface from the sole point normal information and this linear equation system is indeed singular. In order to solve this issue, 20% of the points are not watermarked. The decoding of the watermark needs a modification of the parameter c because of the modification of the normal mean length $d' : c' = c\frac{d}{d'}$. In order to be robust to affine transforms, a non-Euclidian affine invariant norm [34] is used. The watermark can be either a visual logo on the unit sphere either a gaussian white noise. Scalability and computational cost of this scheme are a concern.

Harte et al. [25] have proposed another blind watermarking scheme to embed a watermark in the point positions. One bit is assigned to each point : 1 if the point is outside a bounding volume defined by its point neighborhood and 0 otherwise. This bounding volume may be either defined by a set of *bounding planes* or by an *bounding ellipsoid*. During embedding and decoding, points are ranked with respect to their distance to their neighborhood center. This algorithm is robust against RST transforms, noise addition and smoothing. Likewise the scheme of Wagner et al. [50], this scheme cannot withstand connectivity attacks such as remeshing or re-triangulation. However, this scheme presents a far better computational cost since embedding only needs one vertices traversal and limits computations for each point to the one-connected neighbors.

Cho et al. [18] have proposed a blind and robust extension of the scheme of Yu et al. [53]. This scheme presents the same robustness features with exception to cropping and any re-sampling attack that modifies the position of the center of gravity (e.g. unbalanced point density). They propose to send the position of this point to the detection side which is not realistic. Indeed, combined cropping and rotation or translation attacks can shift the relative positions of the model and the center of gravity conveyed as side-information. This scheme is limited

to star-shaped models[1] but, considering robustness, outperforms the schemes of Harte et al. [25] and Wagner [50]. This scheme is however fragile against cropping.

Similarly, Zafeiriou et al. [57] have proposed to change the point coordinates into spherical coordinates with the center of gravity as origin. A Principal Component Analysis (PCA) is used to first align the mesh along its principal axes. Then two different embedding functions are used to modify geometric invariants. For angle *theta* and radius r, a continuous neighborhood patch is computed by a NURBS patch. A 0 is encoded if the center point radius is less than the mean radius of the neighborhood and a 1 is encoded otherwise. Similar to the scheme of Cho et al. [18], this scheme shows approximately the same advantages and limitations. This scheme is fragile against cropping and unbalanced re-sampling. Center of gravity shifts and PCA alignment perturbations [8] because of density sampling modifications are also a weakness which deserves further research.

More flexible than connectivity-driven algorithms, geometry-driven algorithms enable very different capacity-robustness trade-offs. If steganography and authentication seem better handled by the first ones, copyright protection techniques could be provided by geometry-driven schemes. However, there is still no blind and robust watermarking scheme able to resist against cropping and irregular point density re-samplings.

4.2 Transform Domain

This section is dedicated to watermarking schemes which embed information in a mesh transform domain. These transforms are extensions of regularly signal processing to 3D meshes: the mesh spectral decomposition, the wavelet transform and the spherical wavelet transform.

4.2.1 Spectral Decomposition

Spectral decomposition (a.k.a. pseudo-frequency decomposition or analysis) of 3D meshes corresponds to the extension of the well-known Discrete Fourier Transform (DFT) or Discrete Cosine Transform (DCT). This extension links the spectral analysis of matrices and of the spectral decomposition of signals defined on graphs [45,28]. The *pseudo-frequency analysis* of a 3D mesh is given by the projection of the geometry on the eigenvectors of the *Laplacian operator* defined on the mesh. The Laplacian is usually approximated by the umbrella operator $L = D - A$ where A is the adjacency matrix and D is a diagonal matrix with $D_{ii} = valence(p_i)$. Projecting the geometry canonical coordinates (X, Y, Z) leads to three real-valued spectra often noted (P, Q, R) [12]. Other Laplacian operator approximations have been successfully explored to design transforms which allow an optimal *energy compaction* in pseudo-low frequencies [58,3,56]. Since this transform is based on the eigen-decomposition of a n by n matrix, mesh connectivity partitioning must be used for meshes of more than 10^4 points to speed up the computation as well as avoiding numerical instabilities

[1] For each point of the surface, the segment linking this point to the center of gravity does not intersect the surface in any other point.

such as eigenvector order flipping [28,58]. Observing that partitioning induces artifacts on submesh boundaries, Wu et al. [56] have recently proposed radial basis functions (RBF) to compute the spectrum of 3D meshes with up to 10^6 points without the use of a partition algorithm. A better choice of coordinates than the canonical (X, Y, Z) to project on the spectral basis functions is still an open issue.

4.2.1.1 Informed Copyright Protection. The first scheme based on spectral decomposition has been proposed by Ohbuchi et al. in 2002 [37]. Their approach consists in extending spread-spectrum techniques to this transform. Well-balanced point seeds are interactively selected and initialize a connectivity-based front propagation which builds the partition. An additive watermark is embedded on low pseudo-frequency coefficients (P, Q, R) (the three spectra are embedded in the same way). The informed decoding retrieves the partition and the correspondence between the original connectivity and the watermarked geometry through registration, re-sampling and remeshing. This scheme presents robustness against RST transforms, noise addition, smoothing and cropping.

Benedens et al. [9] have improved the precedent scheme by embedding the watermark only in the transformed local normal component of the point coordinates instead of embedding (P, Q, R). They show this operation results in a better trade-off between imperceptibility and capacity. They show it improves the behavior of the decoder as well.

Cotting et al. [16] have extended the work of Ohbuchi et al. [37] to point-sampled surfaces. A neighborhood is still needed to compute the Laplacian eigenvectors and is provided by a k-nearest neighbors algorithm. A hierarchical clustering strategy is used to partition the surface. They also show that other point attributes such as color values can also be projected on the spectral basis functions and watermarked as well. The watermark is extracted through registration with the original and re-sampling. The re-sampling is based on the projection of new points on a polynomial approximation of the surface. Their algorithm presents robustness features very close to [37]. Furthermore, they show the watermark withstands repetitive embeddings of different watermarks.

Recently, Wu and Kobbelt [56] have proposed an approximation of the Laplacian eigenfunctions by RBF functions. These functions are centered on k (with $k << n$) seeds uniformly distributed on the mesh. A k by n matrix is then decomposed by Singular Value Decomposition (SVD). This scheme uses the embedding strategy of Ohbuchi et al. and presents the same robustness features while allowing real-time processing of large datasets without partitioning. However, when compared with schemes of Cotting et al. and Ohbuchi et al., this scheme presents less robustness because of the importance of selecting the same seeds for computing the RBF functions on the original model as well as on the suspected mesh at the detection side.

4.2.1.2 Blind Copyright Protection. Cayre et al. [12] have proposed a blind and substitutive watermarking scheme based on the flipping of spectral coefficient triplets (P, Q, R). An automatic partition of the connectivity is achieved as in [28].

Here, low pseudo-frequencies are avoided to improve the imperceptibility of the embedding. The watermark is on the contrary repeated on middle and high pseudo-frequencies. This scheme resists against RST transforms if the geometry is aligned on PCA axis. Robustness to smoothing and noise addition is comparable to the non-blind scheme of Ohbuchi et al. However, any modification of the connectivity implies a different partition and different laplacian matrices, which de-synchronises the watermarked data. When compared to geometry-driven blind robust schemes, the robustness to noise addition and smoothing is better using the spectral decomposition. The computational cost of the transform is however much higher.

Finally, the de-synchronization issue for blind spectral watermarking schemes has been explored by Rondao Alface et al. [41] who propose an automatic feature points detection to build a blind and robust partition. This partition is based on a geodesic Delaunnay triangulation leading to a feature base mesh. This base mesh is then remeshed by subdivision. Then each base triangle submesh is watermarked in the mesh spectral domain following the work of Cayre et al. [12]. The robustness to connectivity attacks of the latter approach is significantly improved by the feature points re-synchronization. However, the feature point robustness and the geodesic remeshing can still be improved to better resist against cropping and affine transforms attacks. Furthermore, some meshes may present too few feature points or generally non-uniformly distributed feature points which lead to a badly shaped base mesh. This results in a sub-optimal spectral decomposition and a low capacity.

In conclusion, spectral decomposition enables very good robustness results against watermarking attacks. Spectral watermarking schemes are promising but suffer from the weaknesses of the transform: eigen-decomposition of large matrices, choice of coordinates to project, and de-synchronization for blind watermarks by connectivity attacks. The first issue seems to find a convenient solution with RBF, the second and third have been recently explored but are still open issues.

4.2.2 Wavelet Transform

Wavelet decomposition and the multiresolution framework have also been extended to 3D triangle meshes. Lounsbery et al. [32] proposed a *lazy wavelet* transform. Each triangle of the mesh is quaternary subdivided and deformed to make it fit the surface to approximate. Wavelet coefficients are these local deformation vectors. Multiresolution analysis is computed with two analysis filters A^j and B^j for each resolution level j. Reconstruction is done with two synthesis filters P^j and Q^j which must satisfy:

$$\left[\frac{A^j}{B^j}\right] = \left[P^j|Q^j\right]^{-1} \quad . \tag{7}$$

Let us call C^i the n^j by 3 matrix giving the coordinates of each point at the resolution level j. Then, we can write the following relations:

$$C^j = A^{j+1}C^{j+1} \tag{8}$$

$$D^j = B^{j+1}C^{j+1} \tag{9}$$

$$C^{j+1} = P^j C^j + Q^j D^j \quad . \tag{10}$$

D^j represents the wavelet coefficients of the mesh, necessary to reconstruct C^{j+1} from C^j. Notice that from a theoretical point of view, columns of P^j are scaling functions and columns of Q^j are wavelet functions defined on the mesh topology. In practice, the lifting scheme is applied to build wavelet functions orthogonal to the scaling functions [32]. This transform can only be applied on semi-regular connectivity meshes because of the quaternary subdivision/simplification process. This drawback has been later solved by Valette et al. [47] which extend this scheme to arbitrary connectivity meshes.

4.2.2.1 Informed Copyright Protection. Kanai et al. [27] have proposed the first scheme embedding in the wavelet transform domain. Using the representation of Lounsbery [32], the watermark bits are embedded by modifying the least significant bits of the wavelet coefficients modulus. In order to minimize the visual impact of the watermark embedding, a selection of wavelet coefficients based on geometric thresholds is proposed. Watermark extraction is performed through the comparison of wavelet coefficients of the original and watermarked versions of the model.

Praun et al. [39] have proposed in 1999 an informed robust watermarking scheme which embeds a watermark in wavelet coefficients computed by *progressive meshes* [26] on which are defined RBFs which enable to locally deform the geometry. The embedding consists in the displacement of the points in normal or reverse-normal directions accordingly to the watermark value. The amplitude of this displacement is scaled by the RBF. The extraction of the watermark is performed through the registration and re-sampling of the original model with the watermarked model. This process actually modifies connectivity to make it fit with the original. This step significantly improves detection when compared with the scheme of Kanai et al. [27]. Moreover, this scheme is one of the most robust proposed so far. It resists against similarity, noise addition, connectivity, re-sampling, compression and cropping attacks. Benedens has shown in [9] the imperceptibility of the embedding can be improved by respecting model symmetries through the selection of symmetric features. Compared to other informed robust watermarking schemes, this scheme is the most robust to geometric attacks so far. Improving the registration process enables to also resist against large re-sampling attacks.

Yin et al. [52] have adopted the scheme in [24] to perform the multiresolution decomposition. Watermark information can be embedded into some spatial kernels of the low-frequency component of the shape. This strategy actually deals with the low-resolution representation in the geometry hierarchy which, however, does not not play the same role as the low-resolution components in the frequency domain. Unlike embedding a bit into the low-frequency domain, embedding a watermark bit into a vertex of the coarse mesh does not mean that the bit has been embedded globally into the low-frequency components of the whole mesh. For that reason the scheme is not robust against cropping operations. For other attacks, this scheme shares the same robustness properties as Praun et al. [39].

Spherical wavelets [43] have also been exploited for informed watermarking by Jin et al. [30]. Based on a spherical parameterization of the mesh starting from a canonical octahedron, the multiresolution analysis is close to the lazy wavelets and their corresponding watermarking schemes. Robustness and imperceptibility seem to be improved for genus-0 meshes (topologically equivalent to a sphere). Meshes approximating shapes of different topologies must first be converted in a genus-0 mesh trough hole fillings or cuts (see [55]) which leads to suboptimal results.

4.2.2.2 Blind Copyright Protection. Extending the scheme of Kanai et al., a blind watermarking algorithm has recently been proposed by Uccheddu et al. [46]. The main limitation of blind wavelet-based watermarking schemes is that they cannot withstand connectivity attacks. In the case of the scheme of Uccheddu et al., the input mesh is limited to have a prerequisite semi-regular subdivision connectivity. This limitation has been tackled by Valette et al. [47] by using lazy wavelets defined on arbitrary connectivities, but detection still cannot withstand connectivity attacks. These blind schemes present nearly the same robustness features as their Fourier-equivalent [12].

In conclusion, transform domain watermarking schemes show very good robustness properties for copyright and copy protection applications. Furthermore, wavelets enable the control of the local distortion caused by the embedding and low-frequency components of the spectral decomposition also present good properties when compared to the DCT and DFT for audio, image and video. However, schemes based on these transforms are characterized by a higher computation complexity than schemes embedding in the spatial domain. Scalability is therefore still a concern for very large meshes (with more than 10^6 points).

4.3 Compression Domain

As mentioned before, there is still no widely accepted 3D compression standard because of the lack of maturity of this field [1]. The watermarking schemes of this class are those which directly embed the watermark in the compressed data. Therefore, spectral- and wavelet-based schemes as well as some connectivity-driven schemes can also be classified (with some adaptations) in the compression domain category.

Denis et al. [19] have recently proposed a watermarking scheme based on the compression of 3D meshes through subdivision surface fitting. They have actually adapted the scheme of Ohbuchi et al. [37] to their specific transmission process. This scheme also highlights the difficulties inherent to a joint compression-watermarking strategy since it is less robust to noising and re-sampling attacks than the scheme of Ohbuchi et al. [37].

4.4 Attribute Domain

This category of schemes protects attribute data associated to the points or the faces of the mesh. These attributes can be texture, color, density, transparency etc. If scalar point and face attributes can be watermarked as geometry coordinates by transform-based schemes [37], textures need adapted schemes.

Garcia and Dugelay [22] embed the watermark in the texture of the model. Textures are images that are projected on the surface to enhance the visual content of the model itself. This process is called texture mapping. Embedding is performed by an image watermarking scheme. The decoding/detection phase consists in two steps: texture reconstruction from one ore several 2D views and detection of the watermark in the reconstructed texture. The original model is required to register 2D views and the watermarked model, hence this scheme is not blind. The correct estimation of the rendering conditions and projection parameters is the key to provide robustness to this scheme.

Obviously, compression and attribute domains have not yet received as much attention as spatial and transform domains. Attribute distortion imperceptibility has also not been deeply explored so far. However, these research areas raise more and more interest because of the success of analog research for images.

4.5 3D Embedding and 2D Retrieval

Interestingly, Bennour et al. [10] propose a very different approach to digital watermarking of 3D meshes. They embed the watermark in 3D silhouettes of the mesh and retrieve it in 2D rendered views of the model. Therefore, no 3D data is necessary at the decoding side, detecting unlicensed use of a model is directly processed on screen. This scheme resists against RST transforms and vertex reordering. Future work concerns robustness to simplification and the selection of key-views for embedding.

Table 1. Synthesis of the presented algorithms. Notations : data hiding (d.h.), steganography (steg.), authentication (auth.), informed copyright protection (i.c.p.), blind copyright protection (b.c.p.), spectral (s), wavelet (w),rotation-translation-uniform scaling (RST), vertex reordering (VR), laplacian smoothing (LS), noising (NO), cropping (CR), simplification (SI), re-sampling (RS), compression (CO), multiple watermarks (MW), not available (N-A), number of faces (f), number of points (n).

scheme	application	domain	robustness	capacity
[35,8,4]	d.h.	spatial	RST, VR	$\leq f/4$
[11,54]	steg.	spatial	RST, VR	$\approx 3n$
[51,5,13]	auth.	spatial	RST, VR, CR	$\leq n$
[39,27]	i.c.p.	transform (w)	RST, VR, NO, LS, CO, CR, SI, RS, MW	50
[53,7]	i.c.p.	spatial	RST, VR, NO, LS, CO, CR, SI, RS, MW	50
[4,50,8,25]	i.c.p.	spatial	RST, VR, NO, LS, CO, CR	32
[37,16,56]	i.c.p.	transform (s)	RST, VR, NO, LS, CO, CR, SI, RS, MW	32
[52,29,46]	b.c.p.	transform (w)	RST, VR, NO, LS, CO	N-A
[12]	b.c.p.	transform (s)	RST, NO, LS, CO	64
[41]	b.c.p.	transform (s)	RST, NO, LS, CO, SI	32
[18,57]	b.c.p.	spatial	RST, VR, NO, LS, CR, SI, RS	64

4.6 Synthesis

A synthesis of the presented watermarking schemes is given in Table 1. Schemes are classified by their application context, their embedding domain, their robustness and capacity. Since data hiding, authentication and steganography target the mesh elements, their capacity is given in terms of the number of faces or points. On the contrary, watermarking schemes for copyright protection target the shape and their capacity is usually set from 32 to 64 bits. A quantitative comparison of robust watermarking schemes is proposed in Table 2 for simplification and additive noise attacks. These attacks have been performed on the Stanford *Bunny* model which has been tested by almost all authors cited in this survey. The source of these robustness results are the corresponding and aforementioned referenced publications.

Table 2. Quantitative comparison of robust watermarking schemes for additive noise and simplification attacks on the Stanford *Bunny* model. Transform (s) and (w) respectively stand for spectral decomposition and wavelet transform. Noise addition results refer to the noise amplitude expressed in percentage of the bounding box diagonal (high values correspond to a good robustness). Simplification results are given as the ratio of the number of points after and before the simplification attack (low values correspond to a good robustness). It is however difficult to know which simplification algorithm has been used by the authors of most schemes. These comparative results should therefore be considered as a rough estimation.

scheme	detection/decoding	domain	noise	simplification
[39]	informed	transform (w)	.70%	.125
[30]	informed	transform (w)	.06%	.125
[16]	informed	transform (s)	.10%	.5
[18]	blind	spatial	.10%	.5
[11]	blind	transform (s)	.44%	-
[46]	blind	transform (w)	.17%	-
[47]	blind	transform (w)	.45%	-

5 Conclusions

This survey has presented the evolution of watermarking technology from mesh protection to shape protection. This evolution copes with a large set of open and challenging issues.

Hiding data in mesh elements such as triangles or point coordinates in order to resist to RST transforms and vertex re-ordering has been solved in many ways even though there is still work left for security, computational cost and capacity optimization.

Protecting shapes for forensic applications has been deeply explored. A wide set of original techniques have been proposed based on signal processing extensions to irregularly sampled and manifold data. Their robustness tends to be

satisfactory and now directly depends on the quality of the resynchronization with the original mesh.

However, there is still a need for a more careful analysis on how to modulate the watermark strength accordingly to the local perceived distortion. Assessing the watermarking capacity of a shape according to its curvature information (independently of its mesh representation) is another issue that deserves more research.

Beside these new challenges for informed watermarking schemes, it turns out that blind detection or retrieval is more suitable for copyright protection applications. In this case, although the considerable efforts spent on extending informed techniques to blind detection, there is still no algorithm able to withstand combined cropping and re-sampling attacks.

Finally, there is still no benchmarking platform for 3D watermarking schemes. They would however certainly be desirable for comparing schemes performances and improving their design.

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