Blind Robust 3-D Mesh Watermarking Based on Mesh Saliency and QIM Quantization for Copyright Protection

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Abstract. Due to the recent demand of 3-D models in several applications like medical imaging, video games, among others, the necessity of implementing 3-D mesh watermarking schemes aiming to protect copyright has increased considerably. The majority of robust 3-D watermarking techniques have essentially focused on the robustness against attacks while the imperceptibility of these techniques is still a real issue. In this context, a blind robust 3-D mesh watermarking method based on mesh saliency and Quantization Index Modulation (QIM) for Copyright protection is proposed. The watermark is embedded by quantifying the vertex norms of the 3-D mesh using QIM scheme since it offers a good robustness-capacity tradeoff. The choice of the vertices is adjusted by the mesh saliency to achieve watermark robustness and to avoid visual distortions. The experimental results show the high imperceptibility of the proposed scheme while ensuring a good robustness against a wide range of attacks including additive noise, similarity transformations, smoothing, quantization, etc.

Keywords: 3-D mesh watermarking · Quantization Index Modulation (QIM) · Copyright protection · Mesh saliency

1 Introduction

Due to the rapid development of digital services and the increase in network bandwidth, the transfer of multimedia contents such as image, audio, video and

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3-D model has been increased considerably. These contents can be modified or duplicated easily. Therefore, the need to develop security methods became crucially important. Digital watermarking has been found as an efficient solution to overcome this issue. Its underlying concept is to embed an extra information called watermark into multimedia content to protect its ownership. In the last decade, 3-D meshes have been widely used in medical images, computer aided design (CAD), video games, virtual reality, etc. Each 3-D watermarking system should ensure a three major requirements: imperceptibility, capacity and robustness. The attacks can be divided into two major types. Connectivity attacks including subdivision, cropping, remeshing, and simplification. Geometric attacks that include similarity transformations, local deformation operations and signal processing manipulations. The applications of 3-D mesh watermarking include copyright protection, authentication, content enhancement, indexation, etc. We note that the proposed method aims to protect copyright. It is worth mentioning that in contrast with the maturity of image watermarking techniques [1], there are only few watermarking methods that work on 3-D meshes. In addition, the processing techniques applied to 2D images cannot be used in case of 3D meshes [2–5]. This is due to the challenges in three dimensional geometry related to its irregular topology as well as the complexity of attacks that target this kind of geometrical content [6,7]. The majority of 3-D watermarking techniques have essentially focused on the robustness against attacks. Few 3-D mesh watermarking methods based on saliency have been proposed [8]. In [9], a watermarking 3-D mesh method using the visual saliency is presented. Firstly, the perceptually conspicuous regions using the mesh saliency [10] have been identified. Secondly, the norm of each vertex is calculated and its histogram is constructed. The watermark is embedded in each bin by normalizing the associated vertex norms. Zhan et al. [11] proposed a blind 3-D mesh watermarking algorithm based on curvature. The authors calculated the root mean square curvature for all vertices of the 3-D model. The watermark is embedded by modulating the mean of the root mean square curvature fluctuation of vertices. Rolland-Neviere et al. [12] proposed a 3-D mesh watermarking method where the watermark embedding is formulated as a quadratic programming problem. Son et al. [13] proposed a 3-D watermarking method with the aim of preserving the appearance of the watermarked 3-D model. The method used the distribution of the vertex norm histogram as a watermarking primitive that is already introduced by Cho et al. [14]. The latter inserts the watermark by altering the mean or variance of the vertex norms histogram.

In this paper, a 3-D mesh blind and robust watermarking method based on mesh saliency and QIM quantization is proposed. The watermark bits are inserted in the host 3-D mesh by quantizing its vertices norms. The choice of these norms has been guided by the mesh saliency of the 3-D mesh. Taking the full advantages of QIM scheme as well as mesh saliency, the proposed method can achieve high robustness to common attacks while preserving high imperceptibility. The rest of this paper is organized as follows. Section 2 presents the background. Section 3 gives a description of the proposed method composed by embedding and extraction. The experimental setup, evaluation metrics and experimental results are discussed in Sect. 4. Finally, Sect. 5 concludes the paper.

2 Background

2.1 3-D Mesh Saliency

Mesh saliency can be defined as a measure that captures the importance of a point or local region of a 3-D mesh in a similar way to human visual perception [15]. The visual attention of Human is usually directed to the salient shape of the 3-D model. The evaluation of mesh saliency used in the proposed scheme is Lee et al. [10]. The later evaluates the saliency of each vertex using the difference in mean curvature of the 3-D mesh surfaces from those at other vertices in the neighborhood. The first step is computing surface curvatures. The computation of the curvature at each vertex v is performed using Taubin's method [16]. Let $Curv(v)$ the mean curvature of a mesh at a vertex v. The Gaussian-weighted average of the mean curvature can be expressed as follows:

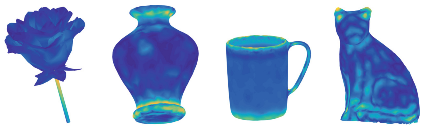
$$G(Curv(v), \sigma) = \frac{\sum_{x \in N(v,2\sigma)} Curv(x) exp(\frac{-\|x-v\|^2}{2\sigma^2})}{\sum_{x \in N(v,2\sigma)} exp(\frac{-\|x-v\|^2}{2\sigma^2})} \tag{1}$$

where x is a mesh point and $N(v, \sigma)$ denotes the neighborhood for a vertex v which represents a set of points within an Euclidean distance σ calculated as:

$$N(v, \sigma) = \{x| \parallel x - v \parallel < \sigma\} \tag{2}$$

The saliency $S(v)$ of a vertex v is calculated as the absolute difference between the Gaussian-weighted averages computed at fine and coarse scale.

$$S(v) = |G(Curv(v), \sigma) - G(Curv(v), 2\sigma)| \tag{3}$$



(a) (b) (c) (d)

Fig. 1. Saliency of 3-D meshes using Lee's method [10] (a) Flower, (b) Vase, (c) Cup, (d) Cat.

Figure 1 shows an example of mesh saliency using Lee's method [10].

2.2 Quantization Index Modulation

Quantization Index Modulation (QIM) approaches have been widely used in image, audio, and video processing. Their application to 3-D meshes is trivial since two quantifiers are needed to insert a binary message in the 3-D data [17]. QIM techniques are simple to implement and have a small complexity. In addition, they ensure a high tradeoff between robustness and capacity. Each watermark bit is associated to a quantizer in the host signal. Let $b \in (0, 1)$ the watermark bit and x the host signal to be quantized. The QIM techniques operate independently on these two elements. In order to embed a bit b, two quantizers Q_0 and Q_1 are needed [18]. They can be defined as follows:

$$Q_b(x) = \Delta[\frac{1}{\Delta}(x - (-1)^b \frac{\Delta}{4}) + (-1)^b \frac{\Delta}{4}] \tag{4}$$

Where [] refers to the rounding operation and Δ is the quantization step. In the extraction process the signal is re-quantized using the same family of quantizer to get the embedded bits. The recovered bits are easily calculated as follows:

$$\hat{b} = argmin \, \|x - Q_b(x)\| \tag{5}$$

3 The Proposed Method

In this paper, a blind robust 3-D mesh watermarking technique based on visual saliency and QIM quantization for Copyright protection is proposed. The watermark is embedded by modifying the salient vertex norms of the 3-D mesh to using mesh saliency and QIM quantization. The mesh saliency of Lee et al. [10] used to obtain candidate vertices aims to ensure high imperceptibility and to improve the watermark robustness. The choice of these points has been driven by the fact that these primitives are relatively stable even after applying several attacks including similarity transformations, noise addition, smoothing, quantization, etc. Figure 2 shows the flowchart of the proposed method. Figure 3 illustrates the Lee's [10] mesh saliency of Bimba model after applying different attacks.

3.1 Watermark Embedding

The proposed method takes the full advantage of the mesh saliency to achieve high imperceptibility. The watermarking bits are embedded by quantizying the vertex norms of the 3-D model using mesh saliency. The motivation behind using the QIM quantization is the good tradeoff between capacity and robustness [17]. In addition, QIM methods are blind. Firstly, the mesh saliency is computed and a threshold is fixed automatically to define the salient and non-salient points. In fact, for each saliency vector, the 70% maximum values represent the salient points while the other points are considered non-salient. Next, the norms of salient points are calculated according to this threshold. After, a watermark is generated using pseudo-random generator using a secret key (key1). Afterwards, two quantizers Q_{zero} and Q_{one} are calculated using Eq. 4 according to the watermark bit. Finally, starting from the modified vertex norms the new vertex coordinates are calculated using Eq. 6 in order to construct the 3-D watermarked mesh. We note that the quantization step can be considered as second secret key (key2) that will be used in the extraction step.

$$V'(x', y', z') = \frac{\|V'\|}{\|V\|} V(x, y, z) \tag{6}$$

where $V'(x', y', z')$ are the new coordinates of new vertices and $V(x, y, z)$ are the old coordinates.

3.2 Watermark Extraction

The watermark extraction is blind since only secret keys (key1 and key2) are needed. First, the mesh saliency of the 3-D watermarked model is calculated and the salient points are extracted according to the threshold used in the watermark embedding. We note that this parameter is chosen automatically since it represents the 70% maximum values of the saliency vector. Next, the norms according to the chosen vertices are calculated. The two quantizers are calculated and the extracted watermark bits are obtained using Eq. 5.

4 Experimental Results

4.1 Experimental Setup

The proposed watermarking method is tested on several 3-D meshes with different shape complexities: Flower (2523 vertices, 4895 faces), Vase (2527 vertices, 5004 faces), Cup (9076 vertices, 18152 faces), Ant (7654 vertices, 15304 faces), Bimba (8857 vertices, 17710 faces) and cat (3534 vertices, 6975 faces) where some of them are shown in Fig. 4((a), (c), (e)). It is worth noticing that for comparison purpose the imperceptibility and robustness evaluation have been performed using the 3-D models: Bunny (34835 vertices, 69666 faces), Horse (112642 vertices, 225280 faces) and Venus (100759 vertices, 201514 faces). The quantization step is chosen in such a way that ensures good tradeoff between imperceptibility and robustness. This parameter is tuned experimentally and we kept $\Delta = 0.08$. Several metrics have been used to measure the amount of distortion introduced by the embedding process. This distortion can be measured geometrically or perceptually. The maximum root mean square error (MRMS) proposed in [19] is used to calculate the objective distortion between the original meshes and the watermarked ones. The Hausdorff distance (HD) is defined as the minimum Euclidean distance between a point of one surface of the original mesh and another surface of the distorted mesh. The mesh structural distortion measure (MSDM) metric is chosen to measure the visual degradation of the watermarked meshes [20]. The MSDM value is equal to 0 when the original and

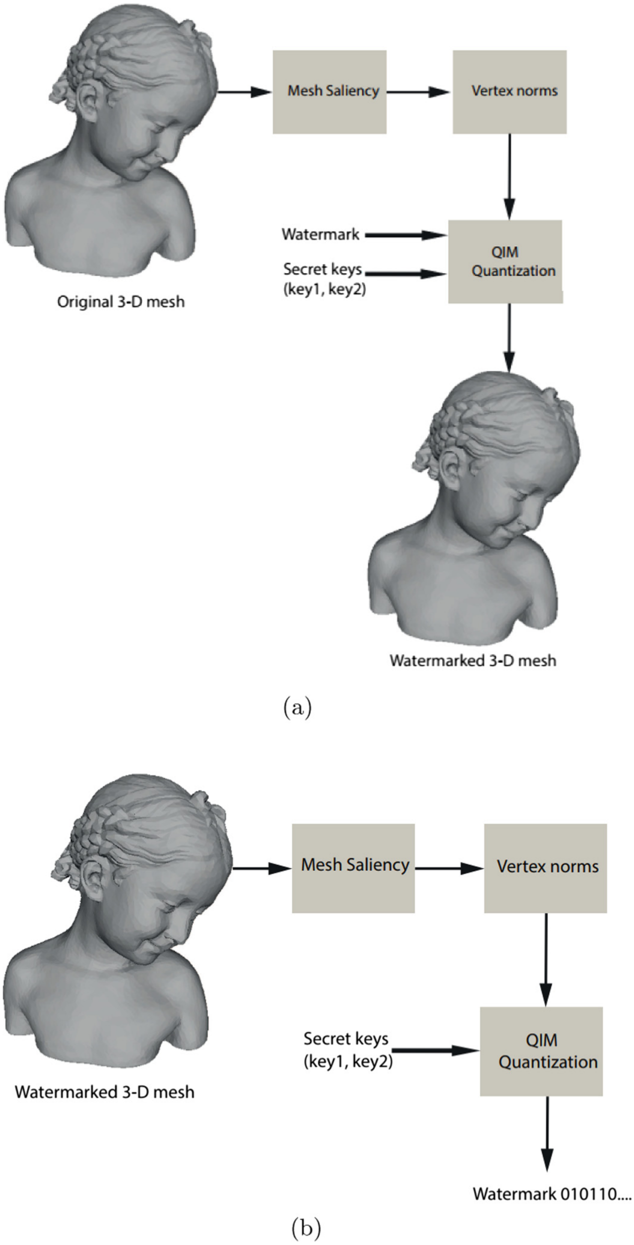


Fig. 2. Flowchart of the proposed method: (a) watermark embedding, (b) watermark extraction.

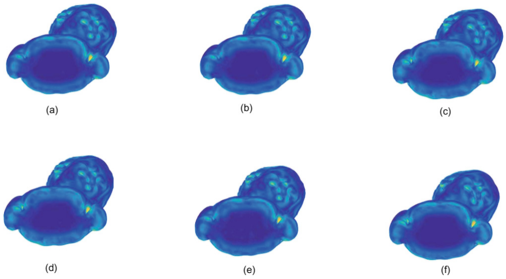


Fig. 3. Mesh saliency of Bimba before and after attacks: (a) before attack, (b) additive noise 0.3%, (c) Similarity transformation 1, (d) Simplification 10%, (e) Quantization 9 bits, (f) Smoothing $\lambda = 0.1$ (30 iterations).

watermarked 3-D objects are identical. Otherwise, the MSDM value is equal to 1 when the objects are visually very different. The robustness is measured using the normalized correlation ($Corr$) between the inserted watermark and the extracted one.

$$Corr = \frac{\sum_{i=1}^{M}(w_i' - \overline{w}^*)(w_i - \overline{w})}{\sqrt{\sum_{i=1}^{M}(w_i' - \overline{w}^*)^2 . \sum_{i=1}^{M}(w_i - \overline{w})^2}} \tag{7}$$

Where $i \in \{1, 2, \ldots, M\}$, $\overline{w}^*$ and $\overline{w}$ are the averages of the watermark bits respectively.

Table 1. Watermark imperceptibility measured in terms of MRMS, HD and MSDM.

Model	MRMS (10^{-3})	HD (10^{-3})	MSDM
Flower	0.63	4.33	0.30
Vase	0.41	3.34	0.37
Cup	0.98	2.95	0.37
Ant	0.62	4.19	0.51
Cat	0.61	1.0	0.16
Bimba	0.39	1.63	0.10
Average	0.61	2.91	0.30

4.2 Results Discussion

Imperceptibility. Figure 4 illustrates the original and watermarked 3-D meshes. We can see that the distortion is imperceptible thanks to the saliency adjustment. In addition, according to Table 1, it can be observed that the proposed method can achieve high imperceptibility in terms of MRMS, HD and

(a) (b) (c) (d) (e) (f)

Fig. 4. (a) Flower, (b) Watermarked Flower, (c) Vase, (d) Watermarked Vase, (e) Cup, (f) Watermarked Cup.

MSDM. We believe that this performance is obtained thanks to the exploitation of mesh saliency to avoid serious distortions. It can be also observed that the imperceptibility results in terms of MRMS, HD and MSDM are different from a mesh to another. This difference is mainly due to the curvature nature of each one of these 3-D meshes.

Table 2. Watermark imperceptibility without using saliency measured in terms of MRMS, HD and MSDM compared to the proposed method.

Model	MRMS (10^{-3})	HD (10^{-3})	MSDM
Flower	0.89/**0.63**	5.03/**4.33**	0.88/**0.30**
Vase	0.58/**0.41**	4.76/**3.34**	0.76/**0.37**
Cup	1.02/**0.98**	3.45/**2.95**	0.87/**0.37**
Ant	0.83/**0.62**	4.43/**4.19**	1.0/**0.51**
Cat	1.2/**0.61**	1.9/**1.0**	0.29/**0.16**
Bimba	0.76/**0.39**	2.98/**1.63**	1.66/**0.10**
Average	0.88/**0.61**	3.76/**2.91**	0.91/**0.30**

To further evaluate the importance of using mesh saliency to improve the imperceptibility of the proposed method, we compare the obtained results with those obtained without using the saliency. Table 2 exhibits the imperceptibility performance in terms of MRMS, HD and MSDM without using the mesh saliency compared to the proposed method based on mesh saliency. We note that the obtained results of our method based on saliency are shown in bold. According to Table 2, it can be seen that the proposed method outperforms which illustrates the imperceptibility improvement achieved using the saliency aspect in the watermark embedding.

Robustness. To evaluate the robustness of the proposed scheme, 3-D meshes have been undergone several attacks. For this purpose, a benchmarking system has been used [21]. The robustness of our scheme is tested under several attacks including noise addition, smoothing, quantization, cropping, subdivision and similarity transformations (translation, rotation and uniform scaling).

Figure 5 shows the model Bimba after several attacks. To evaluate the robustness to noise addition attack, binary random noise was added to each vertex of 3-D models with four different noise amplitudes: 0.05%, 0.10%, 0.30% and 0.50%. According to Table 3, it can be seen that the proposed method is robust against noise addition four all the 3-D models.

For evaluating the resistance of the proposed scheme to smoothing attack, the 3-D models have undergone Laplacian smoothing proposed in [22] using 5, 10, 30 and 50 iterations while keeping the deformation factor $\lambda = 0.10$. Table 3 shows that our method is able to withstand smoothing operation. The robustness of the proposed scheme is evaluated against elements reordering attack called also file attack. According to Table 3 the proposed scheme can resist to element reordering. Quantization is also applied to the 3-D models to evaluate the robustness against this attack using 7, 8, 9, 10 and 11 bits. It can be concluded from Table 4 that the proposed method shows good robustness against quantization regardless of the used 3-D mesh. The robustness of our method is evaluated against similarity transformation in which 3-D models have undergone a random rotation, a random uniform scaling and a random translation. Table 4 sketches the obtained results in terms of correlation. It can be observed that our method can achieve high robustness against these attacks. The proposed scheme is tested against subdivision attack including three schemes (loop, midpoint and sqrt3). The obtained results in Table 4 in terms of correlation exhibit the high robustness against subdivision. Cropping is considered to be one of the most damaging attack since it deletes a region from the 3-D mesh and thus the useful information will be lost. It can be observed from Table 4 that the proposed method is not enough robust to cropping attacks. In fact, if the deleted surface contains salient points, the extraction process will fail. In the future work, we will search a solution to the issue related to the robustness weakness against this attack.

(a) (b) (c) (d) (e)

Fig. 5. Six attacks versions of Bimba: (a) noise addition 0.50%, (b) Smoothing $\lambda = 0.1$ with 5 iterations, (c) quantization 9 bits, (d) Similarity transformation, (e) Cropping ratio 10.0.

4.3 Comparison with Alternative Methods

To further evaluate the performance of the proposed scheme in terms of imperceptibility and robustness we compare it with Cho's [14], Wang's et al. [23],

Table 3. Watermark robustness against additive noise, Laplacian smoothing and elements reordering measured in terms of correlation.

Parameters	Noise addition				Laplacian Smoothing				Elements reordering		
	0.05%	0.10%	0.30%	0.50%	5	10	30	50	Type 1	Type 2	Type 3
Flower	0.98	0.94	0.89	0.81	1.0	0.99	0.98	0.89	1.0	0.95	1.0
Vase	1.0	0.91	0.85	0.71	1.0	0.98	0.97	0.86	1.0	0.96	1.0
Cup	0.96	0.93	0.83	0.78	1.0	1.0	0.90	0.87	1.0	1.0	0.98
Ant	0.97	0.95	0.86	0.77	0.99	0.97	0.93	0.85	1.0	0.98	1.0
Cat	0.99	0.91	0.88	0.73	1.0	0.95	0.95	0.90	1.0	1.0	1.0
Bimba	1.0	0.93	0.90	0.80	1.0	1.0	0.94	0.91	0.99	0.97	0.96
Average	0.98	0.93	0.87	0.77	0.99	0.98	0.94	0.88	0.99	0.97	0.99

Table 4. Watermark robustness against quantization, similarity transformations, subdivision and cropping measured in terms of correlation.

Parameters	Quantization					Similarity transformation			Subdivision			Cropping		
	11-bits	10-bits	9-bits	8-bits	7-bits	Type 1	Type 2	Type3	Loop iter 1	Midpoint iter 1	Sqrt3 iter 1	10%	30%	50%
Flower	1.0	1.0	0.98	0.91	0.80	1.0	0.95	0.98	1.0	0.93	1.0	0.56	0.44	0.28
Vase	1.0	1.0	0.98	0.91	0.78	0.92	0.94	0.98	0.98	0.87	0.96	0.59	0.31	0.12
Cup	1.0	0.99	0.97	0.93	0.83	1.0	1.0	1.0	1.0	0.84	0.94	0.67	0.37	0.16
Ant	1.0	1.0	0.97	0.92	0.77	0.94	0.96	1.0	0.94	0.91	1.0	0.61	0.45	0.21
Cat	1.0	0.97	1.0	0.93	0.76	1.0	1.0	0.96	0.95	0.94	1.0	0.58	0.30	0.22
Bimba	1.0	1.0	0.99	0.98	0.86	0.98	1.0	0.90	0.98	0.95	0.96	0.50	0.22	0.17
Average	1.0	0.99	0.98	0.93	0.80	0.97	0.97	0.97	0.97	0.91	0.97	0.58	0.35	0.19

Table 5. Imperceptibility comparison with Cho's [14], Rolland-Neviere's [12] and Son's [13] schemes measured in terms of MRMS and MSDM for Horse model.

Metric	[14]	[12]	[13]	Our method
MRMS (10^{-3})	3.17	1.48	2.90	0.53
MSDM	0.3197	0.2992	0.3197	0.2865

Zhan's et al. [11], Rolland-Neviere et al. [12] and Son's et al. [13] schemes. We note that for comparison purpose, we have tested the robustness of our method using the 3-D models Bunny, Horse and Venus.

Table 5 exhibits the imperceptibility comparison with schemes in terms of MRMS and MSDM. The obtained results demonstrate the high imperceptibility of the proposed method and show its superiority to the alternative methods. The proposed method is compared to Cho's [14] and Zhan's [11] methods in terms of imperceptibility using MRMS as well as robustness in terms of correlation against noise addition, smoothing and quantization using Bunny and Venus 3-D meshes. Table 6 sketches the robustness comparison in terms of correlation between our method and schemes [11, 14]. It can be concluded from Table 6 that the proposed method is quite robust to additive noise, smoothing and quantization and outperforms the alternative methods.

Table 6. Robustness comparison with Cho's [14] and Zhan's [11] schemes against additive noise, smoothing and quantization in terms of correlation for Bunny and Venus models.

Model	Bunny									Venus								
Attack	Noise addition			Smoothing			Quantization			Noise			Smoothing			Quantization		
Intensity	0.1%	0.3%	0.5%	10	30	50	9	8	7	0.1%	0.3%	0.5%	10	30	50	9	8	7
[14]	0.72	0.72	0.66	0.84	0.60	0.36	0.73	0.58	0.17	0.94	0.87	0.27	0.94	0.63	0.45	0.87	0.48	0.07
[11]	1.0	0.91	0.80	0.92	0.85	0.44	1.0	0.91	0.58	0.95	0.95	0.79	0.95	0.93	0.78	1.0	0.83	0.73
Proposed method	1.0	0.93	0.84	0.97	0.91	0.58	1.0	0.92	0.67	1.0	0.98	0.81	1.0	0.99	0.79	1.0	0.90	0.85

5 Conclusion

In this paper, a blind robust 3-D mesh watermarking method based on mesh saliency and QIM quantization for Copyright protection is proposed. The proposed method achieves both high robustness and imperceptibility. The robustness requirement is achieved by quantizing the vertex norms using QIM while the imperceptibility achievement is ensured by adjusting the watermarking embedding according to the mesh visual saliency. The experimental results demonstrate that the proposed scheme yields a good tradeoff between the imperceptibility and robustness requirements. Moreover, experimental simulations show that the proposed method outperforms the existing methods against the majority of common attacks. In the future work, we will investigate the issue related to the robustness weakness against cropping attack.

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