Chapter 79
Blind Watermarking of Three-Dimensional Meshes: Review, Recent Advances and Future Opportunities

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ABSTRACT
Digital watermarking of three-dimensional (3-D) meshes has numerous potential applications and has received more and more attention from both academic researchers and industrial practitioners. This chapter focuses on the study of blind mesh watermarking techniques, which do not need the original cover mesh for watermark extraction and thus have a much larger application range than the non-blind techniques. The authors first review the existing methods proposed so far, by classifying them into three groups: fragile schemes, high-capacity schemes and robust schemes. They then present their recent work on quantization-based blind watermarking of semi-regular meshes. Finally, some future working directions are suggested.

INTRODUCTION
Nowadays, 3-D models are more and more used in applications such as medical imaging, digital entertainment and computer-aided design, mainly due to the processing capability improvement of ordinary PCs and the bandwidth increase of network infrastructure. A 3-D model is often numerically represented as a mesh, which is a collection of polygonal facets targeting to constitute an appropriate piecewise linear approximation of the surface of a real 3-D object. Although there exist many other 3-D representations (e.g. implicit surface, NURBS or voxel), polygonal mesh has become the de facto standard of numerical representation of 3-D objects due to its algebraic simplicity and high usability.

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Unfortunately, like digital images and audio/video clips, 3-D meshes can be easily duplicated and redistributed by a pirate without any loss of quality. This illegal behavior infringes the intellectual property of mesh owners and could also do harm to the whole underlying commercial chains. Digital watermarking technique appears as an efficient solution to this emerging problem. Actually, since the seminal work of Ohbuchi, Masuda, & Aono (1997), there has been an increasing interest in mesh watermarking research (c.f. Table 1). Besides the robust watermark used for intellectual property protection, fragile and high-capacity mesh watermarks also have many potential applications such as mesh authentication and content enhancement.

Compared with the relative maturity of the research on image, audio and video watermarking, the research on mesh watermarking seems still in its early stage. This situation is mainly due to the fact that a 3-D mesh is normally an irregular structure and that there exist a large number of intractable attacks on watermarked meshes (Wang, Lavoué, Denis, & Baskurt, 2008a). Indeed, existing image watermarking algorithms are rarely applicable on 3-D meshes, and the design of successful blind mesh watermarking schemes, which do not need the original cover mesh for watermark extraction, is particularly difficult. Our objectives in this chapter are threefold: 1) to provide a complete literature review on blind mesh watermarking research, 2) to present some recent advances in this research field, and 3) to propose several potentially interesting future working directions. Before presenting the technical contents on 3-D mesh watermarking, in the following we will first provide some background knowledge on polygonal meshes.

### Background Knowledge on Polygonal Meshes

A 3-D mesh has three different combinatorial elements: vertices, edges and facets (typically triangles or quadrangles). The coordinates of the vertices constitute the geometry information of the mesh, while the edges and facets describe the adjacency relationships between vertices and constitute the mesh’s connectivity information. Mathematically, a mesh $\mathcal{M}$ containing $N$ vertices and $M$ edges can be modeled as a signal $\mathcal{M} = \{\mathcal{V}, \mathcal{E}\}$, where

$$\mathcal{V} = \{v_i = (x_i, y_i, z_i) \mid i \in \{1, 2, \ldots, N\}\}, \quad (1)$$

$$\mathcal{E} = \{e_j = (p_1^{(j)}, p_2^{(j)}) \mid j \in \{1, 2, \ldots, M\}; \quad p_1^{(j)}, p_2^{(j)} \in \{1, 2, \ldots, N\}\} \quad (2)$$

More precisely, each vertex $v_i$ is described by its three-dimensional coordinates $(x_i, y_i, z_i)$; each element in $\mathcal{E}$ stands for an edge connecting two different vertices indexed by $p_1^{(j)}$ and $p_2^{(j)}$, respectively. Instead of the list of edges $\mathcal{E}$, the mesh connectivity information can also be completely described by a list of facets $\mathcal{F} = \{f_k \mid k \in \{1, 2, \ldots, L\}\}$, where $L$ is the number of facets of the mesh. Each facet from the list $\mathcal{F}$ is normally represented by a sequence of indices of its component vertices that are sorted in a certain cyclic order around it. A mesh is called triangular if all its facets are triangles; similarly we can define a quadrangular mesh. Figure 1 shows an example of 3-D mesh. As illustrated

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