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Technical Section

Subdivision surface watermarking

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Abstract

This paper presents a robust non-blind watermarking scheme for subdivision surfaces. The algorithm works in the frequency domain, by modulating spectral coefficients of the subdivision control mesh. The compactness of the watermarking support (a coarse control mesh) has led us to optimize the trade-off between watermarking redundancy (which ensures robustness) and imperceptibility by introducing two contributions: (1) spectral coefficients are perturbed according to a new modulation scheme analysing the spectrum shape and (2) the redundancy is optimized by using error correcting codes coming from telecommunication theory. Since the watermarked surface can be attacked in a subdivided version, we have introduced an algorithm to retrieve the control polyhedron, starting from a subdivided, attacked version. Experiments have shown the high robustness of our scheme against geometry attacks such as noise addition, quantization or non-uniform scaling and also connectivity alterations such as remeshing or simplification.

Keywords: Subdivision surfaces; Digital watermarking; Spectral analysis; Error correcting codes; Surface approximation

1. Introduction

Watermarking provides a mechanism for copyright protection or ownership assertion of digital media by embedding information in the data. A watermark is associated with different characteristics, depending on its purpose. For copyright protection, the watermark has to be *robust* to survive (i.e. remain detectable) through malicious attacks; on the contrary, for applications like integrity verification, the watermark has rather to be *fragile* to detect any change in the document. An other characteristic of a watermarking algorithm concerns the mark extraction which can be *blind* (the original document is not required to extract the mark) or *non-blind* (the original document is needed).

The last important attribute of a watermark is the *imperceptibility*; indeed, the watermarked document has to be visually near identical to the original. More information about digital watermarking can be found in [1].

There still exist few watermarking algorithms for 3D models, moreover, most of the existing methods concern polygonal meshes and ignore other 3D surface representations and particularly subdivision surfaces. A subdivision surface is a smooth surface defined as the limit surface generated by an infinite number of refinement operations using a subdivision rule on an input coarse control mesh. Hence, it can model a smooth surface of arbitrary topology while keeping a compact storage and a simple representation. Subdivision surfaces are now widely used in computer graphics and have been integrated to the MPEG4 standard [2].

In this context we present a robust, imperceptible, non-blind watermarking scheme for subdivision surfaces to serve ownership claims. The algorithm is based on a frequency domain decomposition of the subdivision control mesh and on spectral coefficient modulation. In order to adapt our algorithm to the compactness of the cover object (the coarse control mesh), we have optimized the trade-off between watermarking redundancy (which ensures robustness) and imperceptibility by introducing a new modulation scheme and error correcting codes (ECC). A so-called *synchronization* process was also introduced to

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ensure robustness to attacks against a subdivided version of the surface.

Section 2 presents subdivision surfaces, a state of the art about 3D watermarking and the overview of our framework. Section 3 details our different contributions and the complete watermarking algorithm, while Section 4 gives some results and comparisons with existing methods.

2. Context and overview

2.1. *Subdivision surface presentation*

A subdivision surface is a smooth (or piecewise smooth) surface defined as the limit surface generated by an infinite number of refinement operations using a subdivision rule on an input coarse control mesh. Hence, it can model a smooth surface of arbitrary topology (contrary to the NURBS model which needs a parametric domain) while keeping a compact storage and a simple representation (a polygonal mesh). Moreover it can be easily displayed to any resolution. Today, many subdivision schemes have been developed, based on quadrilateral [3,4], triangular meshes [5] or both [6]. Moreover special rules have been introduced by Hoppe et al. [7] to handle sharp edges. Fig. 1 shows an example of subdivision surface (Catmull–Clark rules). At each iteration, the base mesh is linearly subdivided and smoothed. Subdivision surfaces have been integrated to the MPEG4 standard [2]. Moreover, a lot of algorithms exist to convert a 3D mesh into a subdivision surface [7–13], particularly because this model is much more compact, in terms of amount of data, than a dense polygonal mesh.

2.2. *State of the art on 3D watermarking*

There still exist few watermarking methods for 3D models compared with the amount of algorithms available for traditional media such as audio, image and video. Most of the existing methods concern polygonal meshes and ignore other 3D surface representations. To our knowledge, there do not exist watermarking schemes for subdivision surfaces and quite few authors have investigated NURBS surface watermarking: Ohbuchi et al. [14] embed the mark into the knot equations by knot reparameterization, while Lee et al. [15] create a virtual 2D image by sampling the parametric support of the NURBS surface and then apply 2D image watermarking techniques.

Existing techniques concerning 3D meshes can be classified into two main categories, depending if the watermark is embedded in the *spatial* domain (by modifying the geometry or the connectivity) or in the *spectral* domain (by modifying kinds of spectral coefficients).

Spatial techniques: The first watermarking techniques have concerned the spatial domain and were introduced by Ohbuchi et al. [16,17]. They apply topological modifications by subdividing triangles to produce recognizable patterns. They also propose to perturb vertices coordinates to obtain certain desired ratio for some tetrahedra volumes or triangles heights. Yeo and Yeung [18] and more recently Cayre and Macq [19] follow a similar approach for fragile watermarking. In a different way, Benedens et al. [20,21] modify surface normals, in order to increase the robustness to simplification. Finally, Yu et al. [22] perturb the length of the vectors linking the surface vertices to the centre of the 3D object. Although having the benefit of being quite fast and simple to implement, these *spatial* methods do not yet provide enough robustness with respect to some ordinary attacks like noise addition, and are rather adapted for blind fragile watermarking or steganography, like the recent algorithm from Maret and Ebrahimi [23] which considers a similarity invariant space to embed the mark, or Zafeiriou et al. [24].

Spectral techniques: These algorithms decompose the target 3D object into a spectral-like domain, in order to embed the watermark following some signal processing approaches like *spread spectrum*, by modifying spectral coefficients. The first authors to consider such an approach were Kanai et al. [25], who decomposed the mesh by applying the lazy wavelets introduced by Lounsbery et al. [26]. Their algorithm was recently extended to blind detection by Uccheddu et al. [27]. Unfortunately these approaches require the mesh to have a semi-regular subdivision connectivity. Thus, recently, Kim et al. [28] present a similar approach based on irregular wavelet analysis which allows to process arbitrary irregular triangle meshes. Other authors use multiresolution decomposition to decompose the object in a pseudo-spectral way. Praun et al. [29] consider iterative edge collapse operations to construct the multiresolution hierarchy, similar to the *progressive mesh* technique from Hoppe [30]. With the same idea, Yin et al. [31] consider the multiresolution

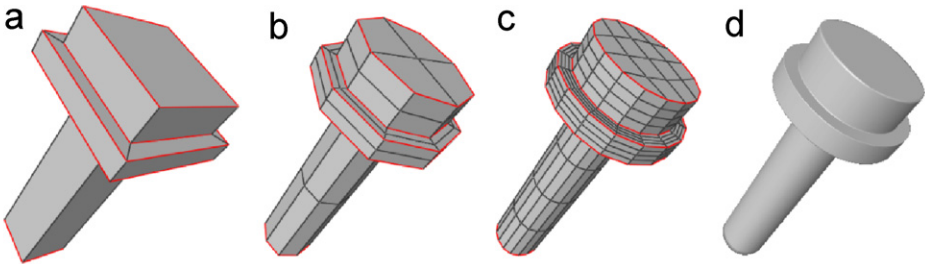

Fig. 1. Example of subdivision surface with sharp edges (in red). (a) Control mesh, (b,c) 1 and 2 subdivision steps, (d) limit surface.