Perceptibility of digital watermarking in haptically enabled 3D meshes

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ABSTRACT

Usage of 3D data and models is receiving a growing interest for several applications, like training, museum displays, multimodal interfaces, aid for impaired people. In such a framework the need will soon raise to protect 3D data from misuse. Among the technologies that can be used to this aim, digital watermarking has a prominent role, due to its versatility and non-obtrusiveness. A basic requirement of any watermarking scheme is that the embedded code is invisible, or non-perceivable, by the end user of the data. This requirement also holds for 3D objects, it is then necessary that the human ability of perceiving a signal hidden in a 3D object is studied. In this paper we present a preliminary analysis aiming at comparing the perceptibility of the hidden signal when the 3D model is sensed through different senses, namely vision (through common rendering techniques and subsequent display on a monitor) and touch (through a haptic interface). Specifically our investigation aimed at assessing whether ensuring watermark invisibility is sufficient to ensure that the watermark presence can not be felt haptically. The answer stemming from our preliminary analysis seems to be no, even if further studies are necessary before a definitive answer can be given.

Keywords: haptic, global sensation, perception

1 INTRODUCTION

In the last decades Virtual Reality (VR) applications have seen a great deal of development, also due the introduction of force-feedback devices, which allow kinesthetic interaction with virtual environments, thus highly increasing the sense of presence inside simulated scenarios. Some examples of such applications are drive and flight simulators [1], training systems for technical maintenance [2] and even for pathology diagnosis and surgery [3, 4].

In this framework, it is easy to predict that the need will soon arise to protect 3D data from misuse, like unauthorized copying and distribution, or false ownership claims. Among the available technologies to protect digital data, digital watermarking is receiving an increasing attention to its unique capability of persistently hiding information within the to the to-be-protected data [5, 6] . The hidden information may serve to prove ownership, to deny the permission of copying the data, to detect tampering etc., but the first requirement that such information must satisfy is its complete imperceptibility. A great deal of research has focused on digital watermarking of audio, images and video, resulting in a number of possible algorithms which exploit the properties of the Human Visual System (HVS) to improve watermark invisibility while preserving hidden information integrity [7] . On the other hand, watermarking of 3D objects is far from this level of maturity. One of the reasons for this gap is the difficulty of extending common processing algorithms used in signal processing to 3D data. In this context, the intrusiveness of the watermark in a 3D object has been judged in term of its visibility in the rendered version of the mesh [8]. A question naturally arising is whether ensuring the invisibility of the watermark when the 3D object is graphically displayed on a monitor is sufficient to ensure also the imperceptibility of the watermark when other senses are used to feel the object, e.g. when the 3D object is haptically enabled and it can be virtually *touched* through a force-feedback device. This work aims at providing an answer to this question.

The scope of this paper is presenting the results of three psychophysical experiments we carried out to measure and compare human visual and haptic abilities to sense the presence of a small signal hidden in a host surface. The target of this preliminary investigation was to understand whether one sensory channel reveals to be more sensitive than the other in detecting the hidden signal. As a consequence, if the visual channel results clearly predominant over the haptic one, watermark designers could ignore the possibility that the marked 3D object is sensed by means of a haptic interface. On the contrary, if the sensitivity of the two channels is comparable, then watermark designers must pay attention to ensure both visual and haptic imperceptibility.

Among the possible formats available to describe a 3D object, we decided to use the 3D mesh for its popularity and flexibility. Accordingly, we assumed that the watermark is inserted by modifying the basic structure of the 3D mesh underlying the 3D model. In order to keep the experiments as simple as possible and to avoid masking effects (that are left for future research), we chose to watermark the simplest possible model, i.e. a flat surface represented implicitly by a 3D mesh. As to the watermark, we considered the simple case of a white noise superimposed to the host surface by a simple additive rule. We measured the minimum watermark strength for which the superimposed noise was perceptible either haptically or visually. The measure was repeated for different resolutions of the underlying mesh.

More specifically, Experiments I and II aimed at estimating watermark perception thresholds for the haptic sensory channel using a PHANToM Desktop and a PHANToM Premium 1.5, respectively. The former device was featuring a stylus type end-effector while the latter had a 3DoFs finger thimble end-effector. Experiment III was addressed to measure the same thresholds for the visual channel, using a common 17” CRT screen.

The results we obtained seem to point out that none of the

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two channels clearly dominates. Nevertheless, in the condition whereby the experiments have been conducted, the watermark resulted slightly more perceptible through the haptic channel.

Though no general conclusions can be drawn from these preliminary experiments, we can safely conclude that when designing a watermarking system for haptically enabled 3D objects, the evaluation of haptic perceptibility must be taken into account.

This paper is organized as follows. In Section 2 a brief introduction to watermarking is given. In Section 3 the method we used for our experiments is described. The actual implementation of our experiments and the corresponding results are given in Section 4 (haptic part) and 5 (visual part). Section 6 presents a critical discussion of the results we obtained, whereas some directions for future work are highlighted in Section 7.

2 Overview of watermarking techniques

Generally speaking any watermarking system can be seen as a communication system consisting of two main parts: a watermark embedder, and a watermark detector. The watermark is transmitted through the watermark embedder over the original to-be-marked object (in our case a 3D surface). The watermark detector extracts the watermark from the marked data. Intentional and unintentional attacks and distortions applied to the mesh hosting the watermark further characterize and complicate the transmission channel. As to the watermark, it usually consists of a pseudo-random sequence with uniform, binary or Gaussian distribution.

The first step towards the definition of a watermarking system consists in the definition of the features that will host the watermark. For instance, in the case of still images the watermark may be inserted in the pixel domain or in the frequency domain. In the case of 3D objects possible approaches include embedding the watermark into the vertex positions or in the wavelet coefficients [12] .

Once the host features have been defined, the most popular embedding rule is the *additive* one whereby:

$$x_{w,i} = x_i + \gamma w_i, \tag{1}$$

where x_i is the i-th component of the original feature vector, w_i the i-th sample of the watermark, γ a parameter controlling the watermark strength, and $x_{w,i}$ the i-th component of the watermarked feature vector. Recently a new approach to watermark embedding has been proposed. This approach, commonly referred to as informed watermarking or QIM (Quantization Index Modulation) watermarking [13], can greatly improve the performance of the system as a whole. According to QIM the watermark is embedded by properly quantizing the host feature, for instance embedding a 0 bit may be obtained by quantizing the host feature to the nearest even value, whereas to embed a 1 the nearest odd value is considered. For sake of simplicity, our analysis focuses on additive watermarking, leaving the analysis of QIM schemes for future work.

Among the characteristics of watermarking algorithms, a crucial role is played by the way the watermark is extracted from data. In *blind* decoding, the decoder does not need the original data (mesh) or any information derived from it in order to recover the watermark. Conversely, *non-blind* decoding refers to a situation where extraction is accomplished with the aid of the original, non-marked data. An important distinction can also be made between algorithms embedding a mark that can be *read* (i.e. the bits contained in the watermark can be read without knowing them in advance) and those inserting a code that can only be *detected*. In the former case, the bits contained in the watermark can be read without knowing them in advance. In the latter case, one can only verify if a given code is present in the document. Though our perceptibility analysis is a general one, we specifically focus on the case of blind watermark detection.

For a more detailed discussion of watermarking issues readers are referred to [14] and [15] .

3 Methods

As we said, our experiments aimed at measuring the perceptibility of the watermark when the 3D object is sensed through a visual or a haptic interface. To simplify the analysis we have chosen the simplest possible model, i.e., a flat horizontal surface, so to avoid considering masking effects certainly present with more complicated surfaces. We assumed that both the host plane and the watermark are represented by a 3D mesh.

3D meshes are encoded in data structures representing the spatial coordinates of all the vertices as well as their interconnections. A virtual mesh can be *haptically displayed* by a force-feedback device that allows single-contact-point interaction. In this case, the information about the shape is conveyed via the direction of the reaction forces, following the direction of the normal unit vectors. In regard to graphic rendering, the virtual mesh is displayed by a common screen and the information about the shape is conveyed via perspective projections on the screen plane and light reflections on the 2D projected image.

¿From a practical point of view, the digital watermark modelled as described above can be embedded by modifying the data structures in the position of the vertices. Each vertex elevation (in the direction of the normal vector) is changed by the amount of the watermark signal in the corresponding point of the mesh. The *strength* of the watermark is represented by the noise spectral power of the equivalent noise model. For both the haptic and the visual experiments, we characterized the watermark sensitivity through the estimation of the minimum noise resulting in a detectable watermark. Since the resolution of the mesh, i.e. the dimension of triangle elements, may vary with the application and the shape of the surface, the experiments were conducted by using several 3D meshes representing the same plane and featuring different resolutions, so to allow us to investigate the relationships between the haptic and visual sensitivities by recording the watermark strength at threshold as a function of the size of the triangular elements forming the mesh.

To make the results of the two experiments comparable, these were carried out with the same experimental paradigm, the only difference being the media used to *sense* the stimuli.

3.1 Subjects

5 subjects, males and females aged 21-28, participated in the experiments. All were right-handed with no known sensorimotor impairments with their hands neither visual deficiencies. Their prior experience with Virtual Reality applications and with haptic devices varied from naïve to expert.

3.2 Stimuli

The stimuli was defined by considering a virtual reality experiment in which a flat horizontal plane of size $20 \times 20cm^2$ is placed in front of the subject, who is then free to either touch or look at it[1]. The flat plane was represented by means of a 3D triangular mesh. More specifically, let us consider a reference frame attached to the object, where the $z-$axis is oriented as the plane normal unit vector. Hence vertices are defined as:

$$v(i) = \begin{bmatrix} x \\ y \\ c \end{bmatrix}, \ \hat{n}(i) = \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix}$$

[1]Though surely interesting, the situation in which the users simultaneously see and touch the surface was left for future work.

where $v(i)$ is a vector with the coordinates of the $i-$th vertex, c is a constant value and $\hat{n}(i)$ is the unit vector in the normal direction. Watermark embedding is achieved by altering the mesh vertices according to the following rule:

$$v_w(i) = v(i) + w(i)\hat{n}(i),$$

where $v_w(i)$ are the coordinates of the $i-$th watermarked vertex and $w(i)$ is the watermark signal. Specifically, in our case $w(i)$'s are independent and identically distributed (iid) random variables with uniform distribution in the interval $[-\Delta, +\Delta]$. In the following the strength of the watermark will be measured by referring to the parameter Δ, so that by sensitivity threshold we will mean the minimum value of Δ that results in a perceptible watermark. In the frequency domain the sequence $\mathbf{w} = \{w(1), w(2)\ldots w(n)\}$ features a constant spectral power over all frequencies.

In regard to plane resolutions, 7 values have been chosen and the corresponding side lengths of triangle elements have been determined by dividing the plane side into 100, 75, 55, 40, 30, 25 and 20 segments, thus yielding the side lengths:

$$l = 2.00, 2.86, 3.64, 5.00, 6.67, 8.00, 10.00mm$$

3.3 Conditions

The virtual environment has been designed in such a way that the virtual surface is displaced in front of the user as depicted in Figure 1: d is the distance between user's eyes and the nearest side of the plane, α is the angle the plane surface forms with the straight line from user's eyes to the plane. The values $d \approx 50cm$ and $\alpha \approx 30^o$ have been chosen so that the subjects can comfortably handle the haptic interface during the first experiment. The same values were used for the visual test.

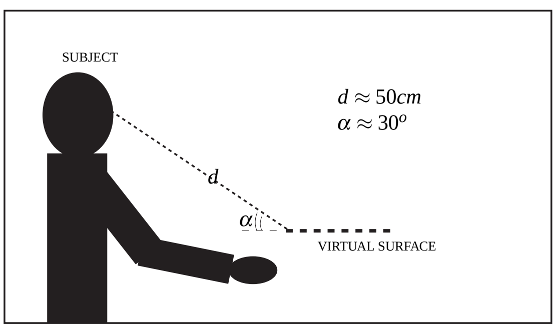

Figure 1: Placement of the virtual surface with respect to the user point of view.

3.4 Procedure

A 3 down/1 up two-interval forced choice (2IFC) adaptive staircase (AS) method was used to estimate the detection threshold [16]. According to the 2IFC paradigm, each stimulus consists of a pair of planes, one of which holding the watermark, presented to the subjects in two subsequent intervals in random order. In each trial, the task is to detect in which of the two intervals the plane with the watermark is presented. After three consecutive correct answers the watermark strength is decreased by a predefined amount (see below), whereas after a single wrong answer the strength is raised again. The stop condition is reached after 6 consecutive reversals, a reversal being defined as a situation in which the watermark strength adaptation changes sign. As a result of the above procedure a typical staircase of values is obtained, indicating the sequence of watermark strengths used throughout the experiment. The detection threshold is computed by taking the average over the last series of reversals within the corresponding staircase. A sketch of a typical staircase produced by our experiments is given in Figure 2.

The experiments were arranged in two blocks per subject: a practice block and an experimental block. Each experimental block consisted of seven sessions, differing in the size of the side of the triangular mesh elements, ranging from 2 to 10*mm*. As a consequence of the AS scheme, the number of trials per session was not fixed *a-priori*, but was adaptively determined during each run to meet the predefined stop condition ensuring the convergence of the process. Each subject performed each session twice. The mean value over

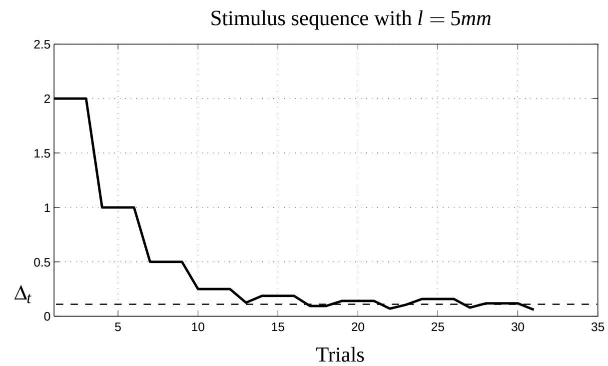

Figure 2: Experimental staircase for one run. In this case the triangle side length was $l = 2.86mm$. The watermark strength is measured by means of the parameter Δ. The dashed line represents the resulting detection threshold.

corresponding sessions was retained for each subject as representative of the sensitivity for the given experimental condition (*i.e.*, the mesh resolution).

Before starting the experiments, a series of pilot tests were conducted in order to set up the parameters that characterize the AS method. For example, the initial value $\Delta(0)$ is the watermark perceptibility at the beginning of the experiment. A fairly perceptible watermark is generally recommended in the initial trials in order to create for each subject the same initial conditions, where stimuli are surely far from the sought threshold. On the other hand, the initial value $\Delta(0)$ together with the step size and the stop condition determine the speed of convergence for the adaptive method. Hence, these parameters have been experimentally tuned to achieve a trade off between the accuracy of the observations and the duration of each experimental run. The initial value $\Delta(0)$ was set to 2mm, and the step adaptation rules were defined by:

$$\begin{cases} \Delta(i+1) = \frac{1}{2}\Delta(i) \text{ (3 correct answers)} \\ \Delta(i+1) = 1.5\Delta(i) \text{ (1 wrong answer)} \end{cases}$$

where $\Delta(i)$ determines the watermark strength at the i-th step. As we said, the stop condition was defined as a set of 6 consecutive reversals of the staircase.

4 Haptic perceptibility: experiments I and II

In this section we describe the implementation of the experiment regarding the haptic perceptibility of the watermark and briefly report the results we obtained. Actually this study involved two experiments conducted using different media to display kinesthetic stimuli: in the first phase we used a PHANToM Desktop force-feedback device featuring a stylus type end-effector; in the second phase we employed a PHANToM Premium 1.5 featuring a 3DoF thimble end-effector (both devices are from SensAble Technologies, Inc., Woburn, MA, USA).

4.1 Displaying stimuli

In both experiments, users sensed stimuli only via the haptic device, i.e. they were not provided with any graphical feedback. Particular attention was reserved to the relative distance between the subjects and the haptic device, in order for the virtual plane displacement to satisfy the experimental conditions described in Subsection 3.3 (see Figure 1).

Each subject stroked the surface as illustrated in Figure 3. Whenever the end-effector avatar was inside the virtual surface, a restoring force F was fed back. The force vector felt by the subjects was computed via the classic god-object algorithm [10] as $F = Kd(t)$, where $K = 1N/mm$ is the stiffness of the virtual surface, and $d(t)$ the penetration vector at time instant t. Obviously, no force was displayed when the avatar was outside the virtual surface. Note that this is a general haptic rendering algorithm, commonly employed in most haptic applications.

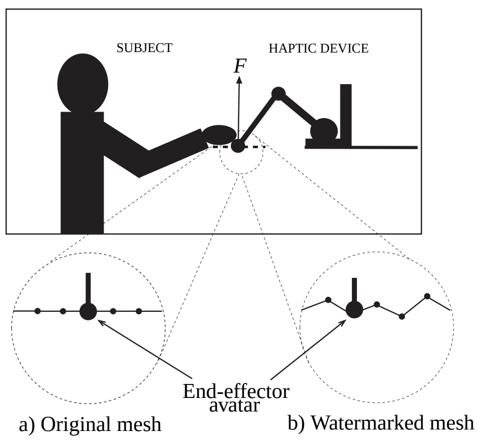

Figure 3: Haptic representation of the stimuli. (a) original mesh: all the vertices lay on a plane. (b) watermarked mesh: vertices heights are altered by the watermark.

4.2 Results

Experimental data consisted of the displayed stimuli during each run. The detectability threshold Δ_t resulting from each experiment was estimated by taking the average over the last 6 reversals of the staircase. We repeated this procedure for all side lengths used in both phases of this experiment. The final average thresholds and standard deviations for each side length were computed as the mean value and standard deviation of all the subject thresholds. Finally, global thresholds and standard deviations were plotted with respect to the triangle side length. Figures 4 and 5 show the results obtained from the two experiments with the PHANToM Desktop and the PHANToM Premium 1.5, respectively.

As it can be seen in Figures 4 and 5, the watermark detectability increases when the mesh resolution increases, since a lower detection threshold is experimented for smaller triangle sizes. The standard deviation of the thresholds resulting from the single experiments is rather large, pointing out the need for more extensive tests, involving more subjects and, possibly, more repetitions of the same tests by the same subjects. A more detailed discussion is reported in Section 6.

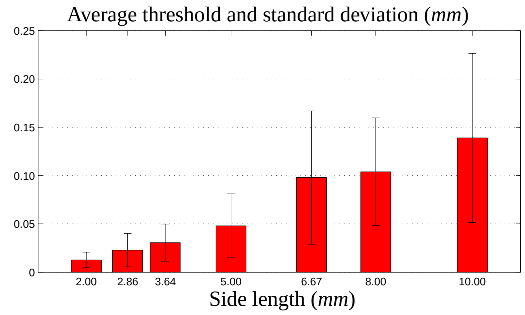

Figure 4: Average thresholds (Δ_t) over triangle side length (mm) for the first haptic experiment, performed using the PHANToM Desktop with stylus end-effector.

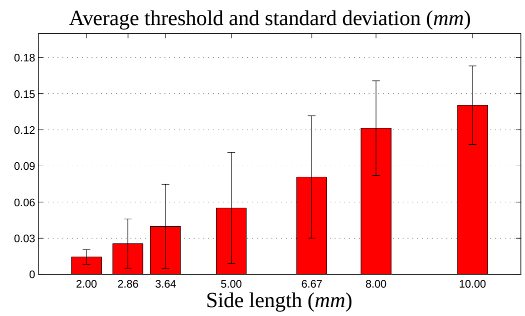

Figure 5: Average thresholds (Δ_t) over triangle side length (mm) for the first haptic experiment, performed using the PHANToM Premium 1.5 with thimble end-effector.

5 VISUAL PERCEPTIBILITY: EXPERIMENT III

We now turn the attention to the visual part of our experiment and to the corresponding results.

5.1 Displaying stimuli

In this case, stimuli were visually displayed via a 17" CRT monitor (model NEC MultiSync FE750+). The object was sensed through a single modality, that is, subjects were not provided with the haptic display of the stimuli. In order to generate the visual stimuli, the 3D mesh was first graphically rendered[2]. The rendering geometry was chosen in such a way that the virtual conditions described in Section 3.3 were matched. In other words, the camera position and plane orientation were chosen in such a way that, when displayed on the monitor, the rendered plane was seen as if it was at a distance $d \approx 50cm$ and viewed with an angle $\alpha \approx 30^o$ (see Figures 1 and 6). As to the lighting conditions, graphic rendering was performed by using gouraud shading. We chose a grey background and a basic diffuse lighting with one white point-light source displaced as shown in the bottom of Figure 6, since we tried to avoid introducing any preferred directions for light reflections and shadows on the rendered mesh.

We smoothed the watermark strength to zero towards the borders of the plane, so to avoid the appearance of ragged contours at the border of the plane that would make the watermark presence more easily detectable. Finally, the visual experiments were performed

[2] We used DirectX Libraries to perform the graphic rendering.

in a dark room. An example of the visual appearance of a watermarked plane is given in Figure 7.

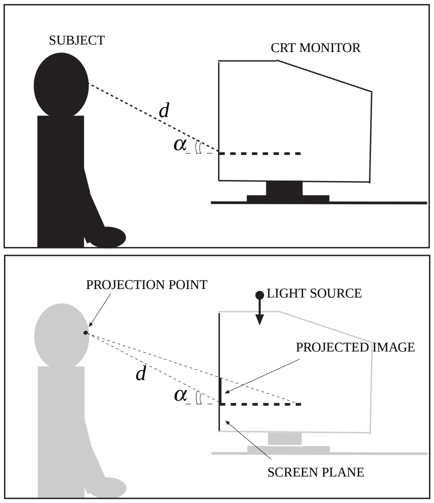

Figure 6: Geometrical setup for the visual stimuli. Top: user's displacement w.r.t. monitor. Bottom: rendering conditions.

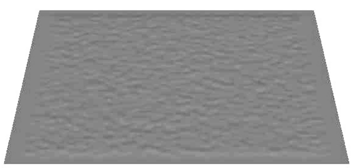

Figure 7: Example of a watermarked plane used for the visual part of the experiment. The visibility of the watermark has been exaggerated to improve the readability of the figure.

5.2 Results

As for the haptic case, for each user the detection thresholds obtained by means of two experiments performed at the same resolution level were averaged to obtain the detection threshold of a given user. The resulting, single-user thresholds were averaged yielding the results depicted in Figure 8, where the standard deviation of the data collected at each resolution level is also given. Once again the detectability of the watermark increases with the resolution of the mesh.

Again, relatively large standard deviations are observed confirms the need for more extensive tests.

6 Discussion of results

The target of this work was trying to understand whether watermarking designers dealing with 3D objects need to care about fruition modalities different than the usual 3D graphic rendering when considering the obtrusiveness of the watermark. Based on the preliminary results we obtained, the answer to our question seems to be yes. In Figure 9 the diagrams obtained in our three experiments are plotted in order for the corresponding thresholds to be

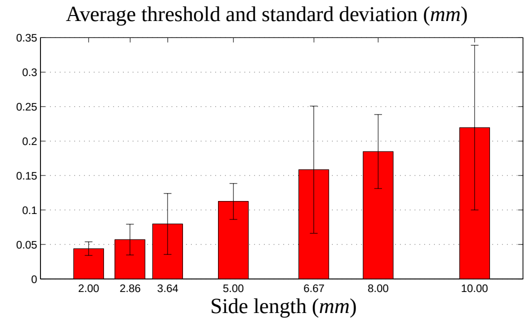

Figure 8: Average thresholds (Δ_t) over triangle side length (mm) for the visual experiment.

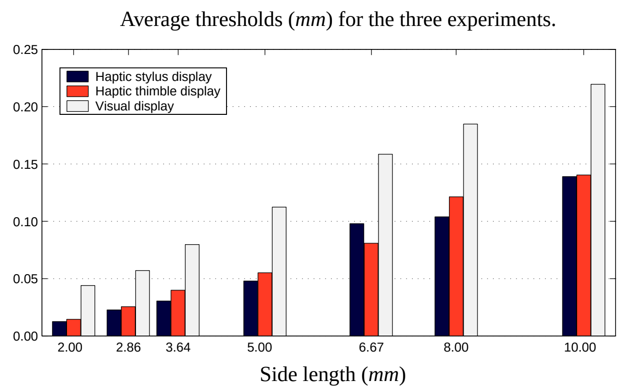

Figure 9: Comparing the average thresholds (Δ_t) over triangle side length (mm) for the three experiments.

easily compared. Even though this is presented as a pilot study, the soundness of preliminary results we obtained is confirmed by the following observations. As shown in Figure 9, the average watermark detectability increases when the mesh resolution increases, for both the haptic and the visual sensory channel. Regarding the haptic experiments, although the two phases were performed with quite different displaying media, a quick comparison between the related plots (Figure 9) shows that the detectability thresholds are almost equal for each side length. This supports the hypothesis that the perceptibility of the watermark could be independent from the particular mediating device. Besides, it is evident that the average watermark perception thresholds are smaller for the haptic sensory channel than for the visual one. This makes haptic imperceptibility an additional requirement to be satisfied in addition to invisibility in all cases in which applications provide a visuo-haptic display of virtual objects.

On the other hand, the experiments described in this paper, and the corresponding results, must still be considered as preliminary. The standard deviation of the thresholds resulting from the single experiments is rather large (see Figures 4, 5 and 8), pointing out the need for more extensive tests, involving more subjects and more repetitions of the same tests. Furthermore, the graphic rendering conditions we adopted, though rather standard, are arbitrary. A non-exhaustive list includes: lighting conditions, geometric position of the plane, shading algorithm, surface color, surface material. Different watermarking algorithms should be tested, since the popular additive noise model used in our experiments is surely too narrow to represent the huge variety of algorithms available in the literature. Finally, different choice of the host model should be considered.

Summarizing, within the limitations pointed out above, we found a case for which the embedded watermark is more easily detected through a haptic interface rather than by visual inspection, and given that the choices we made to design our experiments are routinely made by many applications, we can safely conclude that as long as the marked 3D objects are going to be used in multimodal applications where users are going to *sense* them both by looking at and touching them, the haptic dimension of the problem can not be ignored.

7 Conclusions and future work

With this work we have taken a first step towards the analysis of the haptic perceptibility of digital watermarks. It goes without saying that a lot of work is still ahead of us. A first list of topics for future research stems from the list of arbitrary choices reported in the previous section. Another interesting cue for future work is the analysis of watermark perceptibility by means of truly multimodal interfaces whereby users can simultaneously touch and look at the marked model. It is possible that coupling the capabilities of both vision and touch may result in different sensitivity thresholds with respect to those of the single sensory channels, hence making the challenge for watermark designers harder.

Acknowledgments

This work was supported in part by Fondazione Monte dei Paschi di Siena and by Università di Siena under Grant PAR-2003, by National Science Foundation awards under Grant 0098443-IIS and 0328984-CCF.

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