Turkish Journal of Electrical Engineering & Computer Sciences

http://journals.tubitak.gov.tr/elektrik/

Research Article

Turk J Elec Eng & Comp Sci
(2019) 27: 4518 – 4529
© TÜBİTAK
doi:10.3906/elk-1810-62

Hypothesis-based vertex shift method for embedding secret logos in the geometric features of 3D objects

Arthy RAJAKUMAR[1,*], **Mala KALIAPPAN**[2], **Suresh Babu RAJENDRAN**[3]
[1]Department of Information Technology, Kamaraj College of Engineering and Technology, Madurai, India
[2]Department of Computer Science and Engineering, Mepco Schlenk Engineering College, Sivakasi, India
[3]Department of Electronics and Communication Engineering,
Kamaraj College of Engineering and Technology, Madurai, India

Received: 08.10.2018 • **Accepted/Published Online:** 08.07.2019 • **Final Version:** 26.11.2019

Abstract: A recent challenge in information technology is to protect secret data and preserve the ownership of a product. There are many duplicate products being released on a daily basis. Owners have a high risk in proving their products. Watermarking is a technique used to preserve ownership by hiding the owner's information in their products. The proposed hypothesis-based vertex shifting algorithm embeds 2D secret logos in 3D cover objects. The 3D objects are represented using vertices and facets. 3D watermarking faces various challenges and one among them is capacity. In this work, capacity is addressed by using a hypothesis-based vertex shift method that enables the embedding process for all the coordinates of the vertex. The method works by partitioning the vertex based on a shift factor called svalue. The svalue is chosen based on the visual quality of the watermarked object. The metrics used for testing are bit error rate for the recovered watermark, peak-to-signal noise ratio, and vertex signal-to-noise ratio (VSNR) of the watermarked 3D image. The proposed algorithm shows that a maximum of 3 bits can be embedded in a vertex when compared with the existing algorithms. The VSNR value of the proposed algorithm is high (125.87) compared to the existing algorithms. This shows that the algorithm withstands visual quality inspection. Hence, it is a robust watermarking algorithm for embedding secret logos into 3D objects with better visual quality and higher resilience against translation and uniform scaling attacks.

Key words: 3D objects, watermarking, peak signal-to-noise ratio, bit error rate, vertex signal-to-noise ratio, attack, translation attack, uniform scaling attack

1. Introduction

Privacy maintenance is now a big problem, as people abuse the copyrights of owners and misuse them. Privacy can be attained by hiding the copyright information. There are plenty of techniques to secure logos and one such technique is digital watermarking. Digital watermarking hides the secret logo from an unauthorized user by embedding the secret logo into the cover image. Digital watermarking can be classified based on various factors. Watermarking can be classified based on cover images as 3D watermarking and 2D watermarking. There are many techniques used to perform 2D watermarking [1, 2]. In 3D watermarking, the 3D cover object is taken as the cover image and the secret data can be text, 2D images, or 3D objects.

Classification based on the embedding process is in the spatial domain or frequency domain. Spatial-domain watermarking embeds the secret data in the geometrical features of the cover image. In transform-

*Correspondence: arthyit@kamarajengg.edu.in

domain watermarking, embedding is done in the frequency domain of the cover image.

Watermarking classification can be done based on the extraction process as blind and nonblind watermarking. Blind watermarking does not require any original data for extraction purposes, whereas nonblind watermarking requires original data for extraction. This paper aims at blind 3D watermarking to achieve the properties of watermarking like high visual quality, capacity, and robustness. 3D watermarking is a challenging research area because the embedding process depends on the capacity and the quality of the watermarked object.

This paper focuses on 3D watermarking, which takes 3D objects for cover objects. The 3D objects can be represented in various graphical models like voxel, mesh, and constructive solid geometry or as an implicit set of parameterized equations such as nonuniform rational B-spline.

The embedding process highly depends on the visual quality of the 3D watermarked object. The algorithms proposed in [3, 4] address the visual quality of the watermarked object. A surface-preserving algorithm was proposed in [5], which enforces the distortion of the 3D watermarked object.

Watermarking algorithms are also used for providing authentication. In [6], the heat kernel signature method was proposed, which is based on 3D model hashing dependent on the key and parameter for 3D authentication. There are many applications that use digital watermarking and one such application is in the medical field. Telemedicine applications use digital watermarking to embed patient information into cover images. Li and Kim [7] introduced an algorithm named CAT as an orthogonal transformation that offers considerable simplicity in the calculation of the transform coefficients. In other words, it can improve the quality of watermarked images by reducing energy loss compared with the traditional complicated transform process.

Singh and Ranade [8] addressed the capacity problem. They introduced an accurate ART for a fast and high-capacity robust image watermarking system with low computation time. The high-capacity algorithm has the lack of fragility; also, it is not invariant to similarity transformations.

The embedding process has an impact on the region of interest of any 3D object. Clustering algorithms are used to cluster the region of interest and regions not of interest, and embed the secret logo into the 3D object. In [9], Soliman et al. used K-means clustering and self-organizing maps to perform watermark insertion.

Transform-domain watermarking embeds secret bits in the frequency domain of the 3D cover object. There are a few algorithms that use transform-domain techniques to embed secret logos. In [10–12], algorithms were proposed for depth image-based rendering (DIBR), which utilizes spread-spectrum technology for embedding in DCT coefficients. Spread-spectrum technology addresses the capacity property in the transform domain. The genetic algorithm [13] approach can be used to identify the domain for embedding.

There are a few algorithms that embed the watermark into the spatial domain of the 3D cover object. In [14–16], embedding of watermarks is done as a geometrical feature. In [17], the embedding process is done by identifying the different levels of vertexes, like detail level and coarse level. In [18], vertex grouping is done by calculating eigenvalues and dividing eigenvalues into corresponding bins using the vertex grouping method. In [19], two models are proposed, namely a clean model and a marked model. These models are used to embed the secret logo into the 3D cover object.

This literature survey shows that the main problems in the area of 3D watermarking are capacity and visual quality. This problem affects the quality of the watermarked object. The main objective of the proposed system is to provide an efficient algorithm that traverses the vertex to maintain the traversal path, which will reduce the causality problem. As a result, high quality of the watermarked data can be maintained.

2. 3D mesh representation

The proposed methodology makes use of 3D objects to perform watermarking and as a result it produces a 3D watermarking object. 3D objects can be represented using mesh. The mesh is represented as $M = \{V, F\}$, where V is a set of vertexes and F is a set of facets. The mesh can be represented as a triangular mesh or polygonal mesh. The triangular mesh representation [20] is taken for experimental analysis. Triangular mesh contains facets with three vertices but polygonal mesh contains facets with more than three vertices.

$$V = v_i = \{v_{ix}, v_{iy}, v_{iz}\}, \tag{1}$$

where v_{ix}, v_{iy}, and v_{iz} represent the x, y, and z coordinate values in decimal format.

$$F = \{v_i, v_j, v_k\}, \tag{2}$$

where v_i, v_j, and v_k represent the vertices that make a triangle facet. (1) and (2) show the formation of vertices and facets in triangular mesh.

Table 1. Coordinates of a vertex.

x - Coordinate value	y - Coordinate value	z - Coordinate value
0.238769205544997	21.313797270601664	0.130012607000097

Table 1 shows the coordinates of a vertex representation in .OBJ file format. This shows that the vertex is represented in decimal values. These values are used in the embedding process.

The .OBJ file format represents the 3D objects as shown in Figure 1. The triangular mesh representation of the 3D teddy object looks like a wired view of an object.

3. Hypothesis-based vertex shifting method

The embedding of secret logos in the spatial domain of 3D watermarking adopts various methodologies. The methodology incorporated in the proposed algorithm is a vertex-shifting method. The vertex-shifting method embeds the bits of the secret logo by moving the coordinates of the vertex with respect to a shift value (svalue) and bits in the secret logo. Shifting of all the vertices in a facet will produce a causality problem that may lead to distortion.

The causality problem is addressed in the proposed algorithm by checking the node's nature. The node can be either an immune node or a suspect node. If the node is a suspect node then the embedding process can be done on that vertex. If the node is an immune node then it indicates that the facet contains vertices with embedded data.

Hypothesis 1 *BSegCount = ODD and SBit = 0 BSegCount = EVEN and SBit = 1*

Hypothesis 2 *BSegCount = ODD and SBit = 1 BSegCount = EVEN and SBit = 0*

Here, BSegCount describes the base segmentation count and SBit is the secret bit. The embedding process uses the hypotheses given in Hypothesis 1 and Hypothesis 2 to embed the secret logo in the 3D cover object. The null hypothesis (Hypothesis 1) states that if the base segmentation count is ODD with secret bit as 0 or base segmentation count is EVEN with secret bit as 1, then vertex shifting is done. The alternate

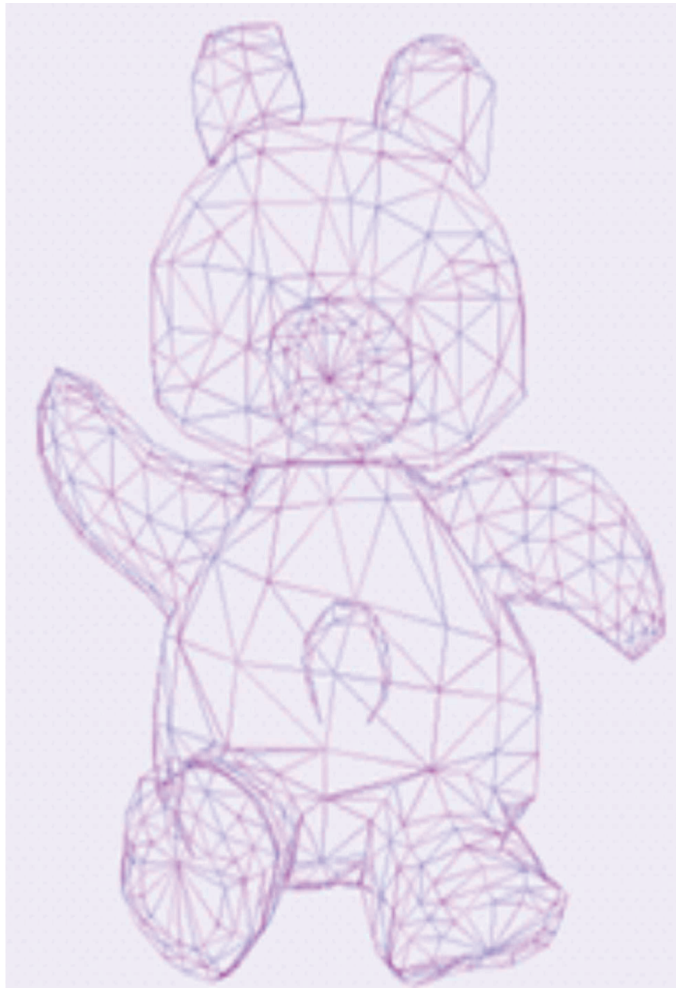

Figure 1. Triangular mesh representation of 3D teddy object.

hypothesis (Hypothesis 2) states that if base segmentation count is ODD with secret bit value 1 or the base segmentation count is EVEN with secret bit as 0, then the vertex will not be shifted.

The hypothesis is explained in Figure 2. Figure 2a describes a single facet f_1 with 3 vertices v_1, v_2, and v_3. Vertex v_1 is a suspected node, which is the node to be taken for embedding the secret bit 0. The vertex is projected towards the bases of the facet. The base of the facet is partitioned based on the svalue until the projection.

The result of base segmentation in Figure 2a shows that there are 5 segments and hence the value of g is 5. Since BSegCount is ODD and the secret bit to be embedded is 0, the NULL hypothesis is taken and the vertex is shifted for svalue. This svalue can be determined based on the application. The svalue also determines the visual quality of the watermarked 3D object.

3.1. Watermark embedding

The proposed 3D watermarking algorithm embeds the secret logo using the hypothesis in the geometric features of the 3D object. The result of the watermark embedding process is a 3D watermarked object. Since the

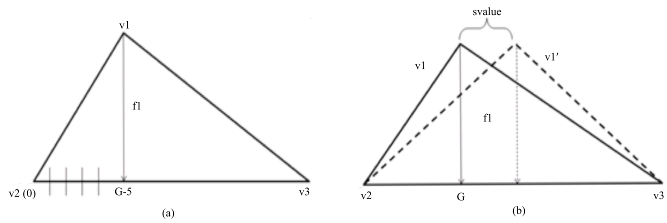

Figure 2. a- Facet before vertex shifting; b- facet after vertex shifting.

embedding is done in the geometric features of the 3D cover image, the geometric feature can be a vertex or an edge. In the proposed method, the vertex is considered for the embedding process.

The vertex-shifting method constructs a vertex table $V_{i,j}$ and facet table $F_{i,j}$. These tables are used for identifying the coordinates of the vertex and neighbor vertices of a facet. This table construction is also used for extracting the secret information.

The algorithm proceeds facet by facet to embed the secret information. Each node is checked for immunity to avoid causality problems. The neighbor node for the suspected node is found from the facet. Since this is a triangle mesh, each facet contains 3 vertices, and so for a node there will be 2 neighbors.

The facet table contains the information about neighbor vertices. If all the vertices in a facet are altered then this leads to a causality problem. To avoid this problem, the suspected vertex in a facet is found and embedding is done in the suspected vertex.

The embedding process is done in all the coordinates of a vertex. While embedding the secret logo, the causality problem is taken into consideration. The triangular mesh contains facets that group three vertices. In the case of embedding, if bits are embedded into all three vertices then the distortion rate will increase. To avoid this, the facet table is constructed, and at the time of embedding, each vertex undergoes infected vertex checking. The vertex can be classified as a protected vertex, suspected vertex, or infected vertex.

A protected vertex is a vertex that can be taken for the embedding process, whereas an infected vertex is a vertex that contains secret data (watermark data). Suspected nodes can be used for the embedding process, which will not lead to causality problems. The svalue is a shift value used to decide the vertex shifting. The facet of the suspected vertex is taken and base segmentation is done based on the svalue.

$$g = round(\frac{V_x}{svalue}) \tag{3}$$

After choosing the svalue the suspected node is projected towards the base using (3), where g is the point that meets the base from the suspected node and it determines the shifting of the vertex.

In Figure 2a, there are 5 divisions from vertex v2 to g, each of size svalue, and hence g is ODD. The shifting is done now based on logic that depends on the nature of g having ODD or EVEN result as shown in Figure 2b.

The proposed hypothesis-based vertex shifting embedding and extraction algorithm utilizes the concept of shifting the vertex based on the hypothesis explained in Figure 2. The hypothesis uses a value named svalue, which determines the visual quality of the 3D watermarked object.

$$mod(g,2) = \begin{cases} 0 & \text{then, one = g * svalue and two = (g+1) * svalue} \\ 1 & \text{then, one = (g+1) * svalue and two = g * svalue} \end{cases} \tag{4}$$

$$S_i = \begin{cases} 0 & \text{then, res = one} \\ 1 & \text{then, res = two} \end{cases} \tag{5}$$

The hypothesis is used to shift the vertex. The vertex shifting depends on g and the secret bit. If g is ODD and the secret bit is 0 then the vertex is shifted for svalue. Otherwise, it is not shifted (see (4) and (5)). The result of (4) gives two values, one and two. The decision of embedding depends on the bits in the secret logo as given in (5). res is a flag to indicate whether the vertex can be shifted or not based on secret bit (S_i).

The embedding process produces the embedded 3D object with distortion tolerance. Algorithm 1 describes the process of embedding.

Algorithm 1: Hypothesis-based vertex shift embedding algorithm.

Input: L: 2D Secret Logo; V: Set of Vertices (M × 3) where M, number of vertices; F: Set of Facets (N × 3) where N, number of facets; k: coordinates of 3D object

Output: W: 3D Watermarked Object

```
S ← flatten(L) /* Converting matrix into vector */
svalue ← 0.5 /* Initial Value */
i ← 1 ;
k ← 1 ;
j ← 1 ;
while i ≤ size(S) do
    while j ≤ N do
        (V1, V2, V3) ← (F_{j,1}, F_{j,2}, F_{j,3}) ;
        if i ≥ size(S) then
            break;
        if j ≥ N then
            j ← 1 ;
            k = k + 1;
        if ¬affected(V1) then
            (p1, p2, p3) ← (V_{1,k}, V_{2,k}, V_{3,k}) ;
            Apply (3);
            Apply (4) based on the value of module of g with 2;
            Apply (5) based on the secret bit S_i ;
            W ← W ∪ (p1, p2, p3) ;
    end
end
```

3.2. Watermark extraction

The proposed algorithm is a blind watermarking algorithm. The extraction process does not require any original model to extract the embedded watermark. Algorithm 2 describes the extraction procedure of the proposed work.

4. Performance analysis

Performance analysis is done using performance metrics like PSNR, BER [21, 22], and VSNR [23]. The PSNR (peak signal-to-noise ratio) is an error comparison metric to ensure that the extraction watermark is not altered.

Algorithm 2: Hypothesis-based vertex shift extraction algorithm.

Input: V: Set of Vertices (M × 3) where M, number of vertices; F: Set of Facets (N × 3) where N, number of facets

Output: M: 3D Cover Object; L: 2D Secret Logo

$svalue \leftarrow 0.5$ /* Initial Value */

$j \leftarrow 1$ while $j \leq N$ $(V_1, V_2, V_3) \leftarrow (F_{j,1}, F_{j,2}, F_{j,3})$;

$(x_1, x_2, x_3) \leftarrow (V_{1,1}, V_{2,1}, V_{3,1})$;

Apply (3) ;

if $g \leftarrow 1$ **then**

  s = 1;

else

  s = 0;

end

$M \leftarrow M \cup (x_1, x_2, x_3)$;

$L \leftarrow L \cup s$

The PSNR value is calculated using the formulas below.

$$MSE = \sum_{i=1}^{H} \sum_{j=1}^{W} \frac{(I(i,j) - I'(i,j))^2}{(H * W)} \tag{6}$$

$$PSNR = 10(log_{10})(\frac{L^2}{MSE}) \tag{7}$$

Here, I(i,j) – Original 3D cover object

$I'(i,j)$ – 3D watermarked object

L - Maximum value of input image

H - Height of the object

W - Width of the object

BER is the number of bit errors divided by the total number of transferred bits during a studied time interval. The BER value is calculated using (8).

$$BER = \frac{\text{Number of pixels wrongly constructed}}{\text{Total number of pixels}} \times 100 \tag{8}$$

Another metric that is used for evaluation is vertex signal-to-noise ratio (VSNR), which shows the variation in the 3D cover object and 3D watermarked object. The VSNR value is calculated based on the SNR value as follows.

$$SNR = \frac{\sum_{j=1}^{M}(X_j^2 + Y_j^2 + Z_j^2)}{\sum_{j=1}^{M}[(X_j - X_j')^2 + (Y_j - Y_j')^2 + (Z_j - Z_j')^2]} \tag{9}$$

$$VSNR = 20log_{10}(SNR) \tag{10}$$

Here, M is the number of vertices, (X_j, Y_j, Z_j) are the 3D cover object coordinates, and (X_j', Y_j', Z_j') are the 3D watermarked object coordinates.

5. Experimental results

The 3D object is represented as a triangular mesh since triangular mesh is easy to process, i.e. the sampling and simplification can be done easily for triangular mesh. The algorithm is tested for various 3D benchmark objects [24]. The 3D objects along with the number of vertices and facets that are used for testing are tabulated in Table 2.

Table 2. Dataset description of 3D object.

Name of 3D object	Number of vertices	Number of facets
Sphere.obj	258	512
Gourd.obj	326	648
Slotmachine.obj	1956	2225
Cow.obj	2904	5804
Teapot.obj	3644	6321
Pumpkin.obj	5002	10000
Casting.obj	5096	10224
Bunny.obj	34835	69666
Dog.obj	649	1286

The vertex-shifting method is proposed by the consideration of a resistant algorithm. The shifting of vertices should also withstand distortion.

High quality can be achieved if the causality problem is addressed because the shift in one vertex will affect the quality of the entire 3D object. If all three vertices in a triangular mesh are altered, then the quality of the watermarked object gets degraded. The proposed algorithm removes the causality problem by identifying the immune node, i.e. the embedding is not done in all the vertices.

The svalue is chosen to determine the quality of the watermarked object. The visibility of the 3D watermarked object varies for different svalues. The 3D object quality increases when the svalue decreases. Table 3 tabulates the performance of the Gourd.obj 3D object with respect to different svalues. This shows that when the svalue is 0.5 the quality of the watermarked object is distorted, whereas high quality is achieved when the svalue is 10^{-12} or 10^{-15}. High quality is attained when the svalue decreases. Similarly, the BER value shows that when the shift value is 10^{-12} there is a bit error rate of 1.33%. The result is tabulated by embedding the secret logo in the x coordinate of the 3D object.

Table 3. PSNR and BER values for various svalues.

svalue	PSNR	BER (in %)
0.1	57.48	30.33
0.5	58.63	29.33
10^{-2}	53.85	24.89
10^{-10}	55.41	4.00
10^{-12}	63.45	1.33
10^{-15}	63.45	3.11

The causality problem is removed when the base segmentation is done with a small svalue. The capacity of the watermark depends on the number of vertices in a 3D object, so if the binary value of secret data or the size of the secret logo is high then it could not be held by the 3D object. The Gourd.obj object contains 326 vertices and so it could hold at most 196 bits of secret data. The PSNR and BER with varying svalues are tabulated in Table 3.

The proposed algorithm embeds the watermark into the x, y, and z coordinates of the cover object. This increases the capacity of the cover object to hold more bit information of the watermark. Table 4 shows the performance of the 3D watermarked object with respect to PSNR, VSNR, and BER with respect to the size of the watermark (secret logo), N. The PSNR value for the watermark with varying size is above 30 and shows good quality. The tabulated BER shows that there is minimum bit error rate. This ensures that the secret logos before embedding and after extraction look similar.

Table 4. PSNR and BER values with respect to embedding coordinates.

3D object	Coordinates											
	x only				x and y				x, y and z			
	PSNR	BER	VSNR	N	PSNR	BER	VSNR	N	PSNR	BER	VSNR	N
Sphere.obj	40.16	0.9	121.64	100	39.67	0.9	121.22	121	38.41	0.9	120.22	144
Gourd.obj	63.41	1.33	122.11	144	62.39	1.33	121.98	169	60.45	1.33	121.98	196
Bunny.obj	68.23	0.13	125.87	225	65.31	0.15	124.37	256	64.11	0.15	124.37	289
Cow.obj	60.24	0.44	124.21	225	58.43	0.44	123.50	256	54.22	0.44	123.39	289
Teapot.obj	64.12	0.2	124.89	225	62.62	0.2	124.00	256	62.20	0.2	124.00	289
Slotmachine.obj	54.09	0	122.34	169	53.33	0	122.25	196	51.45	0	122.25	225

Table 4 shows the performance of various benchmark 3D objects. The PSNR value increases when the embedding process is done in one coordinate. This also shows that the size of the watermark (secret logo N) increases when the embedding is done by varying the coordinates (x, y, and z) of the 3D object.

The VSNR value of the varied 3D objects shows better performance than the existing algorithm. A sample 3D object is taken for comparing the performance of various clustering algorithms with the proposed vertex-shifting algorithm.

Table 5 shows that the proposed algorithm yields 125.87 as the VSNR value for the 3D bunny object that has 34835 vertices. When compared with the existing algorithm, the proposed algorithm produces an improved VSNR. This also ensures that the algorithm can withstand visual quality inspection.

Table 5. VSNR value for Bunny.obj by various algorithms.

Algorithms	VSNR
Soliman's method [9], June 2013	106.73
Li's method [18], January 2017	108.40
Ola's Method I [23], November 2017	119.23
Ola's Method II [23], November 2017	122.53
Proposed method	125.87

6. Watermark robustness

Watermark robustness is analyzed with geometric attacks. The 3D watermarked object is tested against translation and uniform scaling attacks. The robustness measure is done using BER values. Table 6 shows that the BER value is tolerant when the 3D watermarked object undergoes basic geometric attacks like translation and uniform scaling. This shows that the proposed vertex-shifting algorithm withstands attacks.

Table 6. Performance evaluation using attack.

3D object	Translation attack		Scaling attack	
	PSNR	BER	PSNR	BER
Gourd	54.68	4.89	42.39	18.44
Sphere.obj	49.70	20	48.57	20.11
Casting.obj	57.21	4.45	47.34	17.12
Bunny.obj	59.66	5.90	49.71	19.33
Slotmachine.obj	55.12	6.44	43.56	21.42
Pumpkin.obj	56.34	4.34	45.49	15.22
Teapot.obj	56.79	4.22	46.58	12.14
Cow.obj	55.31	5.23	45.78	16.48

Tables 7 and 8 have been formulated from [17], which show an analysis of the various algorithms with the proposed algorithm. Table 7 shows that the capacity of embedding is increased in the proposed algorithms by withstanding attacks like translation and uniform scaling. The proposed system can embed to a maximum of 3 bits per vertex.

Table 7 is tabulated for 3D cover object Bunny.obj with 34835 vertices. The table shows that the distribution of the vertex norms algorithm proposed by Cho et al. embeds a 64-bit watermark (secret logo) into a 3D object. The algorithm proposed by Hu et al. embeds a 55-bit watermark into a 3D object. The proposed hypothesis-based vertex-shifting algorithm embeds 15625 bits in the 3D cover object.

Table 7. Comparison of 3D watermarking algorithms for Bunny.obj as 3D cover object.

Method	Translation attack	Scaling attack	Type	Detection	Capacity
Hu et al., 2007	Yes	Yes	Robust	Blind	55 bits
Cho et al., 2010	Yes	Yes	Robust	Blind	64 bits
Proposed method	Yes	Yes	Robust	Blind	15625 bits

Table 8 compares the proposed algorithm with the algorithms proposed by Bors and Harte et al. for 3D cover object Dog.obj with 649 vertices. Tables 7 and 8 prove that the embedding capacity of the proposed algorithm is high when compared with the existing algorithms.

Table 8. Comparison of 3D watermarking algorithms for Dog.obj as 3D cover object.

Method	Translation attack	Scaling attack	Type	Detection	Capacity
Bors, 2006	Yes	Yes	Robust	Blind	32 bits
Harte et al., 2014	Yes	Yes	Robust	Blind	20 bits
Proposed method	Yes	Yes	Robust	Blind	1398 bits

7. Conclusion

The proposed hypothesis-based vertex-shifting algorithm for embedding 2D binary secret logos into 3D objects has improved the embedding capacity by embedding a maximum of 3 bits per vertex without affecting the visual quality of the 3D cover object and experimental results showed that the algorithm registered better PSNR and VSNR values. The BER value shows that the watermark images before and after embedding look similar. The binary secret logo was embedded into the 3D object and the watermarking process for various 3D objects was observed with different svalues. When the svalue decreased, the quality of the watermarked object increased. The proposed watermarking method was used only for binary images because the base segmentation value was represented as 1 and 0 and the vertex shift depended on the binary value. Experiments were conducted on the available data to prove the quality of the watermarked 3D objects.

The capacity of the cover object is also one of the major factors that influence the watermarking process. If the capacity of the 3D cover object is less than the secret data then the watermarking process can be carried out. The algorithm withstands geometric attacks like translation and scaling. In the future, the robust watermarking scheme with better visual quality and addressing various attacks like cropping, mesh simplification, and remeshing can be adopted for different types of input secret logos along with increased capacity.

References

[1] Lu K, Wang, Xue J, Pan W. 3D model retrieval and classification by semi-supervised learning with content-based similarity. Information Sciences 2014; 281: 703-713. doi: 10.1016/j.ins.2014.03.079

[2] Khan A, Siddiqa A, Munib A, Malik SA. A recent survey of reversible watermarking techniques. Information Sciences 2014; 279: 251-272. doi: 10.1016/j.ins.2014.03.118

[3] Osama H, Yang L, Wei L, Xingming S. Watermarking 3D triangular mesh with high visual quality. International Journal of Digital Content Technology and its Applications 2010; 4 (4): 107-116.

[4] Prathap I, Anitha R. Robust and blind watermarking scheme for three dimensional anaglyph images. Computers and Electrical Engineering 2013; 40: 51-58. doi: 10.1016/j.compeleceng.2013.11.005

[5] Adrian G, Luo BM. Optimized 3D watermarking for minimal surface distortion. IEEE Transactions on Image Processing 2013; 22 (5): 1822-1835. doi: 10.1109/TIP.2012.2236345

[6] Suk-Hwan L, Ki-Ryong K, Won-Joo H, Chandrasekar V. Key-dependent 3D model hashing for authentication using heat kernel signature. Digital Signal Processing 2013; 23 (5): 1505-1522. doi: 10.1016/j.dsp.2013.04.012

[7] Wei X, Kim ST. Optical 3D watermark based digital image watermarking for telemedicine. Optics and Lasers in Engineering 2013; 51 (12): 1310-1320. doi: 10.1016/j.optlaseng.2013.06.001

[8] Singh C, Ranade SK. Geometrically invariant and high capacity image watermarking scheme using accurate radial transform. Optics and Lasers in Engineering 2013; 54: 176-184. doi: 10.1016/j.optlastec.2013.05.016

[9] Soliman M, Hasssanien AE, Onsi HM. A blind 3D watermarking approach for 3D mesh using clustering based methods. International Journal of Computer Vision and Image Processing 2013; 3 (2): 43–53.

[10] Wang S, Cui C, Niu X. Watermarking for DIBR 3D images based in SIFT feature points. Measurement 2013; 48: 54-62. doi: 10.1016/j.measurement.2013.10.028

[11] Al-Haj A, Farfoura ME, Mohammad A. Transform-based watermarking of 3D depth-image-based-rendering images. Measurement 2016; 95: 405-417. doi: 10.1016/j.measurement.2016.10.016

[12] Chen L, Zhao J. Robust contourlet-based blind watermarking for depth-image-based rendering 3D images. Signal Processing Image Communication 2017; 54: 56-65. doi: 10.1016/j.image.2017.02.011

[13] Li XW, Liu Y, Kim ST, Wang QH. Designing a genetic watermarking approach for 3D scenes. Optics and Lasers in Engineering 2017; 93: 83-91. doi: 10.1016/j.optlaseng.2017.01.013

[14] Wang JT, Chang Y, Yu CY, Yu SS. Hamming code based watermarking scheme for 3D model verification. Mathematical Problems in Engineering 2014; 2014 (2): 241093. doi: 10.1155/2014/241093

[15] Hou W, Wang X, Ding M, Zhang S. Adaptive image sampling through establishing 3D geometrical model. Expert Systems with Applications 2014; 41 (16): 7307-7315. doi: 10.1016/j.eswa.2014.05.041

[16] Rollan-Nevière X, Doërr G. Triangle surface mesh watermarking based on a constrained optimization framework. IEEE Transactions on Information Forensics and Security 2014; 9 (9): 1491-1501. doi: 10.1109/TIFS.2014.2336376

[17] Liu J, Wang Y, Li Y, Liu R, Chen J. A robust and blind 3D watermarking algorithm using multiresolution adaptive parametrization of surface. Neurocomputing 2017; 237: 304-315. doi: 10.1016/j.neucom.2016.12.065

[18] Li S, Ni R, Zhao Y. A 3D mesh watermarking based on improved vertex grouping and piecewise mapping function. Journal of Information Hiding and Multimedia Signal Processing 2017; 8 (1): 97-108.

[19] Yang Y, Pintus R, Rushmeier H, Ivrissimtzis I. 3D steganalytic algorithm and steganalysis-resistant watermarking. IEEE Transactions on Visualization and Computer Graphics 2017; 23 (2): 1002-1013. doi: 10.1109/TVCG.2016.2525771

[20] Sorkine O. Differential representations for mesh processing. Computer Graphics Forum 2006; 25 (4): 789-807.

[21] Karn BM, Suresh K. A survey on combination of different features for image watermarking. International Journal of Advanced Research in Computer Science and Software Engineering 2015; 5 (5): 751-755.

[22] Medimegh N, Belaid S, Werghi N. A survey of the 3D triangular mesh watermarking techniques. International Journal of Multimedia Sciforshen 2015; 1 (1): 1-6. doi: 10.16966/ijm.102

[23] Ola M, Zein E, Lamiaa M, Bakrawy E, Ghali NI. A robust 3D mesh watermarking algorithm utilizing fuzzy C-means clustering. Future Computing and Informatics Journal 2017; 2 (2): 148-156. doi: 10.1016/j.fcij.2017.10.007

[24] Wang K, Lavouè G, Denis F, Baskurt A, He X. A benchmark for 3D mesh watermarking. In: Proceedings of the IEEE Shape Modeling International Conference 2010; Aix en Provence, France; 2010. pp. 231-235. doi: 10.1109/SMI.2010.33