A MULTI-SCALE ROUGHNESS METRIC FOR 3D WATERMARKING QUALITY ASSESSEMENT

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ABSTRACT

In this paper an objective metric to measure the perceptual quality of watermarked 3D meshes is presented. The metric relies on a multiscale measurement of the roughness of 3D meshes before and after the watermark insertion. The validity of the proposed metric has been tested against a number of different 3D watermarking algorithms, showing an excellent match with the subjective evaluation of the quality derived from pshycovisual experiments.

1. INTRODUCTION

Watermarking of 3D objects is a relatively recent field of research which has not reached the same level of maturity when compared to techniques applied to still image and video. Similar to other watermarking techniques, *imperceptibility* constraint is also very important for 3D objects watermarking. Study of human perception of geometric defects on 3D surfaces due to 3D watermarking can help in design of efficient watermarking schemes. In this work, we propose a new perceptual metric to assess the visual quality of watermarked 3D objects. This metric is based on the estimation of roughness of the surface of the watermarked 3D objects. To validate our proposed metric, a subjective evaluation methodology to assess distortions due to various processings of 3D objects was designed.

The paper is organized as follows. The next section is devoted to a discussion on related work in this area. Section 3 outlines the approach we use to design quality metrics for watermarked 3D objects. Section 4 discusses the protocol designed for subjective evaluation. Section 5 outlines the subjective experiments carried out. Section 6 proposes the objective metric developed to assess the quality of watermarked 3D objects. Section 7 presents experimental results and validates the proposed metric. Finally, Sec. 8 draws some conclusions.

2. RELATED WORK

Perceptual considerations have been used in Computer Graphics for various operations such as *mesh simplification* and *perceptually-guided rendering*. *Mesh simplification* aims at reducing the number of vertices of a polygonal mesh model while preserving as much as possible its visual appearance. In general, the simplification process is driven by a similarity metric that measures the impact of the changes of the model after each simplification step. Hausdorff distance is often used as a metric to evaluate the distortions due to mesh simplification. Two tools for geometric mesh comparison have been proposed in Metro [1] and Mesh [2]. The Hausdorff distance to compare the distortions due to 3D processing is similar to euclidean distance such as Mean Squared Error (MSE) in the case of still images. Therefore, it suffers from the same weaknesses in terms of correlation with a subjective perception of distortions. In Section 7, the performance of our proposed metric will be compared to two variants of Hausdorff distance, namely *Maximum Geometric Error* and *Mean Geometric Error*.

Another alternative to assess distortions due to mesh simplification is to employ a distance in the space of rendered images. Lindstrom and Turk [3] proposed an image-driven approach for guiding the simplification process: the model to be simplified is rendered by considering several viewpoints and an image quality metric, based on a simplified version of the Sarnoff Model, is used to evaluate the perceptual impact of the simplification operation. More recently, Luebke *et al*. [4] developed a view-dependent simplification algorithm based on a simple model of Contrast Sensitivity Function (CSF) that takes into account texture and lighting effects.

The aim of *perceptually-guided rendering* is to accelerate photo-realistic rendering algorithms by avoiding unnecessary computations that do not bring any perceptually significant improvements on the final result. Some prior works in this field include those of Bolin and Meyer [5] who used a simplified Sarnoff Visual Discrimination Model to speed-up rendering techniques based on sampling. Myszkowski *et al*. [6] incorporated a spatio-temporal sensitivity factor in a variant of Daly Visual Difference Predictor to create a perceptually driven animation quality metric, in accelerating the generation of animation sequences. Ferwarda *et al*. [7] proposed a sophisticated perceptual metric based on the masking effect of a visual pattern, (e.g. a texture) on geometry distortions. In our approach, we do not account for visual masking, leaving that as an important and interesting area for future research.

3. PROPOSED APPROACH

A possible approach to evaluate the visual quality of watermarked 3D objects could be to simply apply an image-based perceptual evaluation metric to the final rendered images. The main problem of this approach is that the perceived degradation of still images may not be adequate to evaluate the perceived degradation of the equivalent 3D model [8]. Our approach consists in evaluating perceived geometric distortions directly on the model's surface by designing a 3D metric. To achieve this, in a first stage, a series of adequate subjective experiments should be carried out to assess and to quantify the characteristics of perceptible distortions which are generated by 3D watermarking operations. Then, mathematical operators capable of quantifying the most important characteristics must be designed. These operators will be used in the definition of the objective metric through an adequate formula, taking into account the relevance of each characteristic. Finally, additional subjective tests will be needed in order to validate the degree of accuracy of the objective metric when compared to a subjective assessment.

4. SUBJECTIVE EVALUATION PROTOCOL

A set of standards and scoring techniques to evaluate quality of video and multimedia content have been defined by ITU-R [9] and ITU-T [17]. However, there are no prescribed standards for the evaluation of impairments in 3D objects. In this paper, we propose a subjective evaluation protocol to assess perceptual distortions due to various processings on 3D objects. We will then use this protocol in the subjective experiments mentioned in Section 3.

Eleven test subjects (one female and ten males) aged between 24 and 30 years old were selected from a pool of students. The 3D models were displayed on a 17-inch LCD monitor, with participants sitting approximately 0.4 meters from the display. The experiment followed the five-stage procedure similar to that proposed in [10]. The stages included: (1) oral instructions, (2) training, (3) practice trials, (4) experimental trials, (5) interview. During the first stage, the subjects were verbally given instructions and were made familiar with the task and the graphic interface. During the training stage, the original models and the watermarked models were shown to establish a range for the impairment scale. The practice trials stage was used to familiarize subjects with the experimentation and to stabilize the subjects' responses. In the experimental trials stage, the subjects were asked to give a score indicating the degree of distortions. Each subject was instructed to enter a numerical value greater than 0 proportional to the perceived distortion. The value of 10 was to be assigned to the strongest distortion in the sample models representing the worst cases shown during the training phase. Finally, in the interview stage, the test subjects were asked for a qualitative description of the perceived defects.

The approach used for rendering and its related parameters have a great impact on the subjective experiments results and therefore must be carefully selected. The rendering conditions should not bias the human perception of the 3D model by privileging, for example, one view of the 3D object rather than another one. To facilitate the repeatability of subjective experiments, as simple as possible rendering conditions were selected. The following list summarizes the rendering conditions used in our subjective experiments.

- *Light source*. All models are illuminated with one white point light source since multiple lights can confuse the observer.
- *Lighting*. A simple local illumination lighting model was used where only the diffusive component of the reflected light is considered to avoid the dependence on the camera's position.
- *Texturing*. Image texture mapping, bump mapping, and other kinds of texturing may mask 3D distortions [7] therefore they were not included in the model.
- *Material properties*. The color of a surface is determined by the parameters of the light source that illuminates the surface, by the lighting model used and by the properties of the surface's material. To render naturally looking 3D objects, a gray color (*granite-like*) was chosen.
- *Screen and models resolution*. The monitor resolution used in the experiments was 1280×600 and each model was displayed in a window of 600×600 pixels. The model occupied around 80% of the display window and the resolution of all models ranged between 50'000 and 100'000 triangles allowing for a a good visualization of the model details.
- *Interaction*. In our subjective evaluation protocol, subjects were allowed to interact with models by rotation and zoom operations. This interaction will avoid false evaluation of distortions that are view-dependent and do not correlate well with the real perception of the 3D object [8].

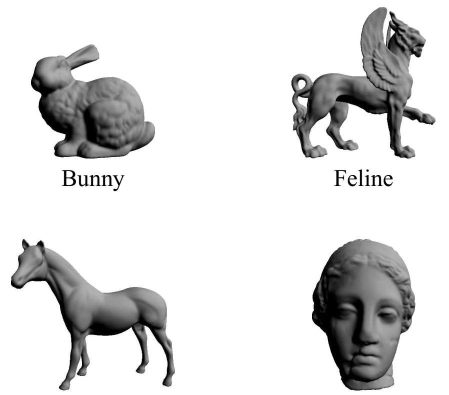

Fig. 1. Original models used for stimuli generations.

5. SUBJECTIVE EXPERIMENTS FOR 3D WATERMARKING DISTORTION EVALUATION

Two subjective experiments with different purposes were proposed. The first experiment (Experiment I), was carried out to investigate the perception of artifacts caused by a single watermarking algorithm on 3D models and to find a suitable metric to measure perceived distortions. Subsequently, a metric based on roughness estimation of the model's surface was designed to measure the amount of visual distortions introduced by the 3D watermarking. Another experiment (Experiment II) was conducted in order to validate the proposed metric with various watermarking algorithms.

The test models used for both experiments were generated by applying the watermarking algorithm to four models depicted in Fig. 1: *"Bunny"*, *"Horse"*, *"Venus"* and *"Feline"*. In Experiment I, test subjects evaluated various 3D watermarked models, ranging from severely down to weakly impaired. The distortions were generated using a specific watermarking algorithm, namely that of Uccheddu *et al.* (UCB) [11]. The amount of distortions introduced by the watermarking varied according to two parameters *i)* the resolution level that hosts the watermark and *ii)* the coefficient determining the strength of the watermark. A total of 40 (4 originals $\times$ 3 watermarking strength $\times$ 3 resolution level + 4 originals) models were used in Experiment I.

In Experiment II, three other different watermarking algorithms were implemented and applied to 3D models to confirm the results obtained from Experiment I. These algorithms were: the Vertex

Flood Algorithm (VFA) [12], the Normal Bin Encoding (NBE) [13], and the method of Kanai *et al.* (KDK) [14]. The objective of this experiment was to validate the objective metric obtained from Experiment I. Each watermarking algorithm exhibited its own characteristic distortions. The UCB algorithm produces a uniform noise that can be described as an increase of the roughness of the watermarked surface. VFA produces a noise similar to marble streak, depending on the viewpoint. The artifacts of the KDK algorithm are similar to those of UCB algorithm. However, due to the geometric tolerance introduced by Kanai to limit the visual impact of the watermarking, the final visual effect of such distortions is not uniformly distributed over the model's surface. Concerning NBE, the visual aspect (crack-like) of its artifacts is different from those in UCB, VFA and KDK and therefore more difficult to perceive. A total of 48 (4 models $\times$ 11 watermarking settings + 4 originals) test models were used in Experiment II.

6. PROPOSED OBJECTIVE METRIC

Experiment I indicated that a good measure of the visual artifacts produced by watermarking should be based on the amount of roughness introduced on the surface. This is in agreement with a similar observation in [15]. In the following, a detailed description of the proposed *multi-scale roughness estimation metric* is provided.

The proposed roughness measure is a variant of the method in [16]. This metric measures the per-face roughness by making statistical considerations about the dihedral angles associated to each face. We indicate with $\mathcal{R}(T)$ the per-face roughness computed with this method.

A rough surface can be considered as a surface with a high concentration of 'bumps' of different sizes. The metric proposed in [16] is able to measure adequately 'bumpiness' of a surface with granularity similar to the size of each face. However, if the granularity of the surface roughness, i.e. the size of the bumps, is larger than the dimension of a single face, this metric fails to correctly measure it. In other words, this measure does not take into account the *scale* of the roughness. For this reason, a modified version of the metric in [16] is proposed to take into account different roughness scales.

The first step to achieve this goal is to transform the per-face roughness estimation to a per-vertex roughness estimation, $R^N(v)$, in the following way:

$$\mathcal{R}^N(v) = \frac{1}{|S_T^N|} \sum_{i \in S_T^N} \mathcal{R}(T_i)\mathcal{A}_{T_i} \qquad (1)$$

where S_T^N is the set of the faces of the *N-ring*[1] of the vertex v, $|.|$ is the cardinality operator and $\mathcal{A}_{T_i}$ is the area of the face T_i.

Considering the N-ring in the calculation of roughness accounts for different roughness scale. In Fig. 2, the bump of size equivalent to the 1-ring (A) is well measured by $\mathcal{R}^1(v)$, while a more accurate value of roughness for the vertex v in case (B) is provided by $\mathcal{R}^2(v)$. In our objective metric, three scales of roughness (1,2,4) were chosen, based on empirical observations.

$$\mathcal{R}(v) = \max\{\mathcal{R}^1(v), \mathcal{R}^2(v), \mathcal{R}^4(v)\} \qquad (2)$$

[1]The N-ring neighborhood vertices of a vertex v is an extension of the 1-ring neighborhood. A 2-ring neighborhood is created from the 1-ring by adding all of the vertices of any face containing at least one vertex of the 1-ring. Additional rings can be added in the same way to form the 3-ring, the 4-ring and so on.

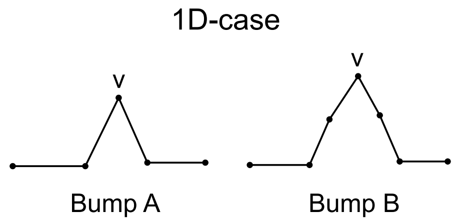

Fig. 2. Bumps with different scale.

The total roughness of the 3D model, M, is the sum of the roughness of all vertices:

$$\mathcal{R}(M) = \sum_{i=1}^{N_v} \mathcal{R}(v_i) \qquad (3)$$

where N_v is the total number of mesh vertices. On the basis of several evaluations we decided to define our objective metric as the increment of roughness between the original and the watermarked model. This increment is normalized with respect to the roughness of the original model, resulting in:

$$\mathcal{R}(M, M^w) = \log\left(\frac{\mathcal{R}(M) - \mathcal{R}(M^w)}{\mathcal{R}(M)} + k\right) - \log(k) \qquad (4)$$

where $\mathcal{R}(M)$ is the total roughness of the original model and $\mathcal{R}(M^w)$ is the total roughness of the watermarked model. The logarithm is employed to better discriminate low values of relative roughness increments. The constant k is used to avoid numerical instabilities and to normalize the metric values between 0 and 10 (that is the same range of values given by the test subjects). Equation 4 was retained as the basis to derive a subjective metric assessing distortions due to 3D watermarking. The subjective data of Experiment I were used to obtain the proposed objective metric $\mathcal{R}^*(M, M^w)$ from Eq. 4 by fitting it with a *Gaussian psychometric function*:

$$\mathcal{R}^*(M, M^w) = g(a, b, \mathcal{R}(M, M^w)) = \frac{1}{2\pi}\int_{a+b\cdot\mathcal{R}}^{\infty} e^{-\frac{t^2}{2}}\,dt$$

where a and b are the parameters to be estimated by fitting the objective metric values versus the subjective data. To estimate such parameters a nonlinear least-squares data fitting by the Gauss-Newton method was used.

The parameters of the Gaussian psychometric curve for the fitting in Experiment I were estimated as: $a = 1.9428, b = -0.2571$ and the same parameters were used to fit the data of Experiment II and to validate the metric.

7. EXPERIMENTAL RESULTS AND VALIDATION

Standard methods have been used to normalize and to screen the judgments provided by the test subjects [17]. From the data gathered the Mean Opinion Score (MOS) of each model was calculated. In order to validate our proposed objective metric, Experiment II was carried out with three other watermarking algorithms (KDK, NBE and VFA). The validation was carried out as follows. The perceptual metric obtained in Experiment I was used to predict the MOS obtained in Experiment II and the correlation coefficient between the subjective MOS and the objective metric was computed. The Spearman correlation coefficient, r_S was used and is reported in Table 1. The rows in the table indicate the watermarking algorithms used. The first two columns of this table also report r_S of the Maximum and Mean Hausdorff distances for comparison purposes. The third column shows the values of r_S for $\mathcal{R}^*(M, M^{\mathbf{w}})$. From this table, it can be noticed that overall, the proposed objective metric outperforms those based on Hausdorff distance in terms of correlation with subjective data. In particular, r_S for NBE and VFA algorithms (third and fourth rows respectively) indicate the ability of the proposed metric to predict impairments introduced by different watermarking algorithms. A deeper examination of Table 1 shows that the proposed metric does not perform as well for distortions generated by the KDK algorithm. This can be due to the fact that distortions produced by this algorithm are *non-uniform*. The fifth row shows the performance of the proposed metric for *uniform* distortions introduced by NBE and VFA algorithms. The overall performance of the metric remains competitive also when both the *uniform* and *non-uniform* distortions are considered (last row of the table).

	Hausdorff Distance		$\mathcal{R}^*(M, M^{\mathbf{w}})$
Algorithms	**Max (r_S)**	**Mean (r_S)**	r_S
UCB	0.6672	0.6595	**0.8680**
KDK	0.6904	0.3230	**0.7171**
NBE	0.7087	0.7026	**0.7917**
VFA	0.4951	0.8815	**0.9389**
NBE+VFA	0.3991	0.6945	**0.7942**
KDK+NBE+VFA	0.3759	0.4853	**0.7062**

Table 1. Metric performance in terms of Spearman correlation, r_S, with subjective MOS.

8. CONCLUSIONS

In this paper, an original study of evaluation metric for assessment of watermarking distortions of 3D models was presented. In particular, an experimental methodology for subjective quality assessment of watermarked 3D objects has been proposed. The analysis of the data collected by two subjective experiments that used this methodology demonstrate that it is well-designed and provides reliable subjective data. An objective metric for 3D watermarking impairment prediction has been developed by making use of a multi-scale roughness estimation. The results obtained by this metric demonstrate its superiority to predict perceptual distortions due to 3D watermarking when compared to other state of the art metrics.

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