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3D Printing Watermarking Method Based on Radius Curvature of 3D Triangle

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ABSTRACT

Due to the fact that 3D printing is applied to many areas of life, 3D printing models are often used illegally without any permission from the original providers. This paper presents a novel watermarking algorithm for the copyright protection and ownership identification for 3D printing based on the radius curvature of 3D triangle. 3D triangles are extracted and classified into groups based on radius curvature by the clustering algorithm, and then the mean radius curvature of each group will be computed for watermark embedding. The watermark data is embedded to the groups of 3D triangle by changing the mean radius curvature of each group. In each group, we select a 3D triangle which has the nearest radius curvature with the changed mean radius curvature. Finally, we change the vertices of the selected facet according to the changed radius curvature has been embedded watermark. In experiments, the distance error between the original 3D printing model and the watermarked 3D printing model is approximate zero, and the Bit Error Rate is also very low. From experimental results, we verify that the proposed algorithm is invisible and robustness with geometric attacks rotation, scaling and translation.

Key words: 3D Printing Copyright, 3D Model Watermarking, 3D Printing Security, 3D Printing Data, Radius Curvature and Clustering.

1. INTRODUCTION

Three dimension (3D) printing is a process for creating objects directly by adding material layer by layer in a variety of ways [1, 2]. 3D printing can be essential in improving the quality of life of individuals whose organs have failed. Applications of 3D printing in the context of health has the potential of increasing the life expectancy of humans in that it saves countless lives that are on the verge of death. Due to the benefits of 3D printing is enormous in all domain and the price of a 3D printer is not expensive, the individual users can buy a 3D printer and download 3D printing models on Internet to print out real objects. This makes a large effect on manufacturers, and they need a copyright protection solution for 3D printing. Moreover, the original providers also desire to identify their products for checking in trade. So, a watermarking solution for 3D printing is necessary for the copyright protection and ownership identification [3].

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Previously, there are many watermarking methods for 3D contents and 3D animals. But these methods are only useful for copyright protection related to 3D contents. They could not be applied to 3D printing. Because the output of 3D printing is a real object. The purpose of 3D printing watermarking is how to extract watermark data from the scanned 3D triangle mesh of a real object. For responding to the issues related to the copyright protection of 3D printing, we proposed a novel watermarking algorithm for 3D printing in this paper. The main content of the proposed algorithm is to classify 3D triangles into groups based on the radius curvature of 3D triangle before embedding watermark data to the groups of 3D triangles. The watermark bit is embedded by changing the mean radius curvature of each group on the reference of special value. The watermark data is extracted from the scanned 3D triangle mesh of real object.

To clarify the proposed algorithm, we organized our paper as follow. In Sec. 2, we look into previous watermarking techniques for 3D model, and explain the relation of radius curvature to the proposed algorithm. In Sec. 3, we show the proposed algorithm in detail. Experimental results and the evaluation of the proposed algorithm will be shown in Sec. 4. Sec. 5 shows the conclusion.

2. RELATED WORKS

2.1 3D Model Watermarking

3D watermarking has been extensively researched since the early 2000s. 3D watermarking schemes are generally focused on geospatial domain and frequency domain [4-8]. The main concept of geospatial watermarking methods is to embed the watermark by modifying the value of vertices or geometric features as length, area or topology features while the main concept of watermarking schemes in the frequency domain is to embed the watermark in the spectrum coefficients of DFT, DWT, and DCT of a sequence of vertices or topologies. Thus, these methods only generated the watermarked 3D models, and then they are used again for the watermark extraction. The end purpose of 3D printing watermarking is to extract watermark data from the print out of watermark 3D models. So, the above proposed schemes cannot apply to the purpose of 3D printing watermarking.

S. Yamazaki et al. [9] proposed a method of extracting watermark from 3D prints created from 3D mesh data. The watermark is embedded to the 3D mesh based on the spread spectrum technique, and then extracted from 3D prints by reconstructing the 3D mesh homologous to the original. This method does not have high accuracy. Because the spread spectrum was changed a lot due to the noises in the scanned 3D model after the scanning process and transformation to the frequency domain.

2.2 Radius Curvature Based 3D Printing Watermarking

The input of 3D printing is 3D triangle meshes [10], which are designed by a CAD software. A 3D triangle mesh contains a set of 3D triangles. Each 3D triangle includes three vertices. Each vertex is presented by three coordinates x, y and z (see Fig. 1a). Radius curvature is the curvature of a triple of points in n-dimensional Euclidean space [11] (see Fig. 1b). Due to the fact that a 3D triangle mesh includes a set of 3D triangles. Each 3D triangle is a triple of points. So, the radius curvature of a 3D triangle is computed by Eq. (1) below:

$$K_R = \frac{1}{R} = \frac{4.A}{a.b.c} \tag{1}$$

Withis the radius curvature of 3D triangle, A is the area of 3D triangle, R is the circumscribed circle radius of 3D triangle, a, b and c are the edge of 3D triangle respectively.

From Eq. (1), we can see that the radius curvature of a 3D triangle is dependent on the circumscribed circle radius of that triangle. After the scanning of real object and reconstruction, we will get the scanned 3D triangle mesh. Due to the effect

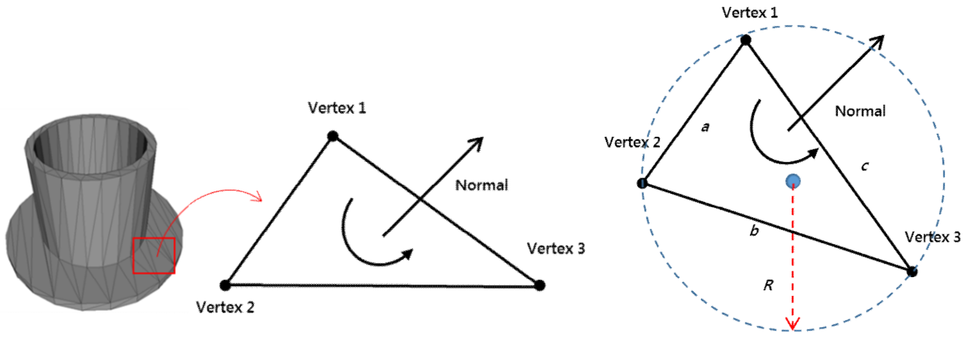

Fig. 1. (a) Structure of 3D triangle, and (b) Circumscribed circle of a 3D triangle.

of noise in the scanning process, the coordinates of vertices of each triangle in the scanned 3D triangle mesh is not the same with original 3D triangle mesh but the overall shape of 3D triangle is not change. Thus the radius curvature of triangle is also not change and we could use the radius curvature of 3D triangle for watermark embedding.

3. THE PROPOSED ALGORITHM

3.1 Overview

The proposed algorithm is described in Fig. 2. Triangles are extracted from the 3D triangle mesh to compute their radius curvatures. After that, triangles are divided into groups by the clustering algorithm based on their radius curvatures. Watermark key is the number of groups that we want to cluster triangles. With each group of triangles, we compute the mean radius curvature of it and embed a watermark bit to that mean radius curvature. The watermarked 3D triangle mesh is generated according to mean radius curvatures which have been embedded watermark data. After the printing process, the real object will be used for

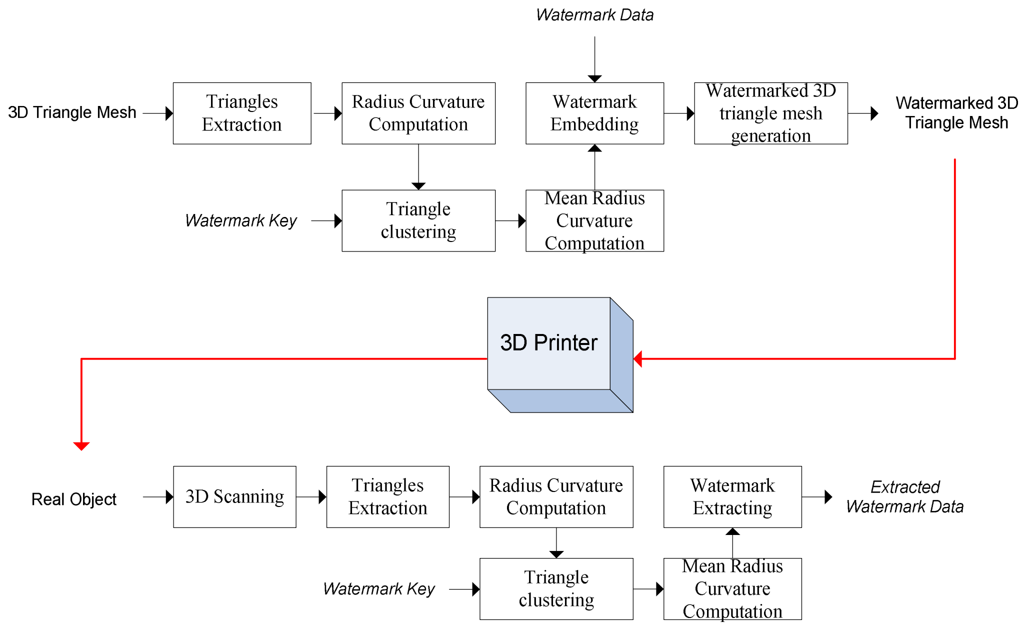

Fig. 2. The proposed algorithm.

scanning and reconstruction in order to generate the scanned 3D triangle mesh. Triangles are then extracted from the scanned 3D triangle mesh for computing radius curvature and clustering triangles into groups. Watermarking data is extracted from the mean radius curvature of each group. We will describe the detailed watermark embedding and extracting processes in Sec. 3.2 and Sec. 3.3.

3.2 Watermark Embedding

A 3D printing file (3D triangle mesh) contains a number of triangles $\mathbf{F} = \{f_i | i \in [1, N]\}$. Each 3D triangle contains three vertices (three points), $f_i = \{v_{ij} | j \in [1,3]\}$. The radius curvature of each facet f_i is computed by its vertices and corresponding area:

$$K_i = \frac{4A}{|v_{i1} - v_{i2}|.|v_{i2} - v_{i3}|.|v_{i3} - v_{i1}|} \tag{2}$$

Therein A is the area of facet. N facets are divided into M groups by clustering algorithm based on the value of radius curvature, $M = \{m_g | g \in [1, M]\}$.

After classifying facets into groups, we find the maximum curvature, minimum curvature of each group, and calculate the mean radius curvature of each group. Assume that $K_{max}^{m_g}, K_{min}^{m_g}$ and $K_{mean}^{m_g}$ are the maximum curvature, minimum curvature and mean radius curvature of group m_g respectively. The mean radius curvature $K_{mean}^{m_g}$ of group m_g is the average value of all radius curvatures in group, with $|m_g|$ is the number of triangles in group m_g:

$$K_{mean}^{m_g} = \frac{\sum K_i \in m_g}{|m_g|} \tag{3}$$

Next, we define Δ_{mg} is the average value of $K_{max}^{m_g}$ and $K_{min}^{m_g}$:

$$\Delta_{mg} = \frac{K_{min}^{m_g} + K_{max}^{m_g}}{2} \tag{4}$$

And each of watermark bits $\omega_g \in \{0,1\} (g \in [1, M])$ is embedded by changing the mean radius curvature of group m_g on the reference of the average value Δ_{mg}. If $\omega_g = 0$, then $K_{mean}^{m_g}$ will be move to be less than Δ_{mg}. If $\omega_g = 1$, then $K_{mean}^{m_g}$ will be move to be greater than Δ_{mg}:

$$K_{mean}^{m_g*} = \begin{cases} K_{mean}^{m_g*} > \Delta_{mg} \text{ if } \omega_g = 1 \\ K_{mean}^{m_g*} < \Delta_{mg} \text{ if } \omega_g = 0 \end{cases} \tag{5}$$

For satisfying the above embedding condition, the watermarked mean distance $K_{mean}^{m_g*}$ will be changed as follows:

If,

$$\text{If } \omega_g = 1, K_{mean}^{m_g*} = \begin{cases} \Delta_{mg} + \frac{\Delta_{mg} - K_{mean}^{m_g}}{2} \text{ if } K_{mean}^{m_g} < \Delta_{mg} \\ \text{No change if } K_{mean}^{m_g} \geq \Delta_{mg} \end{cases} \tag{6}$$

If,

$$\text{If } \omega_g = 0, K_{mean}^{m_g*} = \begin{cases} \Delta_{mg} - \frac{K_{max}^{m_g} - K_{mean}^{m_g}}{4} \text{ if } K_{mean}^{m_g} \geq \Delta_{mg} \\ \text{No change if } K_{mean}^{m_g} < \Delta_{mg} \end{cases} \tag{7}$$

Fig. 3 shows the change of the mean radius cur-

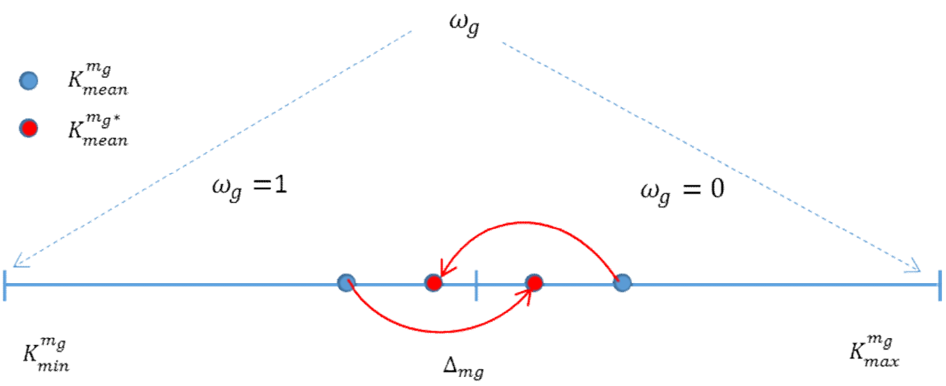

Fig. 3. Watermark bit embedding by changing the mean radius curvature.

vature $K_{mean}^{m_g}$ of group m_g according to the watermark bit ω_g. The curvature $K_{mean}^{m_g}$ is represented by the blue point and $K_{mean}^{m_g*}$ is represented by the red point. When $\omega_g = 0$, $K_{mean}^{m_g}$ will be move to be less than Δ_{mg} if it is equal or greater than Δ_{mg}. When $\omega_g = 1$, $K_{mean}^{m_g}$ will be move to be greater than Δ_{mg} if it is less than Δ_{mg}.

After embedding watermark bit ω_g to the mean radius curvature of group m_g, the change rate α_g is calculated as shown in Eq. (8):

$$\alpha_g = \frac{K_{mean}^{m_g*}}{\Delta_{mg}} \tag{8}$$

The change rate α_g is used to change the vertices of a facet in group m_g. The radius curvature of this triangle must be the nearest value with the watermarked mean radius curvature $K_{mean}^{m_g*}$. Assume that, if f_i is a triangle in group m_g and its radius curvature is the nearest value with the watermarked mean radius curvature $K_{mean}^{m_g*}$, then the vertices of f_i is changed by the change rate α_g as follow:

$$v'_{ij} = \alpha_g . v_{ij} + (\alpha_g - 1). v_{ij} \quad \forall j \in [1,3] \tag{9}$$

Where $v_{ij} \mid j \in [1,3]$ are the new vertices of facet f_i after changing by Eq. (9).

3.3 Watermark Extracting

The watermark extraction process is similar the embedding process. Firstly, we also extract triangles from the scanned 3D printing file to compute the radius curvature of triangles. After that, we classify them into groups by the clustering algorithm based on the value of radius curvature. The watermark key is used for the clustering process. For each group, we find the maximum curvature $K_{max}^{m_g'}$, the minimum curvature $K_{min}^{m_g'}$, and calculate the mean radius curvature $K_{mean}^{m_g'}$ similar Eq. (3). And $\Delta'_{mg} = (K_{min}^{m_g'} + K_{max}^{m_g'})/2$ is the average value of $K_{min}^{m_g'}$, $K_{max}^{m_g'}$. Finally, the watermark bit ω_g can be extracted by comparing the mean radius curvature $K_{mean}^{m_g'}$ and the average value Δ'_{mg}:

$$\omega_g = \begin{cases} 1 \text{ if } K_{mean}^{m_g'} \geq \Delta'_{mg} \\ 0 \text{ if } K_{mean}^{m_g'} < \Delta'_{mg} \end{cases} \tag{10}$$

4. EXPERIMENTAL RESULTS

We experimented the proposed method with test models as Fig. 4. The format of models is STL file [11]. The detailed information of models is shown in Tab.1. Test models are embedded watermark data according to watermark key. The watermark key is the number of groups which is defined by user, and used for clustering facets. We used K-mean algorithm for clustering facets [12]. The number of groups is always less than a half the number of facets. To satisfy above condition, we defined the number of groups M according to the number of facets N as Eq. (11).

$$M = Integer\ part(\frac{N}{2^3 \times Sum}) \tag{11}$$

Withis the number of digits of N. For example, if $N = 2146$ then. The length of watermark bit is equal the number of groups. In order to evaluate the performance of the proposed algorithm, we compute the data accuracy in Sec. 4.1 and evaluate the robustness of the proposed algorithm in Sec. 4.2.

4.1 Data Accuracy

We compute data accuracy to evaluate the invisibility of the proposed algorithm. We calculated the mean Euclidean distance $d^m(v, v')$ between the vertices v' of the watermarked 3D triangle mesh and the verticesof original 3D triangle mesh to analyze the vertices data accuracy and invisibility. The mean Euclidean distance $d^m(v, v')$ is the mean distance of all distances and calculate by Eq. (12).

$$d^m(v, v') = \frac{1}{3 \times \mathrm{N}} \sum_{i=1}^{\mathrm{N}} \sum_{j=1}^{3} ||v_{ij} - v'_{ij}|| \tag{12}$$

Table 1 shows the experimental results with re-

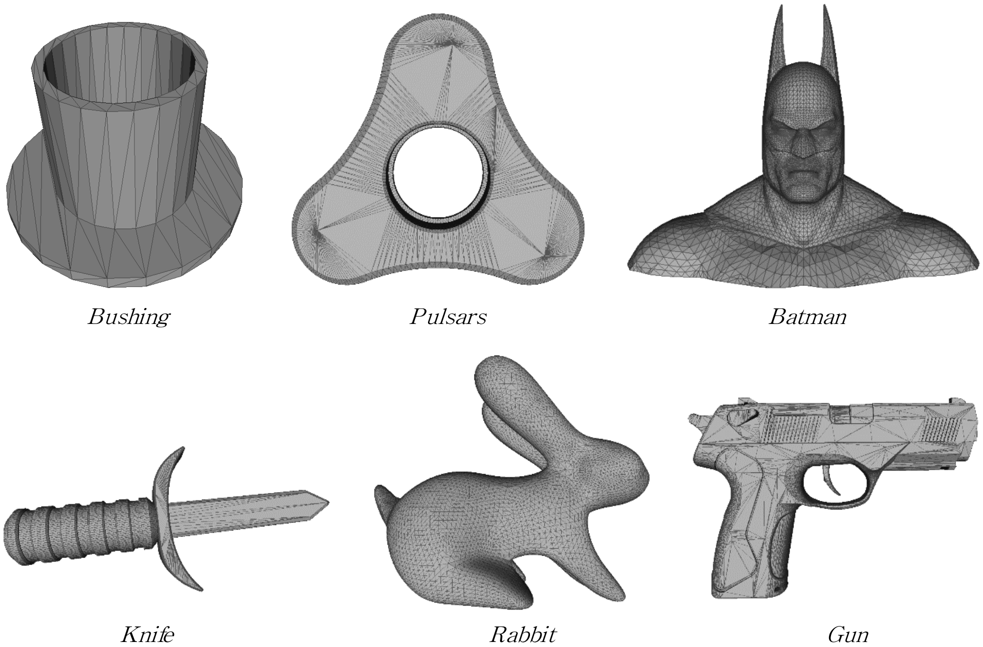

Fig. 4. Test Models.

Table 1. Experimental results

Name	# of facets	# of groups	Distance Error	BER (%)
Bushing	288	12	6.9882 E-06	0.00
Pulsars	4944	154	7.9660 E-06	0.00
Batman	13566	339	8.9872 E-06	0.95
Knife	15032	375	8.9937 E-06	1.47
Rabbit	21056	526	8.9985 E-06	2.42
Gun	32128	803	9.1307 E-06	2.53

spect to data accuracy. We experimented test models with differential watermarks. The distance error between the original 3D triangle mesh and the watermarked 3D triangle mesh is very small. The distance error is dependent on the number of watermarked vertices. The number of watermarked vertices is dependent on the number of groups, the mean radius curvature of each group and the clustering algorithm. From Tab. 1, the distance error is increased according to the number of groups. The distance error is formed from 6.9882 E-6 to 9.1307 E-6. It means the change rate of the watermarked 3D triangle mesh is very small. So, the invisibility of the proposed algorithm is very high.

4.2 Robustness Evaluation

Due to the scanned 3D triangle mesh is affected by noise in the scanning process, it is not perfectly the same with the original 3D printing file. We used visual 3D printer and added random noise, and then performed attacks as rotation, scaling and translation. Due to the fact that translation and rotation only change the spatial location of 3D printing model, thus we only re-scale the scanned 3D printing mesh before extracting facets for watermark extraction. We calculate the bit error rate (BER) by comparing the extracted watermark data with the original watermark data:

$$BER = (1 - \frac{Extracted\ watermark}{Original\ watermark}) \times 100 \quad (13)$$

Experiments showed that the BER is very low. It means the proposed algorithm is robustness with geometric attacks. The BER is dependent on the number of the watermarked triangles. The number of the watermarked triangles is dependent on the number of groups, the number of triangles in each group and the clustering algorithm. The BER of test models is formed from 0.000 % to 0.0253%. Fig. 5 shows the BER of the proposed algorithm according to the number of groups. The BER is increased according to the number of groups. In order to evaluate the performance of the proposed algorithm, we compare the BER of the proposed algorithm with the recent proposed methods. In Ho's method [8], the average BER is 10.5%. In Yamazaki's method [9], the average BER is 12.8 %. In the proposed algorithm, the average BER is 1.5 %. This mean our algorithm is robustness than previous methods. Fig. 6 shows the performance comparison of the proposed algorithm with previous methods by the BER.

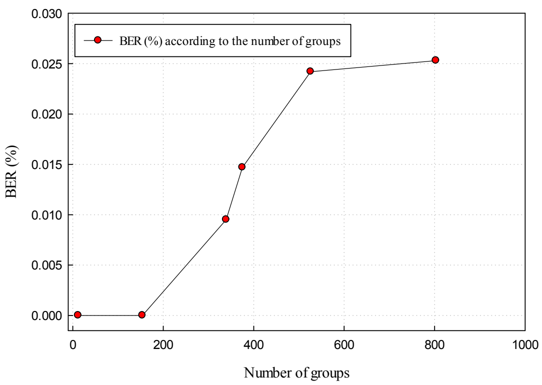

Fig. 5. BER according to the number of groups.

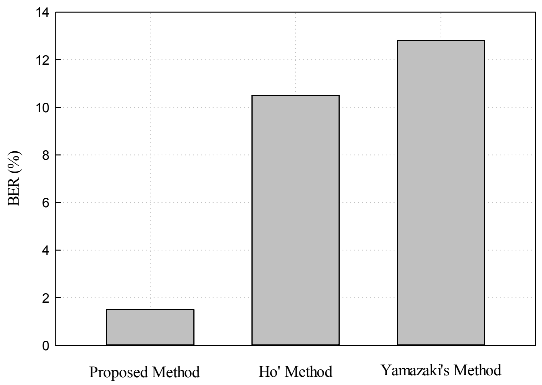

Fig. 6. Performance of the proposed algorithm comparing with previous methods by BER.

5. CONCLUSION

In this paper, we proposed a novel watermarking algorithm for 3D printing. It is based on the radius curvature of 3D triangle and the clustering algorithm. The watermark data is embedded to the mean radius curvature of 3D triangles after the clustering process. Experimental results show that the distance error between the original and the watermarked 3D printing model is low. The proposed algorithm has invisibility and robustness with geometric attacks as rotation, translation and scaling. The experimental results verified that the BER of the proposed method has lower than previous methods. Next time, we will improve the proposed method and apply to copyright protection system.

REFERENCE

[1] United States Government Accountability Office, *3D Printing Opportunities, Challenges, and Policy Implications of Additive Manufacturing*, USA, 2015.

[2] A.T. Kearney, *3D Printing: A Manufacturing Revolution*, 2015.

[3] S. Ira and S. Parker, "Copyright Issues in 3D Printing," *Proceeding of The International Technology Law Conference in Paris, France*, pp. 1-14, 2014.

[4] S.H. Lee, S.G. Kwon, and K.R. Kwon, "Geometric Multiple Watermarking Scheme for Mobile 3D Content Based on Anonymous Buyer-seller Watermarking Protocol," *Journal of Korea Multimedia Society*, Vol. 12, No. 2, pp. 244-256, 2009.

[5] Q. Ai, Q. Liu, D. Zhou, L. Yang, and Q. Xi,

"A New Digital Watermarking Scheme for 3D Triangular Mesh Models," *Journal of Signal Processing*, Vol. 89, pp. 2159-2170, 2009.

[6] X.H Tan, "A 3D Model Asymmetric Watermarking Algorithm Based on Optimization Statistics," *Journal of Theoretical and Applied Information Technology*, Vol. 51, No. 2, pp. 175-181, 2013.

[7] X. Rolland, G. Do, and A. Pierre, "Triangle Surface Mesh Watermarking Based on a Constrained Optimization Framework," *IEEE Transactions on Information Forensics and Security*, Vol. 9, No. 9, pp. 1491-1501, 2014.

[8] J.U Ho, D.G Kim, S.H Choi, and H.K Lee, "*3D Print-Scan Resilient Watermarking Using a Histogram-Based Circular Shift Coding Structure*," *Proceedings of the 3rd ACM Workshop on Information Hiding and Multimedia Security*, pp. 115-121, 2015.

[9] S. Yamazaki, K. Satoshi, and M. Masaaki, "Extracting Watermark from 3D Prints," *Proceednig of The 22nd International Conference on Pattern Recognition*, pp. 4576-4581, 2014.

[10] STL Format in 3D Printing, https://all3dp.com/what-is-stl-file-format-extension-3d-printing/, Accessed 2017.

[11] Hervé Pajot, *Analytic Capacity, Rectifiability, Menger Curvature and the Cauchy Integral,* Lecture Notes in Mathematics of Spinger, Vol. 1979, pp. 29-54, 2004.

[12] Mac Queen, *Some Methods for Classification and Analysis of Multivariate Observations*, University of California Press, Berkeley, California, 1967.

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