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Menger Curvature Based 3D Printing Watermarking Algorithm

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Abstract

Nowadays, 3D printing technology can change the world based on the fact that it enhances the creation of complex structures and shapes that were not feasible in the past. So 3D printing data is often illegally used without permission from the original providers. This paper presents a novel watermarking algorithm for the copyright protection of 3D printing data based on the Menger curvature. Facets of 3D printing data are classified into groups based on the Menger curvature and the mean Menger curvature of each group will be then computed in order to embed watermark data. The watermark data is embedded to the groups of facets by changing the mean Menger curvature of each group based on the reference of special Menger curvature. In each group, we select a facet which has the nearest Menger curvature with the changed mean Menger curvature and change the vertices of the selected facet according to the changed Menger curvature for the watermarked 3D printing data generation. In experiments, the distance error between the original 3D printing file and the watermarked 3D printing file is approximate zero, and the Bit Error Rate is also very low. From experimental results, we verify that the proposed method is invisible and robustness with geometric attacks as rotation, scaling and translation.

Keywords*: 3D printing copyright, 3D model watermarking, 3D slicing, Additive Layer Manufacturing*

1. Introduction

3D printing is a process of creating objects directly by adding material layer by layer in a variety of ways [1, 2]. Thus, 3D printing technology allows users to turn any digital file into a three dimensional physical product. 3D printing can be essential in improving the quality of life of individuals whose organs have failed. In addition, the 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. Summary, it turns users from being passive consumers to active creators.

Due to the benefits of 3D printing is enormous in all domains and the price of a 3D printer is not expensive, individual users can buy a 3D printer and download 3D models on Internet to print real objects out. 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 commercial transactions. So, a watermarking solution for 3D printing is necessary for the ownership and copyright protection [3].

Previously, there are many watermarking methods for 3D contents, 3D mesh and 3D animals. But these methods are only useful for copyright protection related to 3D

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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 the embedded watermark data from the scanned model of 3D printed 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 points of the proposed algorithm is to classify facets into groups based on the Menger curvature of facet before embedding watermark data to the groups of facets. The number of groups is dynamic and defined by user. The watermark bit is embedded by changing the mean Menger curvature of group on the reference of special value. The watermark data is extracted from the scanned model of 3D printed object.

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

2. Related Work

2.1. 3D Model Watermarking

3D model watermarking has been extensively researched since the early 2000s. 3D watermarking schemes are generally focused on geospatial domain and frequency domain [4–17]. The main concept of watermarking methods in the geospatial domain 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 they are then used again for watermark extraction. It is not the end purpose of 3D printing watermarking. The end purpose of 3D printing watermarking is to extract the embedded watermark data from the 3D printed object of the watermarked 3D models. So the proposed schemes above cannot apply to the purpose of 3D printing watermarking.

S. Yamazaki *et al.* [18] 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. The accuracy of this method is not high. Because, the scanned 3D model has many noises in the scanning process and the spread spectrum was changed a lot after transformation.

2.2. Menger Curvature Based 3D Printing Watermarking

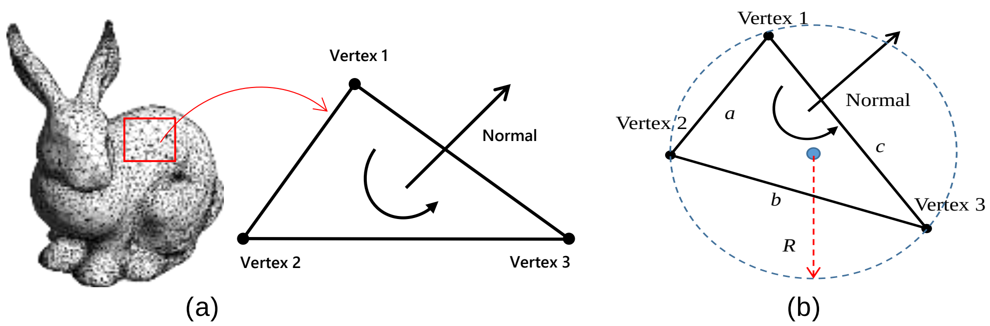


Figure 1. (a) Structure of Facet and (b) Circumscribed Circle of Facet

The input of 3D printing is a 3D triangle mesh [19], which is designed by a CAD software. A 3D triangle mesh contains a set of facets. Each facet includes three vertices and a normal vector. Each vertex is presented by three coordinates x, y and z. Figure 1 shows the structure of a facet. The Menger curvature is the curvature of a triple of points in n-dimensional Euclidean space [20, 21]. Due to the fact that a 3D triangle mesh includes a set of facets. Each facet is a triple of points. So, the Menger curvature of a facet is computed by Eq. (1) below:

$$K_M = \frac{1}{R} = \frac{4.A}{a.b.c} \quad (1)$$

With K_M is the Menger curvature of facet, A is the area of facet, R is the circumscribed circle radius of facet, a, b and c are the edge of facet respectively.

From Eq. (1), we can see that the Menger curvature of a facet is dependent on the circumscribed circle radius of that facet or the length of edges of that facet. After the scanning of 3D printed object and reconstruction, we will get the scanned 3D triangle mesh. Due to the effect 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 facets is not change. Due to the shape of facet is not change, the Menger curvature of facet is also not change. So, we could use the Menger curvature of facet for watermarking.

3. The Proposed Algorithm

3.1. Overview

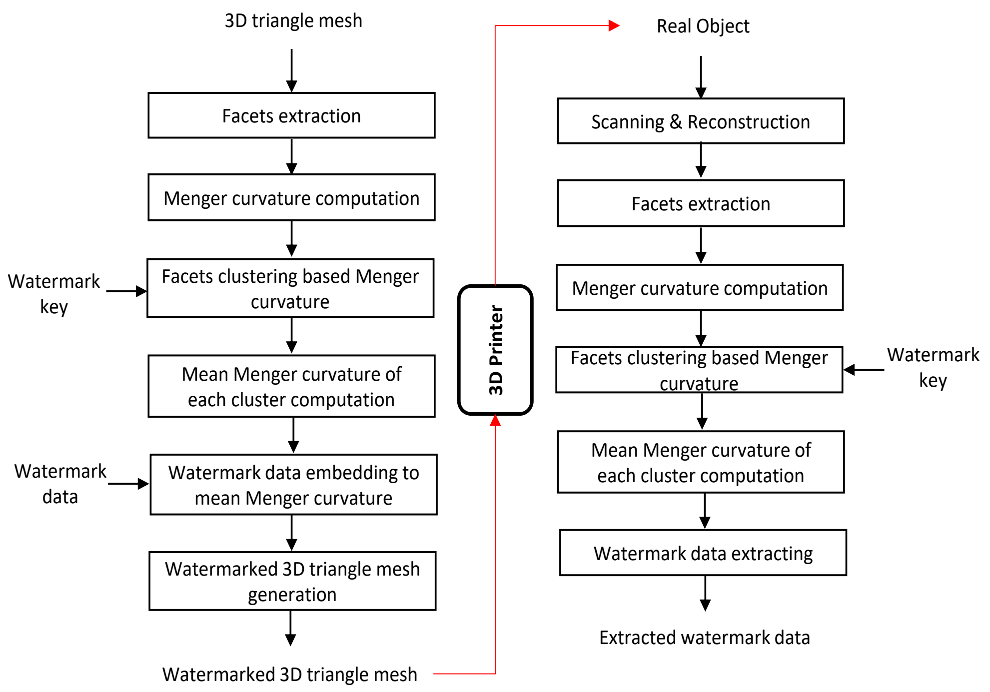


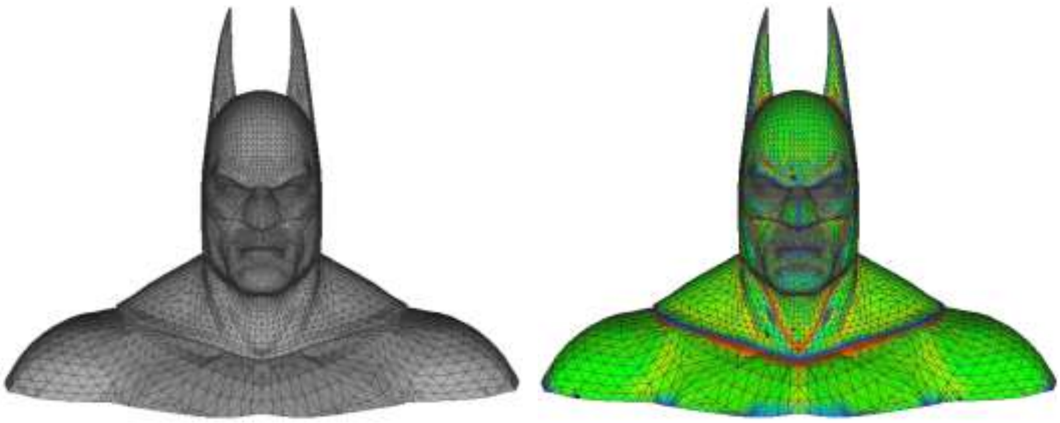
Figure 2. The Proposed Algorithm

The proposed algorithm is described in Figure 2. Facets are extracted from 3D printing file (3D triangle mesh) to compute their Menger curvature. After that, facets are classified into groups by the clustering algorithm based on their Menger curvature. Watermark key is the number of groups that we want to classify facets.

With each group of facets, we compute the mean Menger curvature of it, and embed a watermark bit to that mean Menger curvature. The watermarked 3D printing file is generated according to mean Menger curvatures which have been embedded watermark data.

After printing, the real object will be used for scanning and reconstruction to generate the scanned 3D printing file (the scanned 3D triangle mesh). Then, facets are extracted from the scanned 3D printing file for computing Menger curvature and clustering facets into groups. Watermarking data is extracted from the mean Menger curvature of each group. We will describe the detailed watermark embedding and extracting processes in Section 3.2 and Section 3.3.

3.2. Watermark Embedding



(a) (b)

Figure 3. (a) Original Batman Mesh, and (b) Facets Clustering based on Menger Curvature

A 3D printing file contains a number of facets, $\mathbf{F} = \{f_i | i \in [1, N]\}$. Each facet contains three vertices (three points), $f_i = \{v_{ij} | j \in [1,3]\}$. The Menger 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 the clustering algorithm based on the value of Menger curvature, $M = \{m_g | g \in [1, M]\}$. Figure 3 shows the result of facets clustering of Batman mesh based on the Menger curvature.

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

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

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

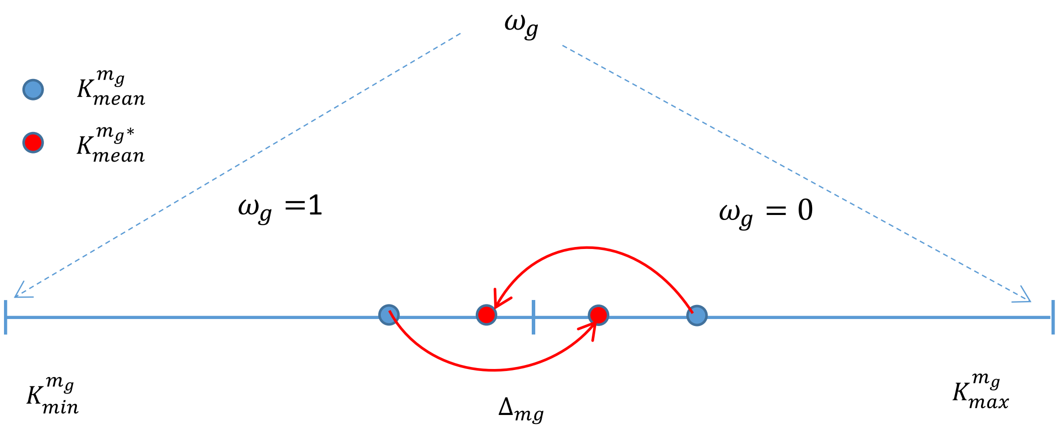


Figure 4. Watermark Bit Embedding by Changing the Mean Menger Curvature

Figure 4 shows the change of the mean Menger curvature $K_{mean}^{m_g}$ of group m_g according to the watermark bit ω_g. The mean Menger curvature $K_{mean}^{m_g}$ is represented by blue point. The watermarked mean Menger curvature $K_{mean}^{m_g*}$ is represented by 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 Menger curvature of group m_g, the change rate α_g is calculated as depicted in Eq. (8):

$$\alpha_g = \frac{K_{mean}^{m_g*}}{\Delta_{mg}} \quad (8)$$

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

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

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

3.3. Watermark Extracting

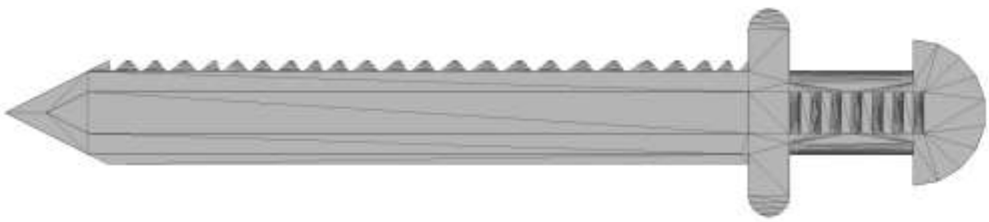
The watermark extraction process is similar the embedding process. Firstly, we also extract facets from the scanned 3D printing file to compute the Menger curvature of facets. After that, we classify them into groups by the clustering algorithm based on the Menger curvature. The watermark key is used for the clustering process. For each group, we find the maximum Menger curvature $K_{max}^{m_g'}$, the minimum Menger curvature $K_{min}^{m_g'}$, and calculate the mean Menger 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 Menger curvature $K_{mean}^{m_g'}$ and the average value Δ'_{mg}:

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

4. Experimental Results and Analysis

Table 1. Experimental Results

Name	# of facets	# of groups	Mean distance error	BER (%)
Sword	2146	67	9.965999E-06	0.0000
Tower	3202	100	9.98818E-06	0.0100
Airplane	9052	282	9.994756E-06	0.0106
Batman	13566	339	9.98718E-06	0.0353
Batman Armor	29496	737	9.989746E-06	0.0081
Gun	33072	826	9.993756E-06	0.0147
Rocket	63497	1587	9.999013E-06	0.0242



Sword

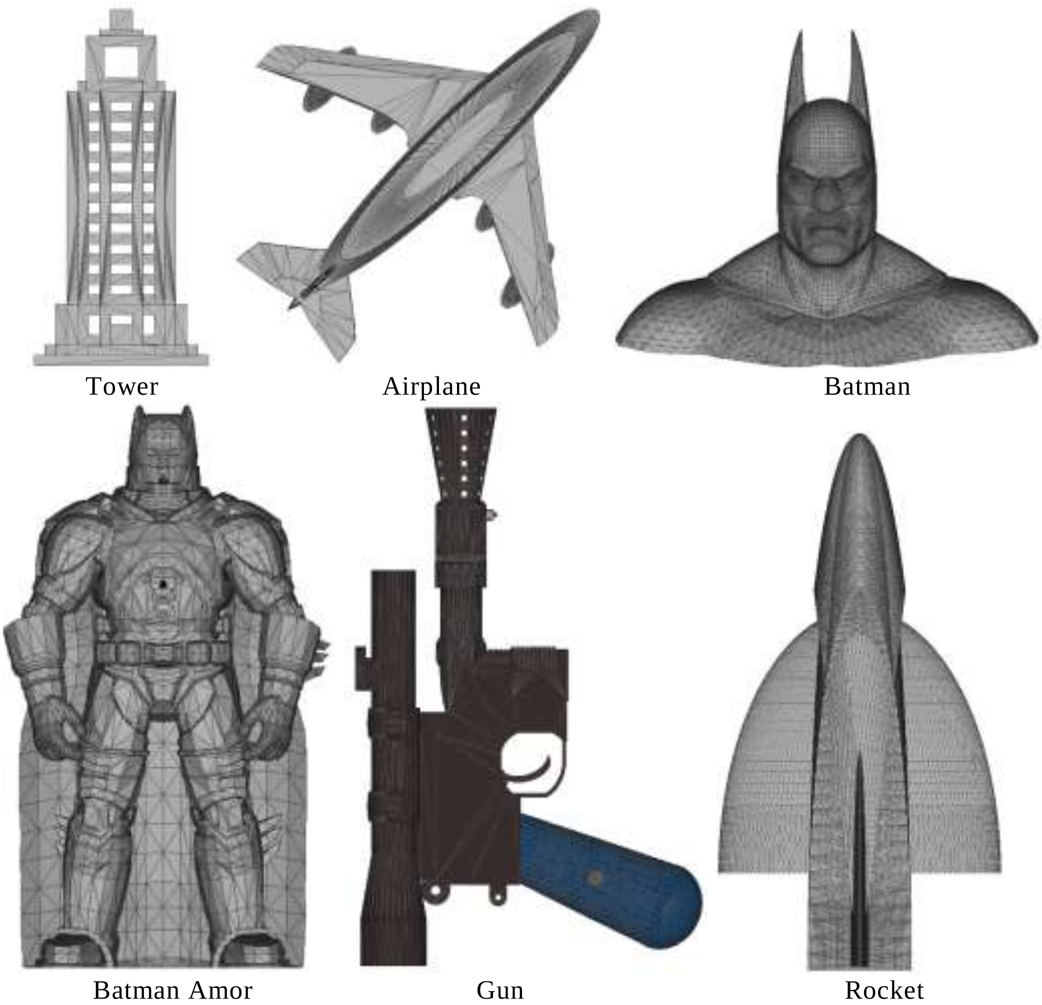


Figure 5. Test Models

We experimented the proposed algorithm with test models in Figure 5. The format of models is STL file. The detailed information of models is shown in Table1. Test models are embedded watermark data according to the 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 [23]. The number of groups is always less than a haft of facets. To safety above condition, we defined the number of groups M according to the number of facets N as Eq. (11).

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

With Sum is the number of digits of N. For example, if $N = 2146$ then $Sum = 4$. 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 and evaluate the robustness of the proposed algorithm.

4.1. Data Accuracy

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

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

Table 1 shows the experimental results with respect to data accuracy. We experimented test models with differential watermarks. The mean distance error between the original 3D printing file and the watermarked 3D printing file is very small. The mean distance error is dependent on the number of the watermarked vertices. The number of the watermarked vertices is dependent on the number of groups, the mean Menger curvature of each group and the clustering algorithm. From Table 1, the mean distance error seems increase according to the number of groups. The distance error is varied from 9.965E-6 to 9.999E-6. It means the change rate of the watermarked 3D printing file is very small. So, the invisibility of the proposed algorithm is very high. Figure 6 shows the mean distance error of test models according to the number of groups.

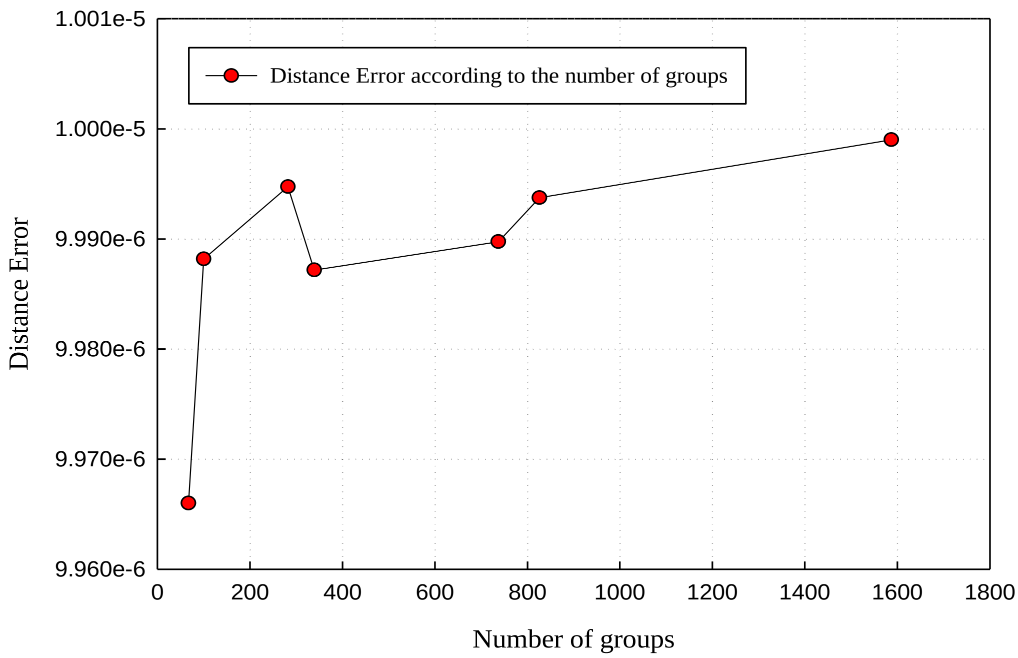


Figure 6. Distance Error According To the Number of Groups

4.2. Robustness Evaluation

Due to the scanned 3D printing file is affected by noise in the scanning process. Thus, it is not perfectly the same with the original 3D printing file. Due to translation and rotation only change the spatial location of 3D printing file. Thus, we only re-scale the scanned 3D printing file before extracting facets for watermark extraction. In order to evaluate the robustness of the proposed algorithm, we calculate the bit error rate (BER). We calculate BER by comparing the extracted watermark data with the original watermark data as shown in Eq. 13.

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

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 facets. The number of the watermarked facets is dependent on the number of groups, the number of facets in each groups and the clustering algorithm. The BER is varied from 0.000 % to 0.0353%. Figure 7 shows the BER of the proposed algorithm according to the number of groups. The BER seems increase according to the number of groups.

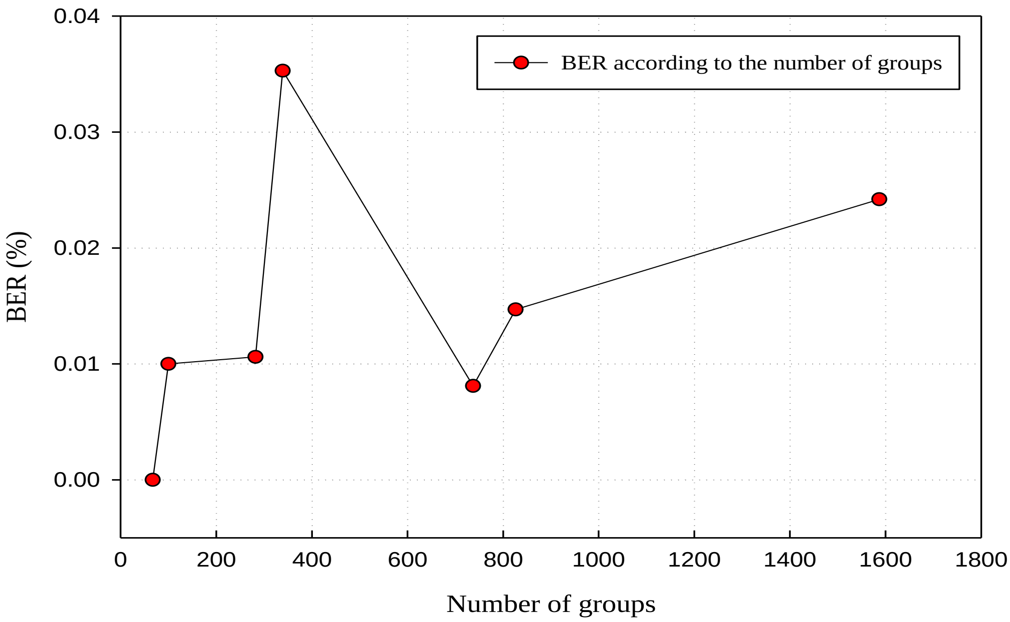


Figure 7. The BER According to the Number of Groups

5. Conclusion

In this paper, we proposed a novel watermarking algorithm for 3D printing. It is based on the Menger curvature of facets and the clustering algorithm. We experimented the proposed algorithm with many 3D printing files. Experimental results showed that the mean distance error between the watermarked 3D printing file and the original 3D printing files is very small. Experimental results verified that the proposed method has low BER. This mean the proposed algorithm is invisibility and robustness with geometric attacks as rotation, translation and scaling. Next time, we will improve the proposed algorithm and apply to the copyright protection system.

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