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Evaluation Metrics used in 3D Mesh Watermarking: A Study

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Abstract

Three Dimensional (3D) models are watermarked to protect their ownership information and to maintain the integrity while transmitted over networked communication. These watermarking operations change the mesh details during data embedding, which in turn affects the perceptual quality or geometrical details of the mesh. There are two different situations where a mesh watermarking technique needs to be evaluated. One of them is to make sure that the watermark embedding function induces minimal perceptual distortion to the original model and the second situation is assessing the similarity between the extracted watermark and the original one to estimate robustness of the watermarking scheme. However surface mesh quality is assessed in two ways: subjective way (observation directly from the human) or objective way where some metrics are formulated by researchers to measure the mesh quality that can meet the human observation. This study covers a detailed discussion of various objective mesh quality assessment metrics proposed for detecting the mesh degradation due to different classes of watermarking techniques. Robustness estimation metrics to assess the similarity of watermarks are also discussed.

Keywords: *3D mesh, watermarking, evaluation parameter, perceptual similarity*

1. Introduction

With the expeditious development in computer graphics and Internet technology 3D portrayal of objects is mostly preferred for better visualization in different processing operations. Watermarking is the process of embedding secret information to the 3D model and the embedded watermark in more general case should be perceptually invisible. If the watermark is visible, it becomes easier for the attacker to locate in the host mesh and it also causes more distortion to the perceptual quality of the mesh. But in case of invisible watermarking, the perceptual quality of the model is sustained. However in both the cases, the mesh geometrical or topological details get distorted. Mesh Quality Assessment (MQA) is studied excessively in the literature in different domain. Authors in [13] and [14] have discussed about various measures for quality assessment of 3D meshes used in various domains of computer graphics. While talking about the quality of a mesh a number of factors get attention like vertex sampling, triangle quality or mesh regularity *etc*. In case of watermarking, the quality is established based on the similarity assessment of the mesh (perceptual or geometrical) with a modified version of the same. This study gives a prospect of various evaluation scenarios in mesh watermarking algorithms. The metrics used for evaluating a mesh watermarking scheme are also discussed. Evaluation parameters are classified on the basis of various mesh quality evaluation criteria.

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1.1. Basics of Meshes and Mesh Watermarking

A 3D model can be represented with a variety of mathematical representation formats, among which polygon meshes are used more often. Here we are talking about the surface meshes, also called as boundary meshes which is basically the 2D representation of the 3D model. These surfaces are tessellated by triangles or quadrilateral polygons or both. Triangular meshes are more often used. A triangular mesh composed of the mesh elements vertices, edges and facets. Watermarking in a triangular mesh changes some of the surface details. By going through different mesh watermarking algorithms, the possible changes that can occur during watermarking are listed down below;

- Change in vertex position or change in edge length, which lead to differ in geometry of the mesh. In such case topology of the mesh is unaltered.
- Change in number of vertices *i.e.,* adding or removing vertices which alters the connectivity information.

While talking about the assessment of the quality of cover content after watermarking algorithms, in 2D images the quality measurement criteria are quite simple like brightness, contrast, color mapping. Whereas in case of 3D meshes quality assessment or to determine the visual equivalence is comparatively a tough job. Different evaluating criteria in 3D surface meshes are discussed in section 1. The block diagram in Figure 1 shows different mesh quality evaluation scenario in mesh watermarking.

2. Quality Evaluation in Mesh Watermarking

The mesh quality evaluation processes are of two types namely, subjective evaluation and objective evaluation. Objective metrics are computed to detect perceptual equivalence, which are again evaluated or rather compared with subjective score (Mean Opinion Score (MOS)) so that it meets the subjective evaluation results for the respective models. Here we are discussing about the various objective metrics. There are several criteria which decide whether a mesh watermarking scheme is acceptable or not, like higher payload capacity of the embedding scheme, imperceptibility and robustness against attacks encountered during transmission. While fulfilling the requirements, a tradeoff between capacity and imperceptibility results. When capacity increases, the mesh distortion increases causing more degradation in the visual appearance. Various mesh watermarking evaluation parameters can be classified based on different criteria as shown in Figure 2.

2.1. Evaluation during Watermark Embedding To the Mesh

Watermark embedding incurs geometrical changes to the mesh. In case of an invisible watermark embedding scheme, the changes occurred to the mesh should be perceptually invisible. measure the transparency of the embedding scheme or similarity between original and marked model, *Imperceptibility measures* are used. The evaluation is carried out with various mesh geometrical similarity assessment measures like, Hausdorff distance, Root mean square error, Signal to noise ratio. But these measures are not well correlated with human observation and sensitive to any smaller geometrical distortion. The evaluation results obtained from objective evaluation need to match the Human Visual System (HVS) perception. A number of perceptual correlation measures are formulated to meet this requirements are discussed in Section 3.2.

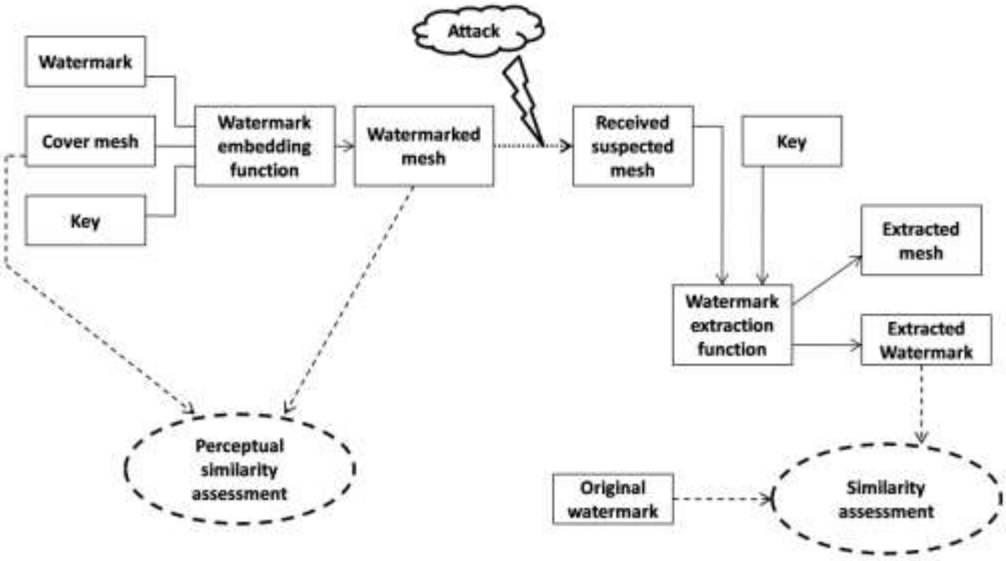

Figure 1. A Block Diagram of Mesh Watermarking Scheme and Its Evaluation

HVS is mostly sensitive to the lighting elements, roughness of the model, shape, texture and resolution, curvature structural features etc. The perceptual similarity metrics estimates similarity between surface models based on change in texture and change in structure (shape). Artifacts produced in the surface models due to mesh watermarking is mostly texture based change. As mesh watermarking operations brings local mesh deformation rather than global which changes the shape of the model. Some of the surface properties like model surface curvature, Laplacian or dihedral angles can be used to detect the change in texture of the surface. There are various evaluation parameters proposed to estimate the change in texture of the model or the roughness of the surface model discussed in subsection 3.2.

2.2. Evaluation after the Watermark Extraction

After watermark embedding the model can be transmitted over the Internet for a point to point communication. While doing so it can be targeted by a third party and various malicious operations can be performed over the model. Watermark extraction function separates the watermark from the suspected (as can be attacked) marked mesh. The watermark extraction is of three types: *blind, semi-blind* and *non-blind.* A blind watermarking scheme does not require any of original cover content and the original watermark at the time of extraction. In case of semi-blind extraction, the original cover content is not required but the watermark is needed. In case of non-blind extraction, both of the original cover content and the watermark is required. There some scenario where the watermark information is related to the model and also need to be secured and cannot be exposed in public (*e.g.*, in case of medical imaging watermark is EPR (Electronic Patient Record)). So, non-blind extraction is not preferable as it requires to send the original cover content with the marked content. After the watermark is extracted, the evaluation process is carried out in two different ways based on the two watermarking application namely; *copyright protection*, *authentication*.

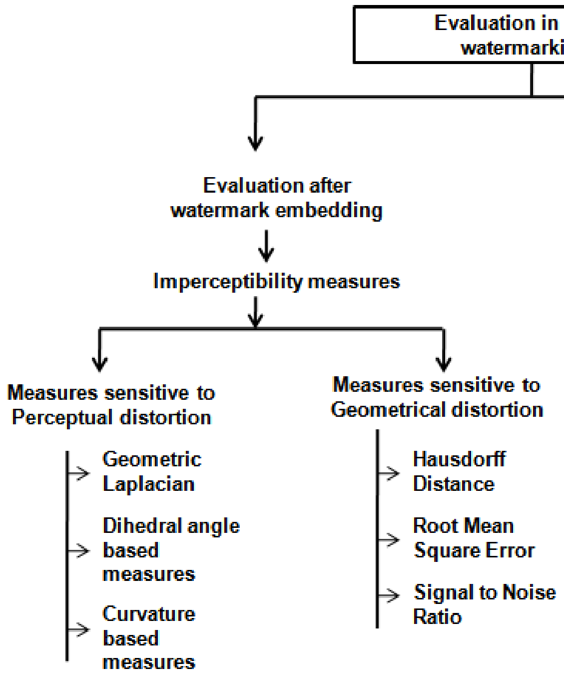

Figure 2. A Classification of the Evaluation Parameters Used In Mesh Watermarking Based On Various Criteria

In case of copyright protection, the owners identity needs to be protected for which robust watermarking is used. In case of robust watermarking, the watermark needs to survive even if the content gets attacked during transmission. So after the extraction is over the watermark is compared with the original watermark using different measures. If the measure indicates to be matched by having a value greater than a threshold, is considered to be robust and the owners identity is protected as well. For the above scenario, different *robustness measures* are used. A robust mesh watermarking algorithm needs to withstand various common mesh attacks are like filtering attacks, topological attacks, noise attacks *etc*.

The second watermarking application is authentication of the cover content to verify the integrity of the mesh which covers detecting the mesh attacks and recovering the original mesh. Fragile watermarking techniques are used to serve the authentication purpose. As the main itself suggests that the watermark is fragile to any smaller modification and becomes undetectable when the mesh gets attacked. Once it is ensured that the mesh is attacked, tamper detection techniques are implemented to detect the changes in the mesh and mesh recovery is also need to be performed. Embedding parameters are used during tamper detection and its performance is decided based on true positive rate *TP* and false positive rate *FP* Again if recovery of the original mesh content is performed, then it is compared with the original one to verify the true positive rate. In case of semi-fragile watermarking, the robustness of the watermarking scheme to some routine operation (not considered as attacks) like rotation, scaling, vertex reordering, quantization is measured using the robustness measures. A detailed discussion on the various evaluation measures is presented in the later section 3 and section 4.

3. Evaluation after Watermark Embedding

3.1. Geometrical Distortion Measures

3.1.1. Hausdorff Distance (HD):

A widely used geometrical distortion measure for meshes is the Hausdorff distance. The Hausdorff distance measures the similarity between two surface meshes based on greatest Euclidean distance. Let M denote the original mesh and M' be its altered version. The Euclidean distance from a point $p \in M$ to M' is given in the equation 1,

$$d(p, M') = min_{p' \in M'} \left| p - p' \right| \quad (1)$$

The Hausdorff distance is calculated using equation2;

$$d_H(M, M') = max_{p \in M} d(p, M') \quad (2)$$

Here $d_H(M, M') \neq d_H(M', M)$, these two quantities are referred to as the forward and backward distances. Symmetrical Hausdorff distance is shown in equation 3;

$$D(M, M') = max(d_H(M, M'), d_H(M', M)) \quad (3)$$

Another work by [1] showed the Normalized Hausdorff Distance (NHD) by calculating the distortion rate R_{dist}, ie the ratio between the maximum distance between the surfaces, λ_{max} and the length of the largest edge L_{max} in the mesh. It is shown in equation 4. Mesh watermarking algorithms [31], [32] have used NHD in their work.

$$R_{dist} = \frac{\lambda_{max}}{L_{max}} \quad (4)$$

Hausdorff distance based distortion measures are sensitive to slightest modification and don't correlate well with HVS, so are suitable to detect small geometric distortions. HD is used by [30], [7] mesh watermarking algorithms to detect perceptual difference between meshes.

3.1.2. Root Mean Square Error (RMSE):

To address the sensitivity to small alterations like local roughness in the mesh, another distance based measure Root Mean Square Error (RMSE) shown in equation 5 is often used instead of the Hausdorff distance. Many of the mesh watermarking algorithms [9, 23, 24, 8, 11, 3, 28] have used RMSE for evaluation purpose.

$$d_{rms}(M, M') = \sqrt{d_{p \in M}(p, M')^2 \, dM} \quad (5)$$

Maximum Root Mean Square Error (MRMSE) was proposed to make RMSE symmetrical [16, 2, 26, 36].

$$MRMSE(M, M') = max(d_{rms}(M, M'), d_{rms}(M', M)) \quad (6)$$

RMSE is also discretized for practical purposes to reduce the computational complexity of traditional distortion measures. RMS ratio also known to be Normalized Root Mean Square Error (NRMSE) consisting of the RMSE values over the diagonal length of the bounding volume is proposed by Wang et.al. [23] for a 3D stego model.

Huang and Tsai [9], Wang *et al.* [23] have used NRMSE as shown in equation 7 where diagonal length of the bounding volume, DL_{BV} is used.

$$NRMSE = \frac{RMS}{DL_{BV}} \tag{7}$$

The small RMSE ratios indicate insignificant positional changes during the watermark embedding. RMSE is less correlated to mesh visual distortion or cannot detect the same. This measure can detect the distortion between meshes with changed connectivity details.

3.1.3. Signal to Noise Ratio (SNR)

Signal to Noise Ratio is another watermark embedding imperceptibility measure [34, 33, 10, 37]. Signal to Noise Ratio for meshes SNR_{mesh} is calculated as given in equation 8.

$$SNR_{mesh} = 10\log_{10}\frac{\sum_{i=1}^{n_v}(x_i^2 + y_i^2 + z_i^2)}{\sum_{i=1}^{n_v}(x_i' - x_i)^2 + (y_i' - y_i)^2 + (z_i' - z_i)^2} \tag{8}$$

3D Signal to Noise Ratio (3D-SNR) is computed by [33] to measure geometrical distortion shown in equation 9 and 10. Here $V = \{v_1, \ldots.., v_n\}$ is the vertex set where every vertex v_i specify co-ordinates, suppose $v_1 = \{v_{1x}, v_{1y}, v_{1z}\}$, $G = \{g_1, \ldots., g_n\}$ is the distorted vertex set.

$$SNR = 10\log_{10}\frac{MS(V - \bar{v})}{MS(G - V)} \tag{9}$$

Here $MS()$ is the mean square function, $\bar{v} = \{\bar{v}_x, \bar{v}_y, \bar{v}_z\}$ is the mean of $V = \{v_1, \ldots, v_n\}$ and the mean square functions are shown in equation.

$$MS(V - \bar{v}) = \frac{\sum_{i=1}^{N}(v_{ix} - \bar{v}_x)^2 + (v_{iy} - \bar{v}_y)^2 + (v_{iz} - \bar{v}_z)^2}{N} \tag{10}$$

$$MS(G - V) = \frac{\sum_{i=1}^{N}(g_{ix} - v_{ix})^2 + (g_{iy} - v_{iy})^2 + (g_{iz} - v_{iz})^2}{N} \tag{11}$$

3.2. Perceptual Correlation Measures

A number of mesh property effects or highlights the models visual quality. Based on those properties a number of mesh perceptual equivalence measures are formulated by researchers in last years.

3.2.1. Geometric Laplacian (GL)

Geometric Laplacian is generally used to detect the geometrical changes occurred due to the mesh compression. But it is also used by mesh watermarking algorithm [18] to detect the perceptual distortion to the mesh. This can be computed by the following equation 12,

$$GL(v_i) = v_i - \frac{\sum_{j\in N(i)} l_{ij}^{-1} v_j}{\sum_{j\in N(i)} l_{ij}^{-1}} \quad (12)$$

Here $N(i)$ is the neighboring vertices of the vertex v and l_{ij} is the distance between the vertices v_i and v_j. The visual equivalence between the mesh M and distorted mesh $M^{'}$ is shown in equation 13.

$$diff(M,M^{'}) = \frac{1}{2|v|}(\sum_{i=1}^{|v|}\left|v_i - v_i^{'}\right| + \sum_{i=1}^{|v|}\left|GL(v_i) - GL(v_i^{'})\right|) \quad (13)$$

This measure is related to the surface smoothness and so is not effected by minimal changes. It takes into account both geometrical and topological details of the mesh.

3.2.2. Dihedral Angle Based Measures

According to Corsini *et al.* [4] the changes occurred due to watermarking a mesh effects the visual quality in the form of roughness to the model surface. A perceptual quality assessment measures was defined by [4] for mesh watermarking based on roughness variation termed 3DWPM1. Another multi-scale roughness estimation measure was computed by Corsini *et al.* [5], where roughness per vertex is computed by making statistical considerations about the dihedral angles. The later measure is a variation of the previous termed as 3DWPM2 used by watermarking algorithms [11, 20, 17]. The per vertex roughness is computed as shown in equation 14.

$$R^N(v) = \frac{1}{|S_T^N|}\sum_{i\in|S_T^N|} R(T_i)A_{T_i} \quad (14)$$

Here A_{T_i} is the area of triangle T_i and $|S_T^N|$ is the set of faces of N ring of vertex v. Again roughness $\rho(T)$ of a triangle T with vertices v_1, v_2, v_3 is estimated as equation 15. Here $G(v_1)$ is the roughness associated with the dihedral angles and $V(v_1)$ are the variances of the roughness.

$$\rho(T) = \frac{G(v_1)V(v_1) + G(v_2)V(v_2) + G(v_3)V(v_3)}{V(v_1)V(v_2)V(v_3)} \quad (15)$$

Dihedral Angle Mesh Error (DAME) is proposed by [22] which evaluate the difference between two meshes of fixed connectivity. They computed oriented dihedral angle and visual masking is dome to indicate the visual distortion as shown in equation 16. This evaluation parameter is comparatively less complex and faster than other objective metrics. In equation, n_e is the number of edges, α and $\overline{\alpha}$ are the respective dihedral angles and m_i and w_i are visibility weight of the mesh.

$$DMAE = \frac{1}{n_e}\sum_{n_e}\left|\alpha_i - \overline{\alpha_i}\right|.m_i.w_i \quad (16)$$

3.2.3. Curvature based Measures

According to HVS the psychometric senses of a human is very much sensitive to the curvature information of a 3D model. Curvature information based metrics are used for detecting the perceptual distortion in mesh. Curvature information is used by Lavoue *et al.* [15] to define Mesh Structural Distortion Measure (MSDM) as shown in equation 22. They defined a local window in the mesh and computed the Local MSDM as shown in equation 17 where x and y are the local windows, M and $M^{'}$ are the original mesh and distorted mesh respectively and $L()$, $C()$ and $S()$ are curvature, contrast and structure comparison function as shown in equation 18, 19 and 20. They calculated Gaussian weighted local distortion measure to calculate the global structural dissimilarity as shown in equation 21. This measure cannot detect connectivity altering changes to the mesh. Some of the mesh watermarking algorithm [26, 25, and 35] has used the measures MSDM1.

$$LMSDM(x,y) = (\alpha \times L(x,y)^{a} + \beta \times C(x,y)^{a} + \gamma \times S(x,y)^{a})1/a \quad (17)$$

$$L(x,y) = \frac{|\mu_x - \mu_y|}{max(\mu_x, \mu_y)} \quad (18)$$

$$C(x,y) = \frac{|\delta_x - \delta_y|}{max(\delta_x, \delta_y)} \quad (19)$$

$$S(x,y) = \frac{|\delta_x \delta_y - \delta_{xy}|}{\delta_x \delta_y} \quad (20)$$

In the above three equation δ_x, μ_x and δ_{xy} are the standard deviation, mean and covariance of the curvature respectively in local windows x and y.

$$MSDM(M, M^{'}) = (\frac{1}{n_w} \sum_{j=1}^{n} LMSDM(x_j, y_j)^{a})1/a \in [0,1] \quad (21)$$

$$d_{MSDM} = (\frac{1}{n} \sum_{j=1}^{n} d_{LMSDM}(p_j, q_j)^{3})^{1/3} \quad (22)$$

Gaussian curvature based local roughness measure was calculated by Wang *et al.* [27]. A visual similarity metric Tensor based Perceptual Distortion Measure (TPDM) is introduced by Torkhani *et al.* [21] which is based on the measurement of a distance between curvature tensors of the two triangle meshes under comparison. To Compute TPDM at first the Local Curvature Tensors (LTD) is calculated by finding the curvature tensors for every vertex of the mesh.

Lavouà [12] Proposed a multi attribute visual similarity index calculated from different perceptually relevant curvature attributes which is an improved version of MSDM1 and termed as MSDM2. Laplacian of discrete Gaussian curvatures are used by Wang *et al.* [27] to calculate the local roughness and normalized surface integrals of the local roughness is used to calculate the global roughness. They termed measure to be Fast Mesh Perceptual Distance (FMPD) which is faster than other visual similarity indexes. Here the local roughness is measured by Laplacian of the discrete Gaussian curvature. Another curvature based roughness estimation parameter is proposed by [6] where Gaussian

Weighted Average of Mean Curvature values in the neighborhood of vertices are used to measure the dissimilarity between meshes. But their parameter can only detect the connectivity preserving changes to the mesh. The Gaussian weighted average of mean curvature is computed as in equation 23,

$$\bar{k}_{mean}(v) = \frac{\sum_{v_{m \in s(v)} exp(-2|v_m - v|^2/\gamma^2)} .k_{mean}(v_m)}{\sum_{v_{m \in s(v)} exp(-2|v_m - v|^2/\gamma^2)}} \quad (23)$$

Here v_m is the spherical neighborhood of the vertex v and $k_{mean}(v_m)$ is the mean curvature of the vertex and γ is the radius of the neighborhood. Another multi-scale visual saliency map was used by [19] on which they computed the local statistics to generate a perceptual similarity index SMQI (Saliency based Mesh Quality Index). These perceptual quality based metrics are correlated with the subjective assessment of the same meshes.

4. Evaluation after Watermark Extraction

4.1. Robustness Measures

Robustness of a watermarking scheme is judged based on its resisting power against different set of attacks ie, although the model gets attacked (altered) the proof of ownership (watermark) should not get changed. So to determine that the extracted watermark is compared with the original one using some evaluation parameters discusses down below.

4.1.1. Bit Error Rate (BER)

BER (Bit Error Rate) measures the ratio of erroneous estimated bits over the total number of transmitted bits to determine the change in bit values in the extracted watermark. BER is computed as shown in equation 24. This is used after the watermark extraction to compute the similarity between the extracted watermark and the original watermark. This metric measures the schemes robustness against various malicious alterations.

$$BER(M, M') = 1 - \frac{1}{n_b} \sum_{n=1}^{n_b} \delta_{(m_i, m_i')} \quad (24)$$

In the above equation $\delta_{(m_i, m_i')}$ is the Kronecker delta and n_b is the number of bits embedded. This measure is mostly used to check the bit error rate between the extracted watermark and the original one [26, 29].

4.1.2. Correlation Measures

Correlation co-efficient is used to determine the robustness of the watermarking scheme after watermark extraction. To check the robustness, this metric correlates the extracted watermark and the original watermark and computed value ranges in between $[-1,1]$. Most of the watermarking scheme defines a threshold for the above which the scheme considered to be robust. If the computed correlation value is 1 then the watermark is perfectly extracted even though any kind of attack is implemented during transmission.

In other case a threshold is defined which decides whether the scheme is robust or not. The equation 25 shows the calculation,

$$corr(w^d, w) = \frac{\sum_{i=0}^{N-1}(w_i^d - \overline{w^d})(w_i - \overline{w})}{\sqrt{\sum_{i=0}^{N-1}(w_i^d - \overline{w^d})(w_i - \overline{w})}} \quad (25)$$

In the above equation w^d is the extracted watermark and w is the original watermark. Spearman and Pearson correlations are used to determine the correlation between between the collected Mean Opinion Score (MOS) (subjective evaluation) and the results obtained from the objective metrics. This correlation result shows how much the objective results match the subjective ones.

5. Conclusion

In this paper an insight to the various objective evaluation metrics used in mesh watermarking in last years is presented. Among the explained metrics there are some of them which are still not yet been used particularly in mesh watermarking. A set of concluding remarks identifying the challenges and its future direction are listed down below;

Distortion caused by the mesh watermarking algorithms are of different types like; some may cause change in geometry, some may change the topology. These changes to the mesh effect the surface differently. One of the problems of evaluating parameters is one particular metrics is sensitive to some specific alterations.

- It is a challenging task to meet the subjective evaluation results in mesh visual quality assessment using the objective evaluation measures.
- Existing mesh watermarking algorithms have explored various geometrical distortion measures more than the other perceptual correlation measures. In future these perceptual measures can be checked.
- In case of mesh watermarking algorithms the distortion to the mesh depends on different parameters while data embedding, like quantization step size or mesh traversal strategy and so on which can be used to control the distortion.
- In certain conditions where authentication or integrity of the content as well as the watermark information is need to be verified (like in case of medical imaging EPR (Electronic Patient Record) is hidden), the original watermark may not be available at the receiver side. In such cases fully blind mesh quality evaluation is needed. Though some literature has addressed such problem, but further study is needed.

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