A Visually-Enhanced Approach to Watermarking 3D Models

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***Abstract*—The recent increasing demand for 3D digital contents has motivated us to develop techniques for watermarking 3D models so that we can hide copyright information behind them. However, existing methods rather focused on the robustness against possible attacks to destroy the embedded watermarks, and have not fully taken care of the associated influence on the visual quality of the target 3D models. In this paper, we present a new approach to watermarking 3D models based on the visual saliency associated with their shapes. Our algorithm begins by segmenting the perceptually conspicuous regions over the given 3D triangular mesh using surface curvatures, and then selectively embeds the watermark to the regions by statistically modulating the distance between each mesh vertex and the barycenter of the mesh. The proposed scheme allows us to hide the watermarks behind the 3D mesh while maximally preserving its visual appearance, and the associated embedded information can be recovered from the watermarked mesh without referring to the original 3D mesh.**

***Keywords*-Digital watermarking; 3D meshes; mesh saliency; blind watermarking schemes; copyright protection;**

I. Introduction

Due to an increasing demand for handling 3D models as digital media in the production of computer animation films and video games, techniques for watermarking 3D models have received more attention in recent years especially for the purpose of copyright protection [1]. Basically, watermarking 3D models itself is more involved because the 3D model is usually represented as a 3D triangular mesh, where the vertices, edges, and faces constitute an rather arbitrary topological connectivity except for the condition that every face is a triangle. This representation form is quite different from traditional media such as images and videos because, for such types of media, regular grid samples are assumed in general.

Because of this, watermarking 3D models has its own research history, which has been initiated by Ohbuchi et al. [2], where they embedded watermarks by modifying the topological connectivity of vertices as well as their geometric coordinates. This has been followed by work by Benedens [3], where he successfully enhanced the robustness of the embedded watermarks by modulating the distributions of surface normals at the vertices. Frequency-based representations [4] have also been introduced for this purpose so that we can embed watermarks into some specific frequency domain of the 3D meshes. Although these approaches successfully augmented the resistance of the embedded watermarks to possible attacks, they are still *non-blind* watermarking schemes in the sense that they require an original 3D mesh as the reference for extracting the watermarks from the watermarked data. On the other hand, several *blind* schemes have been presented recently so as to improve the usability of such watermarking techniques. Ucceddu et al. [5] accomplished a blind watermarking scheme by introducing wavelet transforms into the representation of 3D meshes. The robustness of the blind watermarking strategy has been significantly enhanced by Cho et al. [6], where they employed a statistical approach to modulate the geometric properties of the input 3D mesh.

(a) (b)

Figure 1. Existing watermarking techniques cannot preserve the visual quality of the 3D model. (a) An original 3D mesh and (b) its watermarked version.

Nonetheless, existing watermarking techniques have primarily focused on the robustness against possible attacks to alter the embedded copyright information. This means that the techniques have not fully taken care of the associated influences on the visual quality of the watermarked 3D models, and thus cannot avoid disturbing the original appearance of the 3D models or degrading their visual quality as digital 3D contents, as shown in Figure 1. Actually, it is still hard to find an optimal amount of modulation that balances the tradeoff between the robustness of embedded watermarks and influence on the visual quality, and frequently it would be impossible.

This paper presents a new blind watermarking method based on the visual saliency associated with the shapes of the

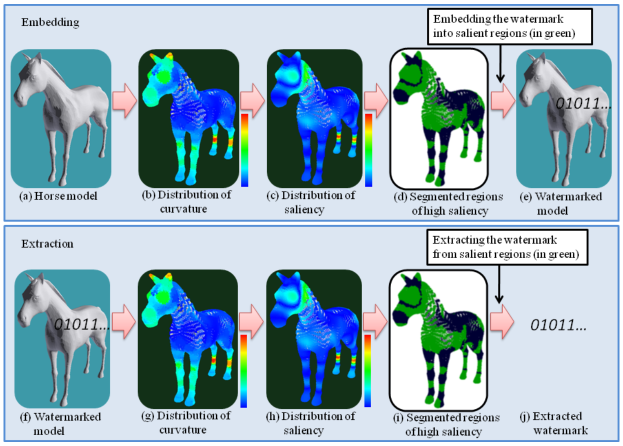


Figure 2. Overview of the proposed watermarking method.

input 3D meshes. The method first identifies the perceptually conspicuous regions over the given 3D mesh using the mesh saliency based on the surface curvatures [7], and then embeds the watermarks to the regions by statistically modulating the distance between each mesh vertex and the barycenter of the mesh. The proposed scheme successfully hides the watermarks behind the 3D mesh while minimally disturbing its visual quality, while the embedded watermarks can successfully extracted the watermarked mesh without referring to the original one. Several experimental results will be accompanied to demonstrate the effectiveness of the proposed method.

II. Method

Figure 2 shows an overview of the proposed watermarking method. Basically, our method consists of two major phases: identifying the salient regions on the 3D mesh surface using the mesh saliency measure, and selectively embedding the watermarks by statistically modulating mesh geometry in the extracted regions.

A. Identifying Salient Regions on a 3D Mesh

Our visual attention is usually directed to the salient shape of the 3D mesh in the sense that it locally differs from its surroundings. For evaluating this saliency, we employ the mesh saliency measure developed by Lee et al. [7], which evaluates the saliency at each vertex by evaluating the difference in mean curvature of the surface from those at other vertices in its neighborhood. This means that the measure calculates how different the surface pattern at the vertex is from those at surrounding vertices. Figure 3(a) illustrates the definition of the mean curvature K_H at the vertex x_i, which can be mathematically formulated as

$$K_H(x_i) = \frac{1}{2A} \sum_{j \in N_1(i)} (\cot \alpha_{ij} + \cot \beta_{ij})(x_i - x_j), \qquad (1)$$

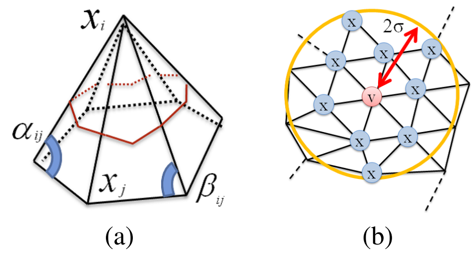


Figure 3. (a) The definition of the curvature at x_i. (b) The neighborhood of the vertex v.

where $N_1(j)$ represents an index set of vertices adjacent to x_i, and A represents the area of the region surrounded by the red edges.

The actual value of saliency at a mesh vertex depends on a scale value σ that controls the locality of the corresponding mesh saliency. In practice, we first search for neighboring vertices x within a radius of 2σ of v and calculate the weighted average of the mean curvature at v using the Gaussian function, as follows:

$$G(K_H(v), \sigma) = \frac{\sum_{x \in N(v, 2\sigma)} K_H(x) \exp[- \| x - v \|^2 / (2\sigma^2)]}{\sum_{x \in N(v, 2\sigma)} \exp[- \| x - v \|^2 / (2\sigma^2)]}, \qquad (2)$$

where $N(v, 2\sigma)$ represents the aforementioned set of neighboring vertices around v, as illustrated in Figure 3(b). The mesh saliency at the vertex v can be computed as the difference of Gaussians, and can be obtained as

$$Saliency(v) = | G(K_H(v), \sigma) - G(K_H(v), 2\sigma) | . \qquad (3)$$

For evaluating the scale σ, we compute the bounding box of the input 3D mesh and define ε in such a way that it becomes 0.3% of the diagonal length of that box. We define σ to be proportional to ε by following the original formulation in [7], while the distribution of mesh saliency heavily depends on the choice of the value σ as shown in Figure 4. Empirically, we employ $\sigma = 10\varepsilon$ because the definition maximally preserve the distribution of mesh saliency over the 3D mesh against possible attacks such as smoothing operations. When watermarking the input 3D mesh, we first refer to the histogram of mesh saliency values first and then explore an appropriate threshold that allows us to segment high salient regions over the 3D mesh in a visually plausible manner (cf. Figure 6).

B. Statistical Approach to Watermarking 3D Meshes

Having extracted salient regions from the given 3D mesh, we embed a watermark into the extracted salient region; otherwise we will disturb the repetitive patterns inherent in the surface shapes when modulating its geometry with the watermark. For watermarking the 3D mesh, we employ the statistical approach developed by Cho et al [6] because it

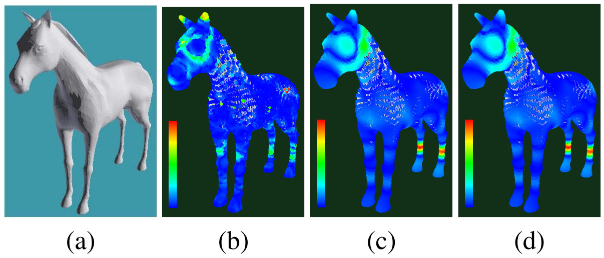


Figure 4. Distributions of mesh saliency according to the scale value σ. (a) An original horse model. Distributions of saliency values over the mesh when (a) $\sigma = 2\varepsilon$, (b) $\sigma = 6\varepsilon$, and (c) $\sigma = 10\varepsilon$. Warm and cold colors correspond to high and low saliency, respectively.

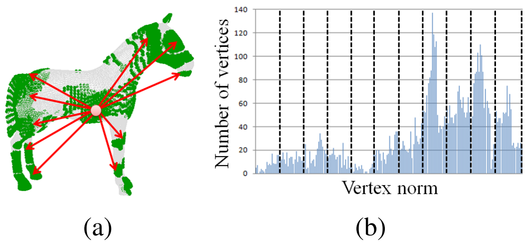


Figure 5. Constructing the histogram of the vertex norms for the mesh vertices in the extracted salient regions. (a) Calculating a vertex norm as the distance of each vertex in a salient region (in green) to the barycenter of the mesh. (b) Constructing the histogram of the vertex norms where the range of the norms is divided into distinct bins of equal size.

provides a blind watermarking scheme while it can still retain the watermark through several possible attacks including transformations that changes local geometry and topology of the 3D mesh (i.e. smoothing and retriangulation) as well as distortion-free (i.e. similarity) transformations.

The statistical approach embeds a watermark into the given 3D mesh as follows: For each vertex within the extracted salient region, we calculate its *vertex norm* as the distance from the barycenter of the 3D mesh (Figure 5(a)) and construct the histogram of the vertex norms. Note that the range of the vertex norms is divided into distinct bins of equal size, where the number of bins is set to be equal to the number of bits to encode the watermark (Figure 5(b)). We can embed one watermark bit to each bin by normalizing the associated vertex norms into $[-1,1]$ and modulating the vertex norms to shift the variance of that bin. In this phase, we use $1/3$ as the threshold variance and modulate the vertex norms in that bin so that the corresponding variance becomes more than $1/3+\gamma$ if we embed 1 as the bit to be watermarked, and less than $1/3-\gamma$ if we embed 0. Here, $(0<)\gamma(<1/3)$ represents a tolerance value to control the robustness of the embedded watermark. For modulating the vertex norms, we iteratively apply the mapping $y = sign(x)|x|^k$ to transform the current vertex norm x to the modulated one y until the corresponding variance meets the condition, where we can increase and decrease the variance by setting $0<k<1$ and $1<k(<\infty)$, respectively.

C. Extracting the Watermark

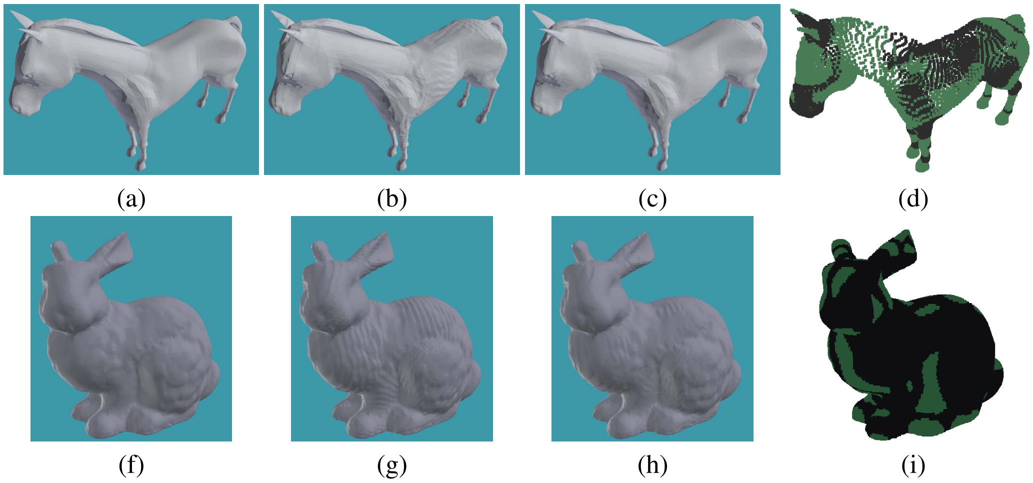
Notice that the process for extracting the embedded watermark can be carried out in a similar fashion, as shown at the bottom of Figure 2. First we identify the salient regions of the watermarked 3D mesh using the mesh saliency measure, and then construct the histogram of the vertex norms by referring to the vertex coordinates contained in the salience regions, and finally compare the variance of each divided bin with the threshold $1/3$ to detect the corresponding embedded watermark bit.

III. Results

We implemented our method on a desktop PC with Intel Core2Duo at 2.33GHz and 2GB RAM using C with OpenGL. We tested our method on a variety of 3D meshes by embedding 32 bits as the watermark, and compared the results with those obtained by applying the existing statistical watermarking method by Cho et al. [6].

Figure 6 shows the comparison between two methods, where two representative 3D meshes are presented. Figures 6(a)-(e) show an original horse model (with 12,152 vertices and 24,208 faces), the watermarked model obtained using Cho et al.'s method, the watermarked model obtained using our method, the extracted salient regions where the watermark is embedded in our scheme, and computation times. As demonstrated in these figures, our method can maximally retain the appearance of the original 3D mesh while the existing method disturbs the shape around the horse body. Here, we employ $\gamma = 0.08$ to make a balance between the visual quality and the robustness of the present watermarking method. The same experiment has been conducted on an bunny model (with 30,680 vertices and 61,174 faces), and the results are exhibited in Figures 6(f)-(j). Again the present method sufficiently respects the original appearance of the input 3D mesh while the existing method incur perceptible striped artifacts over the smooth regions of that mesh. Note that our method includes the overhead of computing the mesh saliency.

Figures 7(a) and (b) show how the statistical watermarking method and our method are robust against additive noise for the horse and bunny models, respectively, and Figures 7(c) and (d) correspond to the robustness against mesh smoothing for the horse and bunny models, respectively. Basically, the success rates of the watermark extraction decreases as we increase the ratio of the additive noise or the number of smoothing operations. Nonetheless, the results demonstrate that our method still can retain the similar success rates of the watermark extraction even when compared with the existing method that does not account for the visual quality of the watermarked 3D meshes.



(e)

Cho et al's	2.62sec
ours	31.73sec

(j)

Cho et al's	4.59sec
ours	196.75sec

Figure 6. Comparison between the statistical watermarking method by Cho et al. and our method. (a) An original horse model. Models watermarked (b) by Cho et al's and (c) our method. (d) The extracted salient regions employed in our method. (e) Computation times (f) An original bunny model. Models watermarked (g) by Cho et al's and (h) our method. (i) The extracted salient regions employed in our method. (j) Computation times.

IV. Conclusion

This paper has presented a method for watermarking 3D meshes by accounting for the visual saliency inherent in the mesh shapes. The present method allows us to embed copyright information into the 3D meshes without significantly disturbing the associated visual appearance of the 3D shapes. Several experimental results have been provided to demonstrate the feasibility of the present method. Our method sometimes fails to keep the good success rate of the watermark extraction when the distribution of vertex norms is highly unbalanced. This is particularly likely to happen when we watermark CAD models that contain large flat regions. In this case, the associated salient regions are rather limited, and thus the associated norms of salient vertices are not uniformly distributed to the divided bins in the histogram. Adaptively adjusting segmentation of salient regions, histogram bin sizes, and the tolerance value of the variance for each bin is left for future work.

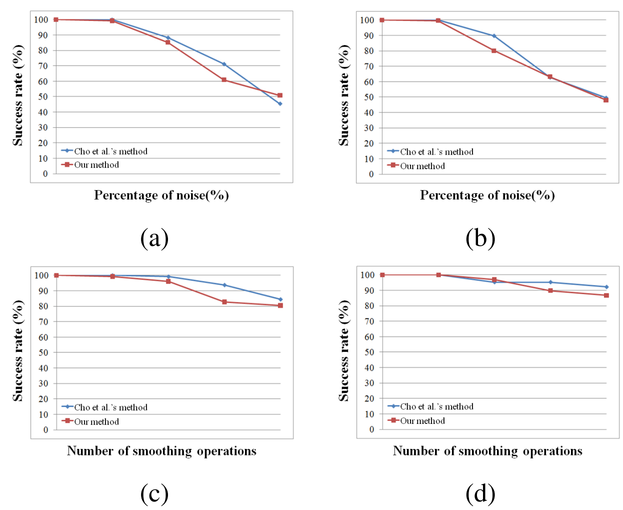


Figure 7. Robustness against additive noise for the (a) horse and (b) bunny models, where the horizontal axis represents the ratio of the noise in terms of the diagonal length of the bounding box. Robustness against mesh smoothing for the (c) horse and (d) bunny models, where the horizontal axis represents the number of smoothing operations. For all the charts, the vertical axis represents the success rate of the watermark extraction, where the blue and red lines represent the results of Cho et al.'s method and our method, respectively.

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