Is Haptic Watermarking Worth It ?

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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 a clear no, even if further studies will be necessary before a definitive answer can be given.

1. INTRODUCTION

In the last decades Virtual Reality (VR) applications have seen a great deal of development. In this context, a fundamental innovation was the introduction of haptic interfaces, that allowed kinesthetic interaction between users and virtual environments, thus highly increasing the overall realism of VR applications. Some examples of such applications are drive and flight simulators,[1] training systems for technical maintenance[2] or for operation in industrial tasks.[3] Recently Virtual Reality simulators have been introduced also into medical disciplines such as pathology diagnosis and surgery.[4,5]

Due to the growing importance that 3D data will have in the future, it is easy to predict that the need will soon arise to protect such 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 a piece of information within the to the to-be-protected data[6,7] . The hidden information can be used to prove ownership, to deny the permission of copying the data, to detect tampering etc . . . . A great deal of research has focused on digital watermarking of audio, images and video. On the contrary, watermarking of 3D objects is far from this level of maturity although 3D models are widely used in several applications such as virtual prototyping, cultural heritage, and entertainment industry. One of the reasons for this gap is that it is difficult to extend common processing algorithms used in signal processing to 3D data. As we said, the first requirement that any watermarking technique must satisfy is watermark imperceptibility. In the case of still images and video sequences, the imperceptibility requirement has triggered a great deal of research about the Human Visual System (HVS), resulting in a number of possible algorithms which exploit the properties of the HVS to improve watermark invisibility while keeping the watermark energy constant[8] . Something similar happened for the case of 3D watermarking, where the intrusiveness of the watermark is judged in term of its visibility in the rendered version of the mesh[9] . A question naturally arising is whether ensuring the invisibility of the watermark when the 3D object is digitally rendered and displayed on a monitor is sufficient to ensure the imperceptibility of the watermark when other senses are used to feel the object, e.g., when the 3D object is virtually *touched* through a haptic interface.

Despite an enormous increase in research activity in the last few years, the science of haptics (perception and manipulation with our hands) is still a technology in its infancy[10] . The most popular haptic interfaces are the PHANTOM, produced by SensAble Technologies (www.sensable.com), and the Delta, produced by ForceDimension (www.forcedimension.com). These are devices that interact with the virtual environment through one contact point only. Interfaces with higher number of degrees of freedom (DOFs) and with multiple interaction points are also available, but are less common or reliable than those with three DOFs and one interaction point. With the term *haptic rendering* we refer to a branch of haptics research that deals with calculating the right interaction force between a virtual representation of the user and a virtual object. In most cases, haptic rendering means rendering the macrogeometry of an object surface. For this purpose, we can use typical single point contact rendering algorithms such as *god-object*[11] and the *virtual proxy*[12] .

It is the scope of this paper to present the results of two 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. Should the visual channel be 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 sensibility 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 format 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 hectically or visually. The measure was repeated for different resolution of the underlying mesh. The results we obtained seem to point out that none of the two channels clearly dominates, with the watermark being slightly more perceptible through the haptic interface. Though no general conclusions can be drawn from these preliminary experiments, mainly because of the several simplifying assumptions we had to make in order to keep the experiments manageable, we can safely conclude that when designing a watermarking system for 3D models it is necessary that all the possible interfaces whereby users can *sense* the model must be taken into account.

The rest of 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 the haptic and visual parts of the experiment and the corresponding results are given in Section 4 and 5. 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[13] .

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,[14] 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 the books by Barni and Bartolini[15] , and by Cox et al.[16] .

3. METHOD

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 is *haptically displayed* by a force-feedback device that allows single-point contact mediated by a stylus. The information about the shape is conveyed via the direction of the reaction forces, following the direction of the normal unit vectors. As regards 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 with the position of 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 required 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 to the watermark strength and the size of the triangular elements forming the mesh.

To make the results of the two experiments comparable, the experiments were carried out by the same subjects and the the same experimental paradigm was adopted for both cases, the only difference being the media used to *sense* the stimuli.

3.1. Subjects

5 subjects, aged 22-25, participated in both the experiments. All were right-handed with no known sensorimotor impairments with their hands or eyes. Their prior experience with the PHANToM device 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 $15 \times 15cm^2$ is placed in front of the subject, who is then free to either touch or look at it*. The flat plane was represented by means of a 3D triangular mesh with varying resolution. To be specific, let us consider a reference

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

frame attached to the object, where the $z-$axis is oriented as the plane normal unit vector. Hence vertices are defined as:

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

where $v(i)$ is a vector with the coordinates of the $i-$th vertex, c is a constant value and 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 sequel the strength of the watermark will be measured by referring to the parameter Δ, so that by Just Noticeable Distortion 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.

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 case.

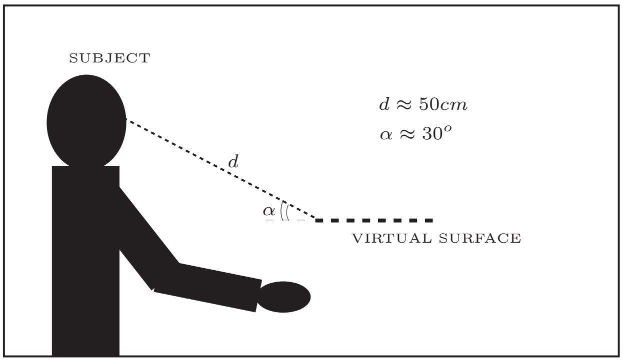

Figure 1. Displacement of the virtual surface with respect to the user point of view.

3.4. Procedure

A 3 down/1 up two-interval forced choice (2IFC) adaptive staircase (AS) method was used to estimate the detection threshold.[17] 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, e.g., the strength is increased after that at the previous step it was decreased. 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 10mm. 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 corresponding

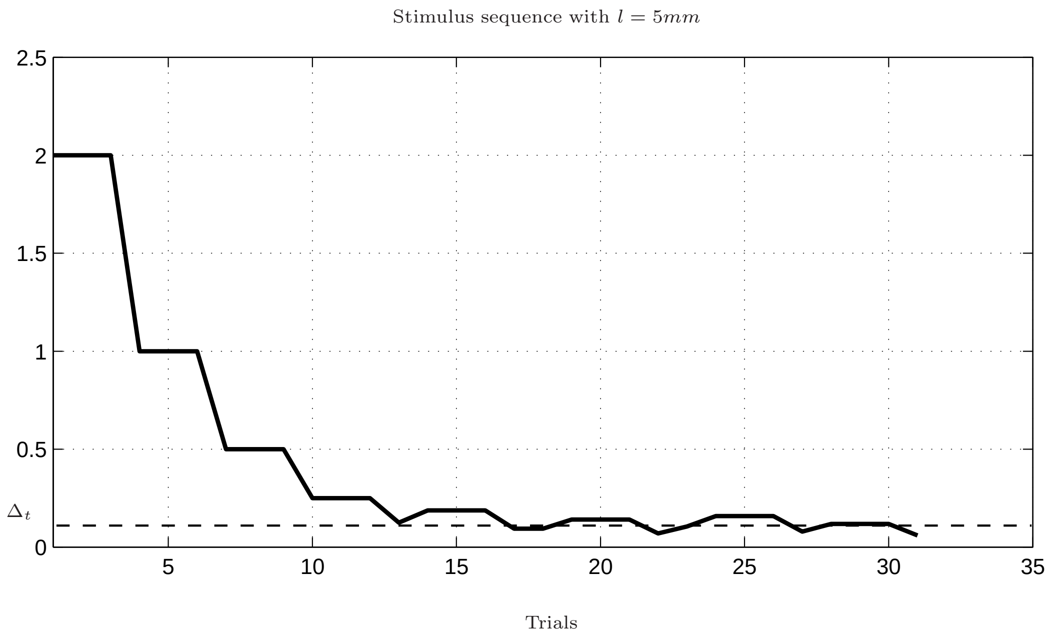

Figure 2. Experimental staircase for one run. In this case the triangle side length was $l = 2.85mm$. The watermark strength is measured by means of the parameter Δ. The dashed line represents the resulting detection threshold.

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 $\Delta(0)$ determines the watermark perceptibility at the beginning of the experiment. A fairly perceptible watermark is generally recommended in the initial trials in order for subjects to familiarize with their task. On the other hand, the initial value $\Delta(0)$ together with the step size and the stop condition may 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 signal probability density function at the i-th step. As we said, the stop condition was defined as a set of 6 consecutive reversals of the staircase.

4. EXPERIMENT I: EVALUATING HAPTIC PERCEPTIBILITY

In this section we describe the actual implementation of the haptic part of the experiment and briefly report the results we obtained.

4.1. Displaying stimuli

In the first experiment, the stimuli were haptically sensed via a PHANToM force-feedback device (model Desktop, SensAble Technologies, Inc., Woburn, MA, USA). Users were not provided with the graphical display of the stimuli. 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 held the stylus of the PHANToM with their right hand and stroked the surface along the x, y-plane, as illustrated in figure 3. Whenever the stylus tip was inside the virtual surface, a restoring force F was applied to the subjects' hands. The force vector felt by the subjects was computed via the classic god-object algorithm[11] as $F = Kd(t)$, where $K = 1N/mm$ is the stiffness of the virtual surface, and $d(t)$ the penetration vector. Conversely, no force was displayed when the stylus was outside the virtual surface. Note that this is a general haptic rendering algorithm, commonly employed in most haptic applications.

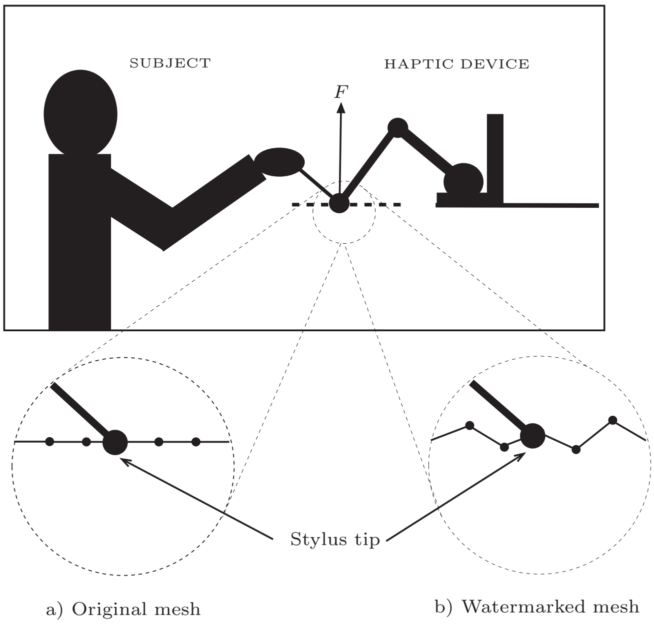

Figure 3. Haptic representation of the stimuli. (a) original mesh: all the vertices lay on a plane. (b) watermarked mesh: vertices heights are altered by the watermark.

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 the experiments. The final average thresholds and standard deviations for each side length have been computed as the mean value and standard deviation of all the subject thresholds. In Figure 4, global thresholds and standard deviations are plotted with respect to the triangle side length.

As it can be seen, the watermark detectability increases when the mesh resolution increases, since a lower detection threshold is experimented for smaller triangle sizes. This is an important result that may be used as a guide for the design of a watermarking scheme that result in a haptically imperceptible degradation of the host object. At the same time, the standard deviation of the thresholds resulting from the single experiments is rather large, thus pointing out the need for more extensive tests, involving more subjects and, possibly, more repetition of the same test by the same subject.

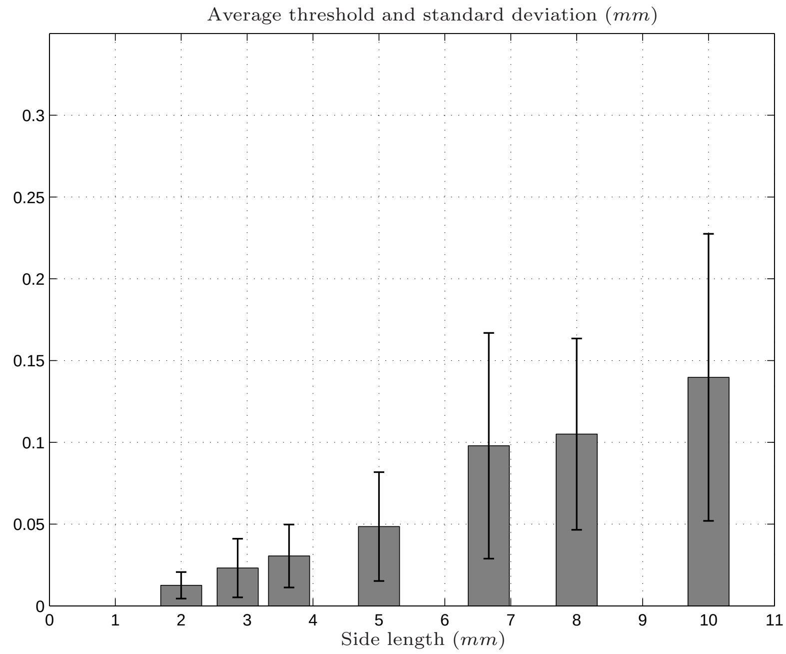

Figure 4. Average thresholds (Δ_t) over triangle side length (mm) for the haptic experiment.

5. EXPERIMENT II: EVALUATING VISUAL PERCEPTIBILITY

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+). Even in this case 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†. 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 display 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 5). As to the lighting conditions, graphic rendering was performed by using Gouraud shading[18] . We chose a grey background and a basic diffuse lighting with one white point-light source displaced as shown in the bottom of Figure 5, 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 in a dark room, thus avoiding possible influences of external lights. An example of the visual appearance of a watermarked plane is given in Figure 6.

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 experiments were repeated for different resolution of the mesh and carried out by 5 users. The resulting, single-user thresholds were averaged yielding the results depicted in Figure 7, 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. Even in this case, relatively large standard deviations are observed thus confirming the need for more extensive tests.

†We used DirectX Libraries to perform the graphic rendering.

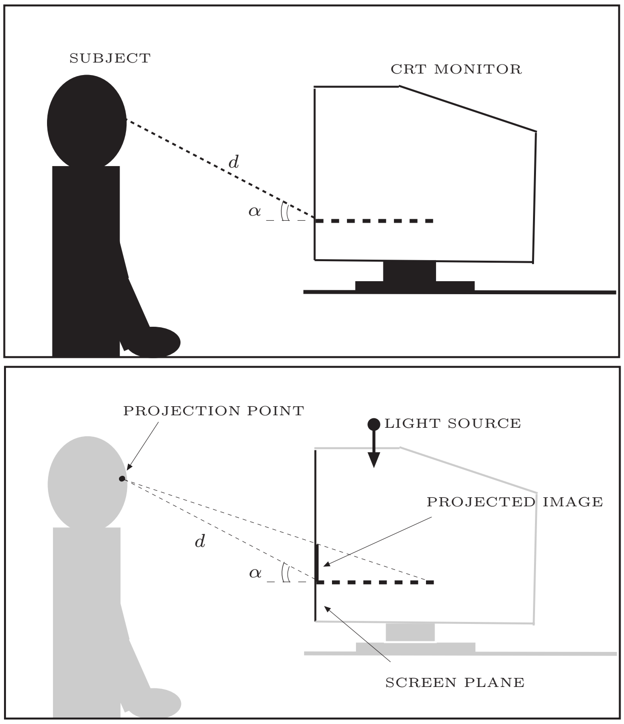

Figure 5. Geometrical set up for the visual stimuli. Top: user's displacement w.r.t. monitor. Bottom: rendering conditions.

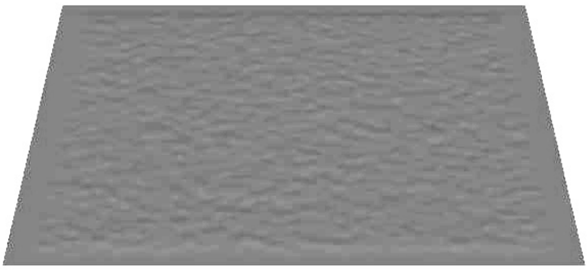

Figure 6. Example of a watermarked plane used for the visual part of the experiment. The visibility of the watermark has been exaggerated to improve the readability of the figure.

6. IS HAPTIC WATERMARKING WORTH IT ?

The basic question we were trying to answer with our experiments is 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 seems to be yes. By comparing the diagrams plotted in Figures 4 and 7, it is evident that the haptic channel is at least as sensitive as (indeed more sensitive than) the visual channel, hence making haptic imperceptibility an additional requirement to be satisfied in addition to invisibility[‡]. Of course, the experiments described in this

[‡]At least when chances there are that the 3D objects will be sensed through a haptic interface.

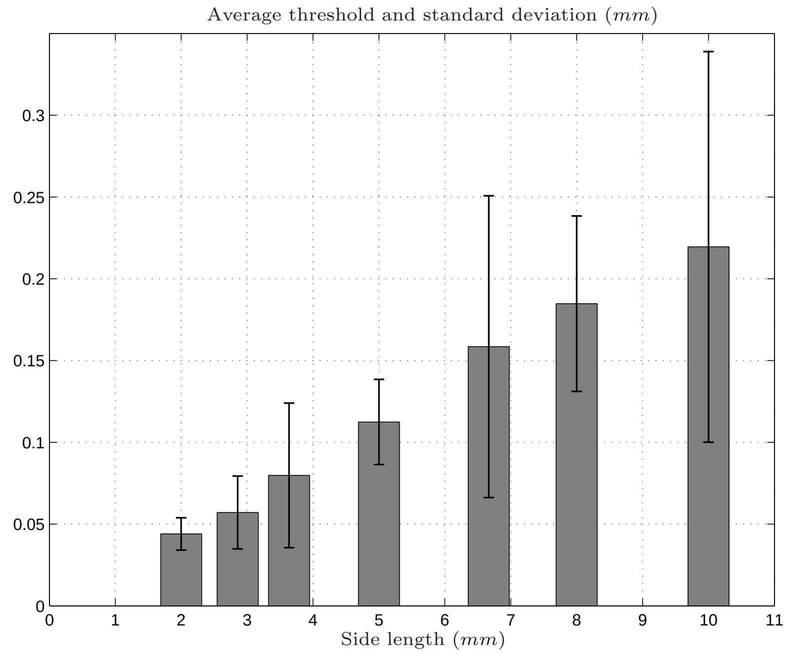

Figure 7. Average thresholds (Δ_t) over triangle side length (mm) for the visual experiment.

paper, and the corresponding results, must be considered as preliminary for many reasons including:

- More extensive tests are needed for a more accurate evaluation of the detection thresholds as it is witnessed by the rather large standard deviations of the data we collected;
- A more precise characterization of the haptic device is needed: specifically the dynamic interaction between the user actions and the forces applied by the engine the haptic interface relies on must be studied;
- The graphic rendering conditions we adopted, though rather standard, are arbitrary. Many different rendering conditions may exist for which the visual channel is more acute than the haptic one. A non-exhaustive list includes: lighting conditions, geometric position of the plane, shading algorithm, surface color, surface material.
- Different watermarking algorithms should be tested, the popular additive noise model used in our experiments being surely too narrow to represent the huge variety of algorithms available in the literature;
- Different choice of the host model should be considered. How would our results change if the marked model was a sphere or a more complicated object instead of a flat surface ?

The list of issues we did not consider and the arbitrary choices we made is so large that one may wonder whether the experiments we carried out maintain some of their meaning. We definitely think so. Given that we find 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 and neglected items 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 not difficult to foresee that coupling the capabilities of both vision and touch will result in lower detection thresholds hence making the challenge for watermark designers harder.

Acknowledgments

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