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INCREASING 3D MESH WATERMARK ROBUSTNESS TO AFFINE TRANSFORMATIONS USING BARYCENTER AS SPHERICAL COORDINATE ORIGIN

Bata Vasic,*Universitu of Nis, Faculty of Electronic Engineering Nis, bata.vasic@elfak.ni.ac.rs*

Abstract – *Hiding data in geometrical structure of a three-dimensional (3D) mesh requires stability of primitives, which are used as data carriers. We introduce a new method for improvement of the watermark robustness to the most common affine transformations as well as translation, rotation and uniform scaling. Firstly, we determine a reference point as the center of mass, which is only dependent from a shape of the mesh. Converting Euclidean vertex coordinates to spherical coordinates, with a center at the computed barycentric point, we achieve immunity of vertices to most common affine transformations. Thus our approach significantly increases the robustness of watermark data that are hidden in geometrical structure of the mesh.*

1. INTRODUCTION

Approaches to data copyright protection have been evolving and changing in response with development of technology and customer and industry needs. Protection of audio and video signals, written data and photographs is becoming increasingly significant due to the increasing number of potential misusers. Such protection is becoming more critical as the spectrum of use of three-dimensional (3D) objects expands. For example, video games are strictly based on 3D graphics and the game creators represent the broadest group of three-dimensional (3D) models users. The use of computer animation in architectural and construction industries, as well as medical simulations, also increases.

The problems of data protection in 3D vector models lie exactly in the simplicity of data, relative to the "perfection" of software tools available to stegoanalyst [1]. The differences of the embedding process in steganograpy of digital images, video clips, audio files and documents [2],[3], in relation to the 3D models are evident. But, requirements, which "embeder" should be met [4], are identical for all forms of multimedia content. However, the specificity of 3D requires a customized approach to analyze the data hiding method.

Choosing a data hiding method is dependent from user needs, but some of watermark needs are the same for all methods. Stability of the data carrier is one of common characteristic, which is required at the begining of the watermark process. Some transformations are destructive and good watermark robustness needs some error corection codes [5] within an watermark extraction algorithm. Even a such exelent algorihms gives a better results if use stabile carriers in a some of initial steps of the watermark embeding. This paper gives an improvement of watermark robustness, introducing a new reference point that is dependent from a geometric characteristic of the 3D mesh.

Improvement of watermark robustness to the most common affine transformation as well as translation, rotation and uniform scaling represents a preparation of the 3D geometry for the watermark embeding, but allso an important step in an efficient data extraction in combination with Quantization Index Modulation (QIM) and Low Density Parity Check (LDPC) Codes [5].

This paper is organized as follows: A section 2 describes background of the watermark process and specificity of 3D watermark requirements. In the section 3 we show essence of our method with detailed mathematical explanation, whereas the section 4 gives numerical results. Conclusions and some notes of a future work are in the section 5.

2. BACKGROUND

The area of audio and video watermarking is mature, and a myriad of methods have been developed in the past two decades. Basic ideas and methods developed for one-dimensional (1D) and two-dimensional (2D) signal watermarking hold for 3D watermarking as well, but these methods are not directly applicable to 3D objects. For example handling and editing of 3D objects may involve a variety of complex geometric and topological operations including affine transformations –scaling and rotation, mesh smoothing and mesh optimization, and cropping, etc [6].

In the other case watermarks for most multimedia formats replace the headers or sections of the object’s file format, which may contain arbitrary amount of user-defined data. However, this kind of watermark storage in a 3D model geometry is almost impossible. Headers and sections of 3D model are changed usually during modification or format conversion. Some problems are similar to problems of the standard media types, but 3D model representation is different from other media representations and need specific approach to requirements analyzing.

2.1. 3D model watermarking requirements

Whereas various 3D watermarking applications have specific requirements, based on the previous considerations, there are some universal characteristics which each watermark must satisfy [7]:

Unobtrusiveness - The result of the embedding process should not disturbs the 3D model visibility, as its main purposeful feature. Watermark embedding should cause only small modifications of the 3D object structure. These modifications should also be completely controlled by the embedder and extractor, and they should not cause perceptual structural damage of the original model. 3D watermarking is usually invisible, because its preview is not the target of a misuse, but it is the illegal distribution and commercial use of renderings.

Robustness - The robustness has crucial importance in public watermarks. Private watermarks must only demonstrate resistance to all geometric and topological operations, which significantly degrade the visual quality of the model: rotation, translation, uniform scaling, polygonal simplification, mesh smoothing, cutting or removal of parts of the model. Low prices of 3D objects and widespread knowledge of embedding processes reduce the need for the watermark indestructibility.

Space efficiency - The watermark system has to allow embedding of sufficient amount of information (referred to as capacity). For example, the serial number may require a 32 bits of capacity, while the proof of ownership requires the capacity to accommodate the hash value. For example the hash value is 128 bits for Message Digest (MD5) hash function and 160 bits for Secure Hash Algorithm (SHA) [6]. Space requirements for public watermark embedding information range from 32-bit for serial number data, to a minimum of 256 bits for link to the necessary copyright information of the 3D model.

2.1. Related work

Watermark protection of 3D geometric models is a relatively new research direction in the steganography field, and practically basic directions are taken from researches of other multimedia content watermarking. The main difference of 3D objects representation in comparison to other multimedia contents is the three-dimensional geometric structure of meshes that are built from nodes connected with edges. Therefore, those primitives with their own features determine all further phases of research. The following table classifies object features with respect to their invariance to various transformations according to the work by Ohbuchi *et al* [7]:

Table 1 *Object feature invariance classification*

Features	Transformation				
	Translation	Rotation	Uniform Scaling	Affine transf.	Projection transf.
Coordinates of vertices					
Length of polygon line field	√	√			
Polyhedron volume	√	√			
The two values which define a set of similar triangles, e.g. two angles	√	√	√		
Two polygons area ratio	√	√	√		
The length ratio of two straight line segments				√	
Volume ratio of two polyhedrons				√	
Cross ratio of four points on a straight line					√

Although this categorization is fundamental, we have note that listed primitives are derived from vertex coordinates, which are sensitive to all transformations. The increasing of their invariance to transformations needs conversion of basic vertex coordinates to system, which actually provides their dependence of other features (invariant to transformations). Idea of our approach is making a connection between vertex coordinates and mesh specific feature point: the barycenter.

3. INCREASING WATERMARK ROBUSTNESS TO AFFINE TRANSFORMATIONS

Efficient watermark embeding and extraction include variety of operations to ensure robustnes. It involve operations for improving robustnes to simplification and vertices deletion, but allso visual hiding by rougness masking effects. In this paper we are dealing with ensuring 3D watermark robustnes to most common affine transformations in order to effectively implement QIM.

In 3D watermarking the cover signal consists of points (mesh vertices) in the three-dimensional space, and Human Visual System (HVS) imposes restrictions on the Quantization Index Modulation (QIM) embedding design. In this section we introduce the coordinate system changes and operations necessary to make the watermarked object robust to common affine transformations.

Let V be a set of points in the three dimensional Euclidean space. We refer to these points as vertices. An oriented edge from point u to point v is defined as the ordered pair (u,v). An oriented m-sided face is an m-tuple composed of edges $((u_0,v_0), (u_1,v_1),\ldots, (u_{M-1},v_{M-1}))$ satisfying $u_{i+1 \bmod m} = v_{i \bmod m}$, $m>2$. Let F be a set of m-sided faces with vertices in V. A tri-dimensional-m-angular mesh (3D-mesh) is defined as a pair (V, F)[1].

The mass center of the vertices in the set V is calculated as

$$\mathbf{k}^c = \frac{1}{|V|}\sum_{v\in V}\mathbf{u}_v^C \tag{1}$$

where $\mathbf{u}_v^C = (x_v, y_v, z_v)$ is the position of the vertex v given in Cartesian coordinates, and $|V|$ denotes the size of the set V.

Following our idea and using results from [8], to ensure invariance to translation and rotation, the coordinate system is changed by translating the coordinate origin to the mass center $\mathbf{k}^c$, and by aligning the principal component vector with the z axis. After the translation, the vertex positions in the new Cartesian coordinate system are

$$\mathbf{v}_v^C = \mathbf{u}_v^C - \mathbf{k}^c \tag{2}$$

where $\mathbf{v}_v^C = (x_v', y_v', z_v')$. To achieve robustness against rotation the 3D-mesh is rotated to align the principal component vector of the vertices with the z-axis. The principal component axis is the eigenvector that corresponds to the largest eigenvalue of the vertex coordinate covariance matrix

$$C = \begin{bmatrix} \sum_{v\in V}(x_v')^2 & \sum_{v\in V}x_v'y_v' & \sum_{v\in V}x_v'z_v' \\ \sum_{v\in V}x_v'y_v' & \sum_{v\in V}(y_v')^2 & \sum_{v\in V}y_v'z_v' \\ \sum_{v\in V}x_v'z_v' & \sum_{v\in V}y_v'z_v' & \sum_{v\in V}(z_v')^2 \end{bmatrix} \tag{3}$$

[1] The mesh features such normal, smoothing groups and faces are ignored in this treatment as they are not used in the proposed algorithm. For example, QIM [5] modulation of the unit normal direction is a straightforward generalization of our method. Other extensions are also possible.

To achieve robustness to scaling, the Cartesian coordinates of the point v are then converted to spherical coordinates.

$$r_v = \sqrt{x_v + y_v + z_v}$$
$$\theta_v = \arccos\left(\frac{z_v}{r_v}\right) \tag{4}$$
$$\varphi_v = \arctan\left(\frac{y_v}{x_v}\right)$$

wherein $r_v \in [0,\infty)$, $\theta_v \in [0,\pi]$ and $\varphi_v \in [0,2\pi)$, are the radial distance, inclination angle, and the azimuth angle, respectively of the point v. Thus the vertex position in spherical coordinates are

$$\mathbf{v}_v^S = (r_v, \theta_v, \varphi_v) \tag{5}$$

The original variant of the QIM operates only on the radial distance from the center of mass, i.e., moves a point v with the coordinates $(r_v, \theta_v, \varphi_v)$ to a point $(Q_{u_v}(r_v), \theta_v, \varphi_v)$, where u_v is the bit hidden in the point v. The new center of the mass $\mathbf{k}^{c'}$ of the watermarked object has the following Cartesian coordinates

$$x^{c'} = \sum_{1 \le i \le n} Q_{u_i}(r_i) \cos\varphi_v \sin\theta_v$$
$$y^{c'} = \sum_{1 \le i \le n} Q_{u_i}(r_i) \sin\varphi_v \sin\theta_v \tag{6}$$
$$z^{c'} = \sum_{1 \le i \le n} Q_{u_i}(r_i) \cos\varphi_v$$

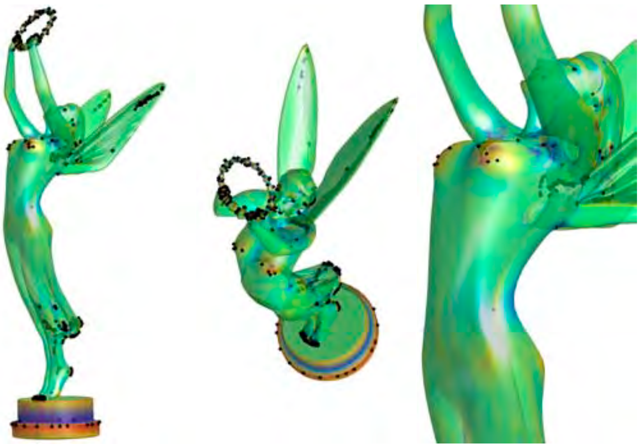
If a hidden binary sequence contains equal number of zeros and ones, and if the vertex positions are uncorrelated with the quantization levels, then for a sufficiently large object $(x^{c'}, y^{c'}, z^{c'})$ converges to a zero vector**.** The above conditions are satisfied in practice, and the watermarked object is therefore invariant to affine transformations.

4. NUMERICAL RESULTS

We have improved watermark robustness to affine transformations by converting system of vertex coordinates, whereat it did not affect the geometry and topology of original 3D mesh. In the other hand, the watermark embedding using QIM operates after the coordinate system conversion, thereby it is ensured very low level of error. Actually, the conversion can only occurs rounding error, which is defined by the number of decimal places of given vertex coordinates. Default precision, i.e. the number of decimal places, for some converters to simplest *obj* file format, is four, but for precise calculation we can increase this number and calculate more accurately. After watermark embedding, we can preserve "blindness" of hidden data by saving watermarked mesh in previous format: using four digits for representation of vertex coordinates.

For experimental calculations we have used Naisa by Bata [9] 3D mesh model (33465 vertices and 66922 faces), whereas affine transformations are applied using 3D Studio Max 2012 software [10].

Most common affine transformations were applied to the experimental mesh model with following values: (δ_X = 15 cm), rotation (α_X = 75^0, α_Y = -25^0, α_Z = 0^0) and uniform scaling (k = 3.5 where $X' = k\ X$, $Y' = k\ Y$ and $Z' = k\ Z$). Results are shown on Fig. 1. One thousand identically selected vertices for watermark embeding even as perceptually demonstrate accuracy of our approach.



(a) (b) (c)

Fig. 1. *Perceptual effects of affine transformations, which were applied to the Naisa by Bata 3D mesh model [5]: (a) Translation, (b) Rotation and (c) Uniform scaling. Black points denote 1000 selected vertices for watermark embedding.*

For a better comparison we present additional plots of 1000 selected vertices of the original and rotated mesh (see Fig. 2.a and Fig. 2.b respectivelly).

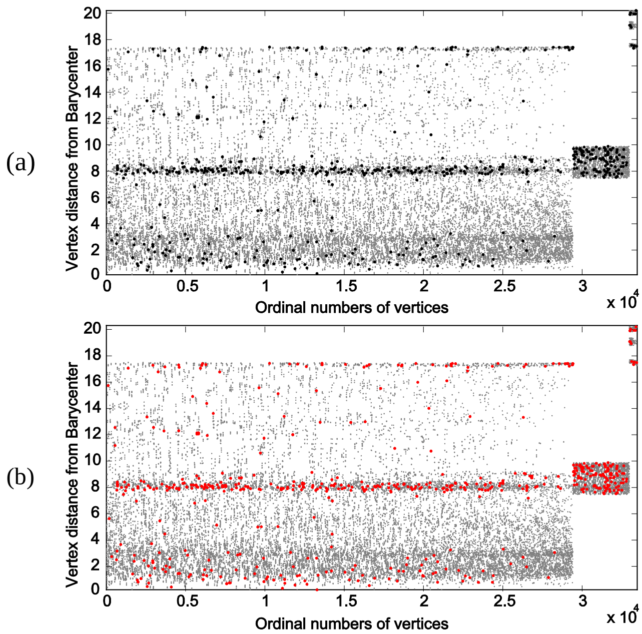


Fig. 2. *Comparison of 1000 vertices shown on Fig. 1, in relation to distance from the Barycenter: (a) Original mesh (black dots) and (b) Rotated mesh (red dots).*

The fully matching of selected vertices is obvious perceptual as well as topologically. This is very important for watermark extraction even though it looks pretty trivial. In the next table are shown the first five numerical values of watermarked vertex coordinates, without coordinate system converting.

Table 2 *First five Cartesian vertices coordinates of the original and rotated experimental 3D mesh*

Original Mesh			Rotated Mesh		
4.3379	8.0804	-0.2491	14.6679	5.4882	-0.2491
-0.8812	4.2057	0.5295	-0.6336	3.5229	0.5295
5.7087	8.8739	-1.0138	18.6868	5.6110	-1.0138
0.2054	4.5890	0.8693	2.5520	4.2302	0.8693
-3.1936	-12.2298	2.2262	1.0262	-26.8045	2.2262

From the Table 2, one can see completely different coordinates of same geometrical structure, thus in this case the watermark data finding and extracting are very difficult. However, uniform scaling is a more complicated transformation regarding of generating error. High values of the scaling constant k or long translations increase integer values which define coordinates; the using of a fixed number of digits imposes the calculation with a decreased number of decimal places i.e. with a low precision.

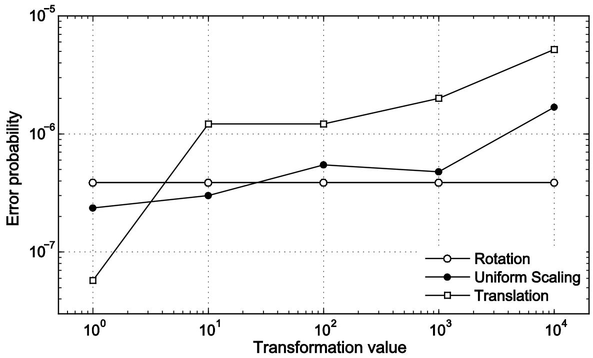


Fig. 3. *Probability of error as the function of transformations*

For the calculation of error probabilities (see Fig. 3.) were used folowing values of transformations: translation ($\boldsymbol{\delta}_X$ = [1 cm, 10 cm ,100 cm, 1000 cm, 10000 cm]), rotation[2] (α_X = 75^0, α_Y = -25^0, α_Z = 0^0) and uniform scaling ($\boldsymbol{k}$ = [1, 10, 100, 1000, 1000]). Coordinates are defined by default number of digits (six, i.e. integer plus four decimal places).

The original mesh had subjected to initial values of all mentioned transformations using following numbers of digits for the coordinates definition: 6,7,8,9,10,11,12. Next figure presents probabilities of error for all transformations, which were generated by decimal places rounding:

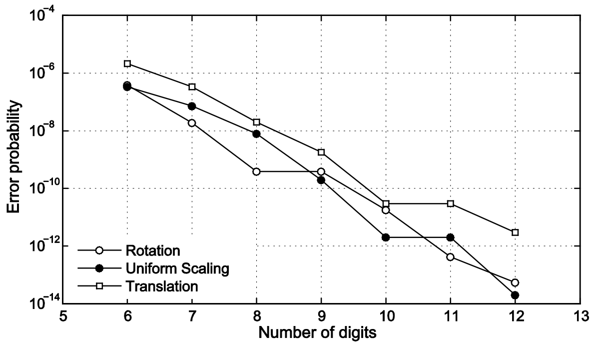


Fig. 4. *Decimal places rounding error probabilities.*

[2] Rotation does not affect the maximum value of coordinate digit. This type of transformation changes coordinates within limit values.

5. CONCLUSIONS AND FUTURE WORK

In this paper we proposed the efficient method for increasing the watermark data robustness to common affine transformations. The paper is in same time an important segment of the our wide work in the 3D geometry area and research of using QIM, LDPC and error correction codes for 3D mesh watermarking [5]. Our method shows excellent results of watermark extraction as well as low level of error probabilities. Contrary to shown results, one can see difficulties of the watermark data finding and extraction as effects of afine transformations to 3D mesh, but without using the our approach.

Future work will be directed to the study of geometric methods for increasing robustnes to other types of transformation on 3D mesh models. Features of optimization, simplification, non-uniform scaling and smoothing processes will be our primar research goals.

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