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Perceptibility of Digital Watermarks Embedded in 3D Meshes using Unimodal and Bimodal Hapto-Visual Interaction

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Abstract *– In this paper, a study is conducted in order to measure and analyze the perceptibility of watermarks embedded in 3D meshes when (1) visual feedback is present, (2) haptic feedback is present, and (3) visual and haptic feedback are simultaneously available. More specifically, our experiments are intended to assess whether the use of a bimodal approach, where a subject is looking at, and touching a 3D mesh could in fact improve the perceptibility of a watermark as opposed to when only a single modality is available. The experiments are performed using a hapto-visual interface which integrates a haptic device with stereo graphics for an immersive high quality 3D experience. Overall, the results suggested that relying on bimodal hapto-visual feedback is better than any of the single modalities when detecting a watermark embedded in a 3D model. Further experiments with a greater number of subjects would however be necessary to better confirm this conclusion.*

Keywords *– haptics, vision, watermarking, bimodal, hapto-visual.*

I. INTRODUCTION

The increased processing capabilities of today's modern computers has contributed to the widespread use of 3D models in several fields, such as in entertainment (video games, movies), the medical industry (3D visualization of medical data, education and training) and the Internet (3D virtual worlds, e-commerce). In turn, the protection of 3D models from theft or tampering has received much attention in the literature. An effective measure that overcomes the limitations of traditional encryption is digital watermarking; a research field which deals with the process of embedding information into digital data in an inconspicuous manner to identify the origin, owner, use, rights, integrity, or destinations of multimedia content (e.g. digital images, video, audio and 3D models). Recently, considerable progress has been made in 3D watermarking, where the main focus has been on triangle meshes which consist of the most common digital representation of 3D models. The fundamental requirement of digital watermarking techniques regardless of the addressed media or application is imperceptibility. Imperceptibility refers to the invisible degradation of the digital data when watermarked. Ideally, the perceptual quality of the watermarked media must be identical to the original. The evaluation of 3D watermarking algorithms against the imperceptibility constraint has been thus far exclusively based on the sensitivity of human vision to distortion. Moreover, currently available perceptual metrics generally used to assess the quality of watermarked 3D meshes [1, 2], have been validated solely through psycho-visual experiments. However, in recent years, the integration of haptics into immersive virtual environments to enable sensing and manipulation of virtual 3D objects through touch, has become increasingly popular due to its many potential applications including medical training, physical rehabilitation and entertainment. In consequence, the recent advancements of haptic technology have raised an important question in the 3D watermarking research community: Does touching while looking at a watermarked 3D model improve the perceptibility of the embedded mark as opposed to when only performing a visual assessment? Despite its importance, only one other research group has investigated watermarking of haptic-enabled 3D models. In [3], a haptic watermarking technique is introduced where the watermark is embedded into a host surface texture signal. They demonstrate how a haptically imperceptible sinusoidal watermark that is superimposed onto a sinusoidal host signal can be detected by means of a spectral analysis. In [3, 4], psychophysical experiments are conducted in order to measure the perceptibility of a watermark embedded in a 3D virtual object. The watermark perceptibility is inspected through a visual or a haptic interface, i.e. the user can only see or feel the virtual object. Experiments in which the subject can inspect the watermark perceptibility while simultaneously looking at and touching the virtual surface were never demonstrated.

In this paper, our aim is to measure and analyze the perceptibility of a watermarked 3D surface when, (1) only the sense of vision is available, (2) only the sense of touch is available, and (3) the sense of vision and touch are simultaneously present. The experiments are performed using a hapto-visual interface that enables users to see and touch virtual objects at

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the same location in space. This approach enables a superior integration of vision and touch than a conventional 2D screen-based display. Hence, user interactions are more natural, and in turn providing the ideal environment for high precision hapto-visual experiments. Moreover, the advantages of the use of a hapto-visual interface stem from the fact that human perception is multimodal, i.e. the senses of touch and vision do not operate independently, but are in fact closely coupled. The hapto-visual device used in the undertaken experiments is the Reachin Display [5], which integrates a haptic device with stereo graphics for an immersive and high quality 3D experience.

The rest of the paper is organized as follows. In Section II, the materials and methods of the conducted experiments are described in detail. In Section III, the experimental results are illustrated. In Section IV, a discussion of the obtained experimental results is presented. Finally, conclusive remarks are outlined in Section V.

II. MATERIALS AND METHODS

As previously mentioned, the objective of the undertaken experiments is to measure the perceptibility of a watermark embedded in a 3D mesh while looking at, touching, or simultaneously looking at and touching the virtual surface. In order to simplify the analysis of the experiments, the virtual object is selected as in [3] and it consists of a flat plane surface represented using a triangle mesh. All three experiments, the visual, haptic, and hapto-visual, are conducted using the aforementioned Reachin Display system. The haptic stimulus is sensed using the SensAble PHANTOM Desktop force-feedback device, which is equipped with an encoder stylus that provides 6-degree-of-freedom single contact point interaction and positional sensing.

A. Subjects

Altogether, 6 participants (6 males, aged 23-28) 5 right handed and 1 left handed with no known sensorimotor impairments with their hands took part in the experiments. Their prior experience with PHANTOM haptic devices ranged from novice to expert.

B. Haptic Watermark Embedding and Detection

The watermark is embedded in the haptic-enabled virtual surface by perturbing the coordinates of the mesh vertices. This is achieved using the following method:

$$H_w(i) = H(i) + \beta \cdot w(i) \cdot n(i), \qquad (1)$$

where

$$H(i) = [\, x \quad y \quad z \,]^T \;\; and, \;\; n(i) = [\, 0 \quad 0 \quad 1 \,]^T.$$

More precisely, $H(i)$ corresponds to the i'th vertex of the host plane, whereas $H_w(i)$ denotes the i'th vertex of the watermarked plane. $w(i)$ is an independent and identically distributed watermark embedded along the surface normal $n(i)$, and consists of random numbers that follow a Gaussian distribution with zero mean and unit variance. Finally, β is a parameter that controls the watermark embedding strength. Conversely, the watermark detection is performed by (1) looking at the plane, (2) touching the plane, and (3) looking at, and touching the plane.

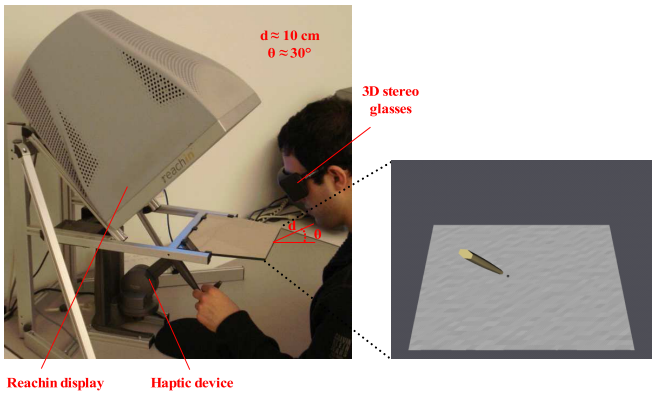


Fig. 1. The participant's position and orientation with respect to the Reachin Display (left), as well as an example of the (watermarked) haptic-enabled virtual environment presented to the user (right).

C. Conditions

There were three experimental conditions in our analysis which depended on the type of sensory feedback presented to each participant during each experiment. The following sensory conditions were used for our study:

(1) only visual feedback
(2) only haptic feedback
(3) visual and haptic feedback

Under all three conditions, for the sake of consistency, the participants were requested to sit comfortably in front of the Reachin Display at a distance $d \approx 10\ cm$ and an orientation

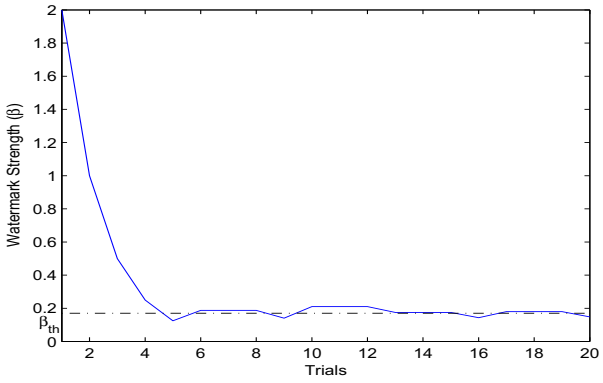
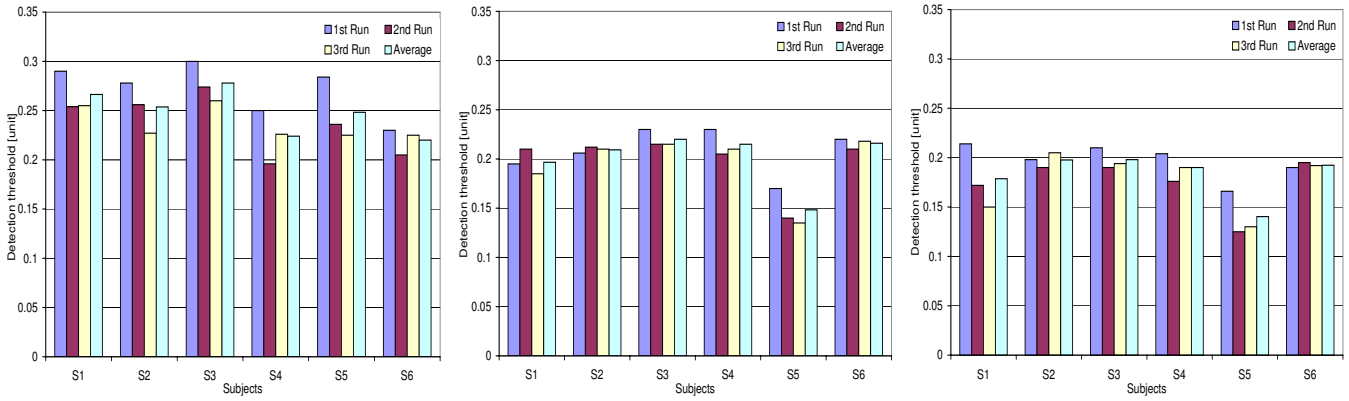


Fig. 2. A typical experimental staircase procedure for one run. The dashed line represents the resulting detection threshold (β_{th}).



(a) (b) (c)

Fig. 3. Results obtained in experiments I, II, and III, where (a) visual feedback, (b) haptic feedback and (c) visual and haptic feedback, were provided. The surface used in these cases is a low resolution rectangular mesh of size $24\ cm \times 18\ cm$ represented using 672 triangles.

$\theta \approx 30^\circ$ from the device's half-mirror (used to display a virtual environment in the haptic workspace) as it is depicted in Fig. 1 (left). An example of the virtual environment presented to the user during a hapto-visual experiment is shown in Fig. 1 (right). It encompasses a (clearly watermarked) virtual plane and the virtual stylus used to interact with the surface mesh. Moreover, the color of the surface used in the experiments is in fact blue. A light-gray color is used in Fig. 1 (right) for better quality black and white printouts of the paper. Furthermore, the experiments were conducted in a dark room in order to avoid any effects of ambient lighting.

D. Procedure

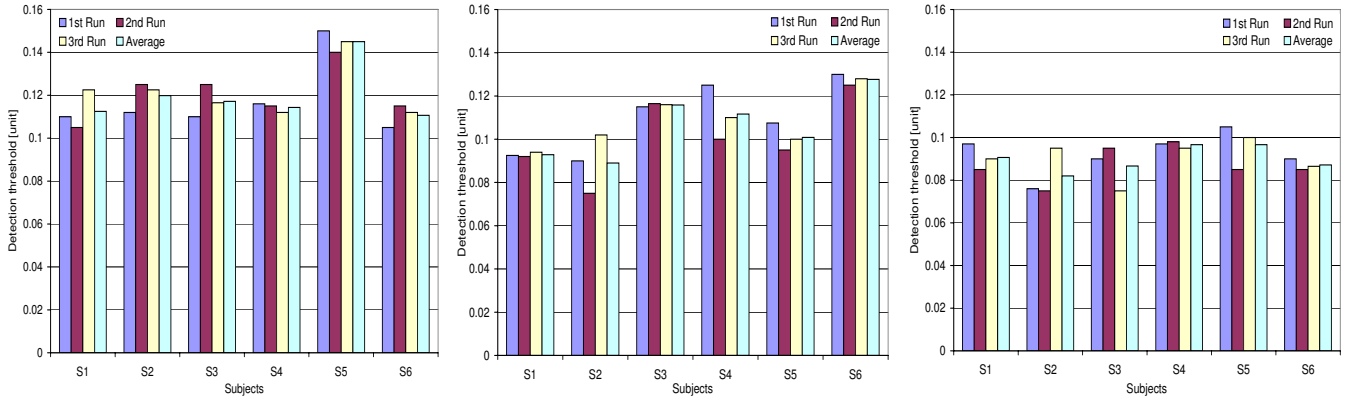
The watermark detection thresholds for each subject, and for the three experiments, were determined using the 2-interval forced choice (2IFC) paradigm along with the adaptive staircase (AS) method [6]. In each trial, subjects viewed two stimuli in subsequent intervals and in random order. One of the stimuli was the host plane, the other was the watermarked plane. The subjects' task was to report which of the two stimuli contained the watermark. In order to determine the detection threshold β_{th}, a "lead-in" 1-up 1-down AS rule was initially used to speed up the approach to the β region of interest. During this phase, β was halved after each correct response, until the first error occurred. The staircase then followed a 1-up 3-down rule (β is only decreased after three consecutive correct answers, and raised again following a single wrong answer). In this second phase, β was increased or decreased by multiplying it by a factor $k = 1.5$ or 0.75 respectively. After three reversals are obtained, a third phase is initiated (also follows the 1-up 3-down AS method) where β is increased or decreased by multiplying it by a factor $k = 1.25$ or 0.825 respectively. Trials continued until a total of three reversals were obtained in the third phase of the staircase. The detection threshold β_{th} is computed while taking the average over the last phase of reversals. As an example, a plot of one of our experiments using the adaptive staircase procedure is presented in Fig. 2.

III. RESULTS

In this section, the average detection thresholds resulting from each of the three experiments, (i.e. visual, haptic, and hapto-visual perceptibility of the watermark) and for every participant are presented. The plane mesh displayed in our experiments was a rectangular surface of size $24\ cm \times 18\ cm$. For each of the three experiments the participants were presented with a lower and a higher resolution version of the virtual surface where the former is represented using 672 triangles, whereas the latter is constituted of 2048 triangles. Furthermore, haptic rendering (i.e. the synthetically generated haptic stimuli) is performed via the common virtual proxy method [7]. Moreover, for each participant, the three experiments were collectively performed while using the following order: (1) visual feedback (first run), (2) visual-haptic feedback (first run), (3) haptic feedback (first run), (4) visual feedback (second and third runs), (5) visual-haptic feedback (second and third runs), (6) haptic feedback (second and third runs). This order is initially followed for the lower resolution surface and subsequently repeated for the higher resolution mesh. Effort was made to make sure that subjects be well rested prior to the experiments, as lack of rest could impact the subject's sense of vision and touch, as well as their ability to focus.

A. Experiment I : Visual Perceptibility

In this experiment, the participants were requested to detect the watermarked plane while relying solely on visual feedback. Three runs of the experiment were conducted for each of the two available resolutions of the surface, and the corresponding detection thresholds were obtained using the aforementioned adaptive staircase technique. The average of the



(a) (b) (c)

Fig. 4. Results obtained in experiments I, II, and III, where (a) visual feedback, (b) haptic feedback and (c) visual and haptic feedback, were provided. The surface used in these cases is a high resolution rectangular mesh of size 24 $cm \times 18$ cm represented using 2048 triangles.

resulting detection thresholds for the lower and the higher resolution meshes were subsequently computed as it is illustrated in Fig. 3 (a) and Fig. 4 (a) respectively.

B. Experiment II : Haptic Perceptibility

In the second experiment, the participants were requested to detect the watermarked plane while relying solely on haptic feedback. Three runs of the experiment were carried out for each of the two available resolutions of the surface, and the corresponding detection thresholds were obtained using the adaptive staircase technique. The average of the resulting detection thresholds for the lower and the higher resolution meshes were subsequently computed as it is illustrated in Fig. 3 (b) and Fig. 4 (b) respectively.

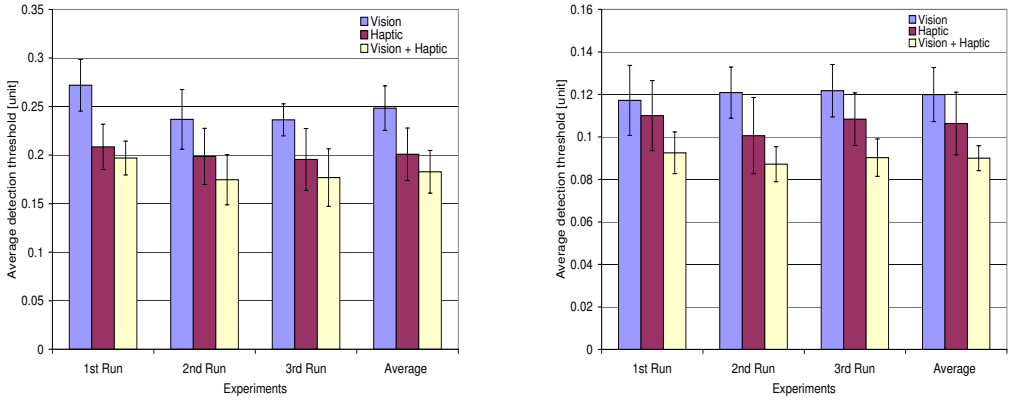
C. Experiment III : Visual and Haptic Perceptibility

As for the hapto-visual case, the participants were requested to detect the watermarked plane while relying on both, visual and haptic feedback. Similarly to the first two experiments, three runs of the experiment were performed for each of the two available resolutions of the surface, and the corresponding detection thresholds were obtained using the adaptive staircase method. The average of the resulting detection thresholds for the lower and the higher resolution meshes were then computed as it is illustrated in Fig. 3 (c) and Fig. 4 (c) respectively.

IV. DISCUSSION OF THE RESULTS

In order to better visualize and analyze the results considering that the obtained detection thresholds across the different modalities are fairly similar, the threshold values of all the participants, for each run of every experiment were averaged and plotted for the lower and the higher resolution meshes as shown in Fig. 5 (a) and Fig. 5 (b) respectively. Several observations can be made from the results presented in figures 3, 4 and 5. First, for all 6 subjects, the average detection thresholds obtained in the haptic-alone experiment, are for the most part below the detection thresholds determined when the participants relied solely on visual feedback. This suggests that the watermark can be more easily detected when touching a surface mesh as opposed to performing a visual assessment. This finding is in agreement with the results already obtained in [4], where the perceptibility of a watermark embedded in a 3D mesh is also inspected, using vision-alone and haptic-alone (bimodal hapto-visual experiments were not conducted). However, in [4], the results illustrated that the average detection thresholds of the haptic-only experiments are in most cases less than half the threshold values obtained with vision-only. Conversely, in the results presented here, it can be observed from Fig. 5 that the average detection threshold values of the haptic-only conditions are only approximately 20% less than the threshold values obtained with vision-only. This variation in the results is possibly due to several reasons. First, in [4], a fewer number of participants took part in the experiments and a smaller number of runs per experiment were performed. These factors can evidently lead to less precise results. Moreover, the haptic-only experiments performed in [4] make use of the same high-precision haptic device used in the experimental setup exploited in this paper. However, their vision-only experiments were performed using a primitive computer display (CRT monitor). Conversely, the experimental setup presented here relies on stereo graphics for an immersive and high quality 3D experience, which in turn enabled us to perform high precision vision-based experiments. Thus, the large margin between the detection threshold values of the haptic-only and vision-only experiments presented in [4] is probably also due to the considerable difference in quality between their haptic and visual displays.

Another observation that can be deduced from the results illustrated in Fig. 5, is that the detectability of the watermark



(a) (b)

Fig. 5. Average detection threshold values of all the participants, for each run of every experiment and the corresponding standard deviations. The results for the low resolution and the high resolution meshes are presented in (a) and (b) respectively.

increases with the resolution of the surface mesh. This finding is also in agreement with the results already obtained in [4]. Moreover, from Fig. 5, it is shown that the between-subject variability (the standard deviations) of the detection thresholds for both experiments and the two presented resolutions is quite high. Conversely, from Fig. 3 and Fig. 4 it can be seen that the within-subject variability is relatively low, suggesting that our experimental procedure and setup are accurate. The large between-subject variability however, is probably due to the fact that when performing a perceptual judgment, participants exploit in different manner the information available through their distinct sensory channels. In addition, it is known that PHANTOM haptic devices induce low, but perceivable backdrive friction which can negatively affect a user's haptic perception [8]. In turn, during the haptic and hapto-visual experiments, it is believed that certain observers were not able to isolate the backdrive distortion as well as others when attempting to feel the barely noticeable watermark. This could also have contributed to the relatively large between-subject variability of the results.

Furthermore, in the bimodal case, it seems that hapto-visual feedback is better than any of the single modalities when detecting a watermark embedded in a 3D mesh. This can be best observed from the results depicted in Fig. 5, where the lowest detection threshold values were obtained in the hapto-visual conditions. This finding suggests that the addition of a second modality provides information, some maybe redundant and some non-redundant, that improve the detectability of watermarks embedded in 3D models.

V. CONCLUSION

Haptic watermarking is a brand new research challenge that is expected to significantly expand the field of 3D digital watermarking in the very near future. In this paper, we presented an experimental study to investigate the effectiveness of multisensory feedback in the perception of a watermark embedded in a 3D mesh. The obtained results suggested that the lowest detection threshold values were obtained when vision and haptic feedback were simultaneously available, as compared to either modality alone. In other words, the participants were able to integrate the input from the two modalities in such a manner to produce a percept that is better than that provided by either single modalities. This finding is expected to stimulate the reevaluation of existing mesh watermarking algorithms (using a hapto-visual setup), and will serve as a basis for further studies in bimodal hapto-visual watermarking.

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