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Perceptual Analysis of Level-of-Detail: The JND Approach

Abstract

Multimedia content is becoming more widely used in applications resulting from the easy accessibility of high-speed networks in the public domain. An important component in multimedia content is 3D geometry, which in the past had low resolution due to acquisition, computational and network limitation, and was not able to approximate 3D surfaces realistically. Although processing speed and network capacity have been greatly increased in the last decade, the increase in demands for multimedia content surpass the increase in resources. Consequently, techniques for data simplification especially for 3D mesh data is inevitable in order to achieve shorter latency and satisfactory interactivity in applications. This paper presents a perceptual analysis to evaluate the visual quality associated with a change in level-of-detail. Our analysis is consistent to how the human visual system evaluates 3D objects in the real world and is based on the Just-Noticeable-Difference methodology. Experimental results show that our approach presents an accurate estimation of visual quality and thus provides a systematic method to evaluate the performance of different simplification algorithms.

1. Introduction

Online multimedia applications such as virtual-museum, collaborative design, Tele-learning and Tele-health, are becoming commonplace with the support of advanced network technology. Compare to stand-alone applications, online applications face additional challenges due to limited network bandwidth. There is always a demand for higher bandwidth and better quality of service, and such demand often surpasses the supply provided by existing computational and communication infrastructures.

3D geometry is an important component of multimedia content. An essential consideration in transmitting 3D geometry data is to adaptively adjust the mesh representation to available resources, while preserving satisfactory visual quality as perceived by a viewer. When transmitting a high-resolution 3D mesh mapped with photorealistic texture, an application has to optimize the resources allocated to, and thus the relative qualities of, both texture and mesh data. In earlier perceptual experiments [19], it was observed that after reaching a certain minimum required mesh resolution, further increase in mesh resolution does not have significant visual impact; while further increase in texture resolution continues to improve the overall visual quality of a 3D object. Given limited resources, it is therefore more efficient to transmit only the minimum mesh data required, and to allocate the remaining resources to texture data in order to achieve a higher overall quality. A challenging problem is how to define the "minimum" data with respect to mesh resolution, without significant degradation in visual quality. To address this problem, level-of-detail (LOD) has been studied extensively in the last fifteen years. However, there is no systematic method to verify and compare the performance of these LOD techniques. In this paper, we propose a quantitative metric integrated with perceptual analysis to measure the performance of LOD techniques. Our approach is based on the Just-Noticeable-Difference (JND) methodology, which is consistent to how the Human Visual System (HVS) evaluates the quality of 3D objects in the real world.

The rest of this paper is organized as follow: Section 2 reviews LOD techniques in the literature. Section 3 explains the proposed perceptual analysis approach based on the JND methodology. Section 4 applies our perceptual evaluation on the Progressive Meshes and Quadric Error Metric Simplification techniques, and analyzes the results. Finally, Section 5 concludes our work and a discussion on future research is provided.

2. Review of LOD Techniques

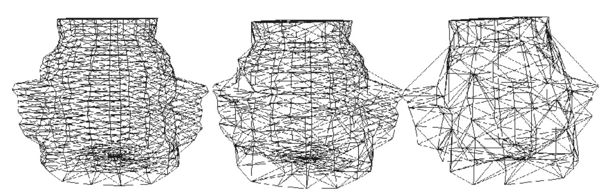


Figure 1: The mesh of a nutcracker toy model at various levels-of-detail, with (left) 1260, (middle) 950 and (right) 538 triangles respectively.

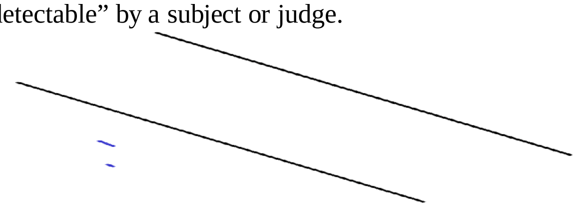
Many level-of-detail (LOD) (Figure 1) algorithms have been proposed in the last fifteen years [6, 7, 9, 10]. However, these techniques use geometric metrics to measure the deviation from the original 3D mesh surface. The simplification operation causing the least deviation is performed next. These decisions based on geometric measurement do not take human perception into consideration. Note that a geometric deviation does not affect visual quality if it is imperceptible to the human visual system (HVS). Two 3D objects can be geometrically different but visually similar if the difference is below a certain visual threshold that cannot be detected by the human eyes. Since human observers ultimately determine visual quality, using a perceptual metric is believed to be more accurate and practical.

Perceptually adaptive graphics [18] has received increasing attention in the visualization community in recent years. A state-of-the-art report was presented in EUROGRAPHICS 2000 [16] on visual perception. Considerable efforts have been put on verifying geometric deviation with perceptual evaluation experiments in order to achieve a higher visual quality of 3D displays [14, 21, 25, 26]. Most perceptually driven techniques developed so far focus on view-dependent rendering [5, 15]. A number of these techniques are based on dynamic scenes [21, 17], and can be used to determine the relative resolutions between the region-of-interest and the periphery [21, 2]. Another approach is to apply user-guided simplifications [20, 13]. By contrast, the Just-Noticeable-Difference (JND) approach [4] is view-independent, applied to relatively static 3D objects, and does not require user intervention when predicting visual quality. Luebke et al. [14] use Gouraud-shaded meshes, while photorealistic texture mapping is used in the JND approach. In Luebke’s method, vertices are removed only if the operation does not degrade visual quality. However, as discussed in their conclusion, the simplified meshes still contained redundant data and could be reduced further two to three times in polygon count without perceptible effects. An efficient simplification technique should avoid generating redundant data, which do not improve visual quality. Experimental setting is crucial in order to obtain reliable psychophysical experimental results. Watson et al. [25] applied naming time, rating and preference techniques in their perceptual experiments. They presented only a limited number of views of each object to the judges, while the JND experiments [4] provided a full 360° comparison to allow the judges to assess all the silhouettes interactively. The disadvantage of using naming times is that the results tends to be affected by an individual’s prior knowledge of the stimuli, i.e., different LODs of an object can be recognized and named within the same response time period due to some prominent features on the 3D surface. A more reliable and commonly used technique is two-alternative-forced-choice (2AFC) [4], where a judge is forced to choose one of the two given answers.

Perceptual analysis improves the result of geometric measurement, and can identify redundant data that cannot be identified using conventional geometric metrics. The proposed JND analysis on LOD is an application of our previous JND psychophysical experimental finding [4]. Interested readers can refer to that paper for detail of the method used to estimate an average JND threshold. In Section 3, we will discuss the JND concept before applying it to measure the performance of LOD techniques in Section 4.

3. The JND Concept

The JND approach follows the same spirit as Weber’s Law on contrast, computed as the change relative to the original value. It is the minimum amount by which the stimulus intensity must be changed in order to be noticeable to human sensation or perception [24]. When a stimulus value x is examined, we are interested in the smallest change Δx, defined as JND, such that $x + \Delta x$ is “just detectable” by a subject or judge.



(a) (b)

Figure 2: An example of human perception on line length. The absolute difference between the two lines in each pair is the same, but the relative change in pair (a) is larger than that in pair (b).

Weber’s Law can be applied to a variety of sensory and perceptual aspects, including brightness, loudness, mass, line length, etc. Figure 2 shows how the perceptual impact of a change is relative to the original stimulus’ magnitude for line length.

In our experiments, user groups composed of more than a hundred judges in total were asked which of the two lines in Figure 2 (b) is longer. More than half of the judges said they are equal, half of the remaining chose the upper one, and the rest selected the lower one. When asking the same question on the pair of shorter lines in Figure 2 (a), every judge identified the upper line as the longer one. Notice that the absolute difference in both pairs of lines is the same. However, the relative difference is much bigger in the shorter pair than in the longer pair, which makes it perceptually more difficult to discriminate the longer line lengths. The lines were displayed relatively close to each other on the projected screen, and it was found that the judges sharing the same answer were quite evenly spread in the room. Thus in this test, the different viewing directions did not mislead the judges’ decisions.

When displaying the line pairs in 3D space, the visual angle subtended by a stimulus on the retina plays an important role in determining the degree of visual impact [23]. Let θ be the angle between the line orientation and the direction of sight. When $\theta = 0°$ both lines appear as a dot to the viewer and discrimination of line length is impossible. Suppose ε is the difference in line length. As θ increases, the projection of ε onto the retina also increases and the projection is maximum when $\theta = 90°$. Since the JND approach is designed for view-independent manipulation of 3D objects, we assume the worse scenario and consider maximum projection (maximum perceptual impact).

Weber’s Law has been tested for surface curvature discrimination [12]. The JNDs were in the range 0.08 to 0.17 with a mean value of 0.11, which compares well with the JND of around 0.1 found in the experiment for a curvature discrimination task in which cylinders defined by binocular disparity were used [11]. The outcome from visual discrimination experiments based on Weber’s Law means that changes of decreasing magnitude relative to the original stimulus of a fixed dimension are difficult to discriminate. This is consistent with the perceptual experimental results [19] showing that after a 3D mesh has reached a minimum required resolution, further increase in mesh resolution does not have significant perceptual impact, as the faces in the refined mesh gets smaller. In any given viewing direction when a 3D object is projected onto a display device, it is visualized as a 2D shape. The silhouettes define visible surfaces, which generate different degrees of impact on the HVS during mesh simplification or refinement. A perceptual value can be computed by comparing the visible surfaces between two levels of detail. An image-based edge cost approach was introduced for determining the visual similarity between an original and a simplified model [15]. Their edge cost measure is based on the mean square error (MSE) between the two projected images. MSE is associated with the averaging effect and tends to hide numerical compensating errors. Also, since complex visual shapes are represented in terms of distributed collections of parts, which are processed independently in visual search [1], computing the cumulated MSE without taking object segments into consideration is not consistent with the HVS.

In the next section, we will apply the JND concept to perceived similarity on 3D textured mapped mesh surface, based on the understanding that a complex object, as processed by the HVS, can be segregated into atomic parts in visual search.

3.1. Perceptual Value and JND

When a 3D object moves closer to the viewpoint in a virtual scene, mesh refinement is beneficial only if the resulting mesh improves visual quality. To determine whether mesh refinement should be performed requires measuring perceptual impact on the HVS. Adding or deleting a vertex (surface structure) from a mesh generates a stimulus to human vision. To compare the perceptual impacts of these stimuli, the dimension of a structure is used as a visual cue in the JND model.

In each edge collapse operation during preprocessing, when a vertex V_R is removed and integrated with its closest neighbor V_C, we record the surface change as the difference $\Delta\rho$ between R_R and R_C. R_v denotes the shortest distance between vertex v and the skeleton (Skeleton generation is described in our earlier paper [22]). For a spherical object, the skeleton is represented by the center of the object (Figure 3). $\rho_R = (R_R\text{-}R_C)/R_C$ is defined as the perceptual value of V_R. If the edge V_QV_C collapse after V_PV_Q, the perceptual value of the combined operation is $(R_P - R_C)/R_C$. Our model is designed for view-independent simplification. In a given view, when a 3D object is projected onto a 2D display, the stimulus can be interpreted by Weber’s fraction on shape. Also, note that the visual impact of a stimulus is dictated locally by the closest adjacent vertex and the closest distance to the skeleton. For example, collapsing V_RV_C has higher impact than collapsing V_QV_C, and we can disregard the overall shape and dimension of the object.

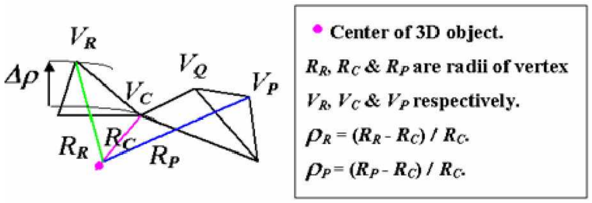


Figure 3: V_R and V_P have perceptual values ρ_R and ρ_P respectively.

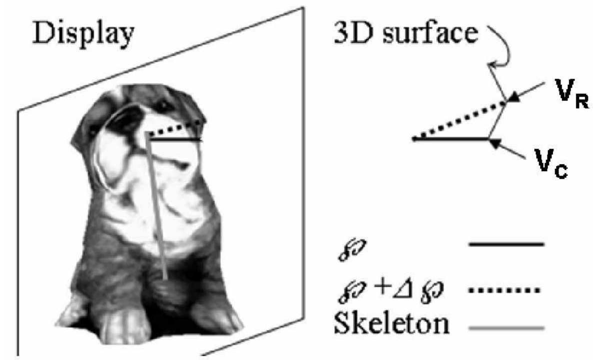


Figure 4: An example of a perceptual impact generated by removing vertex V_R.

Let $\Delta\wp$ be the change when removing V_R and $\wp$ be the distance of V_C from the skeleton. When viewed on the display device, the difference $\Delta\wp$ generates a stimulus to the retina (Figure 4). The JND is the minimum change in perceptual value in order to produce a noticeable variation in visual experience. Weber's Law [8] states that at the JND threshold,

$$\frac{\Delta\wp}{\wp} = K \qquad (1)$$

where K is a constant. A relative change, which is greater than K will generate a significant perceptual impact on the HVS. This concept can be extended to evaluate perceived similarity on a textured mapped 3D mesh surface. Instead of representing the stimulus linearly, an alternative is to use the volume of the quadric error generated by removing V_R and compute the projected area on the display. Experimental results show that our JND perceptual metric predicts visual quality well, closely following human perception.

Online applications have benefited from high-speed communication infrastructures introduced in recent years. Meshes with a few hundred triangles do not create much problem in term of latency and frame rate. The focus is therefore on suppressing redundant data from high resolution meshes composed of thousands of triangles or more. Perceptual impacts can be generated when there is a change of detail or when individual vertices are inserted or removed. In either case, the perceptual value associated with each vertex is used to estimate the visual impact. The perceptual values are computed by running a simplification algorithm during preprocessing. To verify the JND approach, we used the scale-space filtering (SSF) technique [4] to generate different scales of detail. During mesh refinement, the dimensions of the inserted 3D structures decrease towards finer scales. An important feature of SSF is that structures of similar size are grouped between adjacent scales. If we take a *conservative* approach, the maximum perceptual value among these structures should be used assuming the viewer can detect the maximum impact. An *aggressive* approach would be to take the minimum impact. In the experiments, an *intermediate* approach was adopted using the average value. The average perceptual value is a good estimate provided that the standard deviation is small.

Table 1: An example of cumulative perceptual values generated from a nutcracker to a mesh based on the JND approach.

From scale	To scale	Perceptual value
0	1	0.0410
0	2	0.0616
0	3	0.0677
0	4	0.0759
0	5	0.1080

We performed SSF on the nutcracker object with 1260 faces at the original scale S_0 (Figure 1 left). For each scale change, the perceptual values of the vertices removed were recorded. The cumulative perceptual values were also computed and stored in a lookup table (LUT) so that the perceptual impact between any scales S_i and S_j can be retrieved (Table 1).

Previous refinement techniques assume that visual quality increases as the number of vertices increases. However, user studies show that not every set of vertices has significant impact on visual quality [3]. Note that the perceptual value column in Table 1 indicates that different changes of scale generate stimuli of different magnitudes. Notice that the value decreases when moving from bottom to top in the column. Remember that the HVS is insensitive to stimulus below a certain dimension, which is defined by the JND threshold. In Section 4, we will apply the JND analysis on the Progressive Meshes and Quadric Error Metric simplification, and analyzes the performance of these LOD techniques.

4. Evaluation of LOD techniques using the JND approach

LOD techniques have been discussed extensively in the literature. However, despite the simplification result presented by each technique, so far there is no systematic way to measure and compare the performance of difference simplification techniques, other than a visual inspection on the simplified meshes. In this Section, we will apply the JND analysis to evaluate the performance of two simplification techniques – Progressive Meshes (PM) and Quadric Error Metric (QEM). We will discuss the observations and compare the JND analysis with a visual analysis.

In order to have a fair comparison between the performances of simplification techniques, it is necessary to divide simplification operations into three types.

4.1. Type I – Simplification on super high resolution meshes

The original geometry data captured by 3D scanners, *e.g.* laser or structure light scanner, are often very dense containing redundant data with respect to human perception. The data are redundant because the human eyes are insensitive to minute details smaller than a certain dimension. When a super high resolution mesh is simplified to another super high resolution mesh, the change on the 3D surface is not noticeable (less than the JND threshold) that any simplification technique can produce equally impressive visual quality. For example, in Figure 5 when the head mesh of 233,216 faces is simplified to 100,000 faces, the visual quality of the silhouettes is preserved by most simplification algorithms. However, computation using quantitative metrics based on signal-to-noise ratio (SNR) will show that simplification technique α causes less deviation from the original surface than technique β and thus technique α performs better. Such quantitative comparison is not fair; the performances of the techniques should be scored the same based on visual quality.

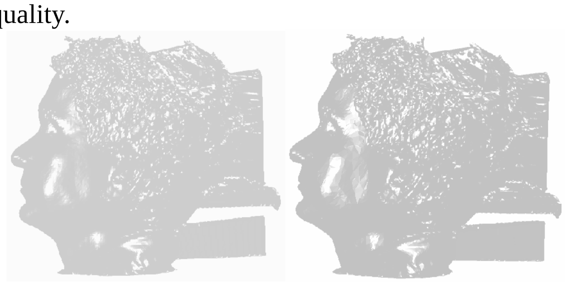


Figure 5: The left mesh (233,216 faces) is simplified to the right mesh (100,000 faces) but there is no significant difference in visual quality, shown by most simplification algorithms.

4.2. Type II – Simplification on oversimplified coarse meshes

Based on the psychophysical experiments performed by Pan et al. [19], it was found that the mesh quality increases exponentially as the number of vertices increases after a certain minimum required mesh resolution is reached. Below the minimum required resolution (the linear portion of each exponential curve in Figure 6), the visual quality of a coarse mesh is unsatisfactory in general and can be improved by increasing the number of vertices. In other words, simplification performed on these coarse meshes, using any simplification technique, will continue to deteriorate the visual quality (simplifying from middle to right in Figure 7). However, technique α may maintain a better silhouette than technique β with respect to visual quality, as illustrated in Figure 9 below.

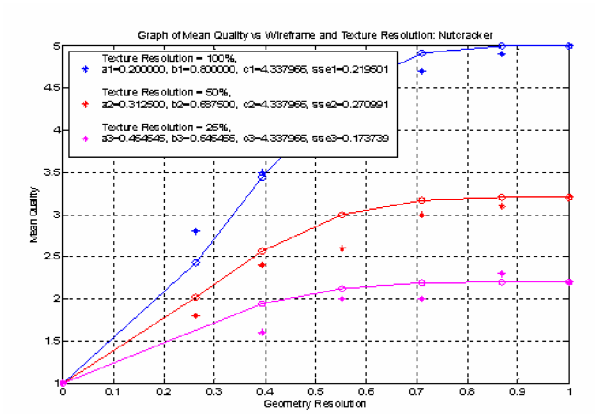


Figure 6: Pan et al. [19] showed in perceptual experiments that mesh quality increases exponentially as the number of vertices increases after the minimum required resolution is reached. The visual qualities (Y-axis) of three different 3D objects were plotted against the normalized geometry resolution (X-axis).

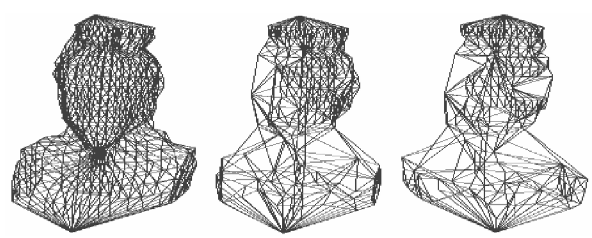


Figure 7: The left mesh (1,296 faces) is the original. Both the middle (614 faces) and the right mesh (502 faces) are of unsatisfactory visual

quality because important features on the 3D surfaces have been removed.

4.3. Type III – Simplification on Perceptually Rich Meshes

A perceptually rich mesh is defined as one that does not contain redundant geometry data with respect to human perception, and is not oversimplified.

In other to evaluate the performance of the PM and QEM techniques, we performed simplification on a *Type III* and *Type II* mesh. A *Type III* mesh can be obtained by carrying out simplification repeatedly until the removal of the next vertex will create a visual stimulus greater than the JND threshold as described in Section 3.1. Before we explain how to use our JND approach to analyze the performance of the PM and QEM techniques, let us have a visual inspection on the meshes generated by the two algorithms.

4.4. Visual Analysis

In the PM algorithm, an energy function is computed so that the next vertex to remove is the one, which will generate the minimum energy. Figure 8 shows an example of four different levels-of-detail generated by PM, implemented using JDK 1.42 and Java3D 1.31. Observe that the distortion on the silhouettes become more obvious when the number of faces is reduced to about 1,000 or less (Type II meshes). A close-up of the mesh composed of 700 faces, shows that visual quality presented by the QEM algorithm (Figure 9 Bottom) is better than that presented by the PM algorithm (Figure 9 Top). The QEM algorithm better preserves critical features.

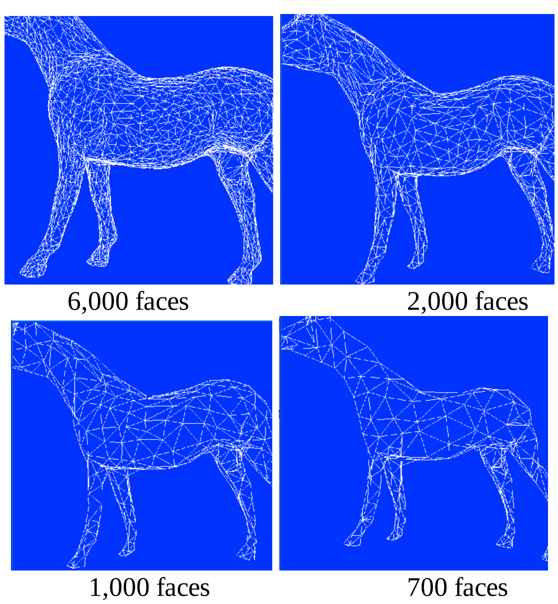


Figure 8: A horse mesh with original resolution of 6,000 faces, and three other levels-of-detail generated by the PM algorithm.

Now let us look at the simplified mesh composed of 3,000 faces, generated by the PM (Figure 10 (a)) and the QEM (Figure 10(b)) algorithms. We can see that the mesh generated by PM has more regular triangles than that generated by QEM. Most of the triangles in (a) are of similar size and shape, while triangles in (b) are very different in both size and shape. This is because PM has a spring energy constraint, which preserves regular shaped triangles and uniform length edges. Although the spring energy constraint may prevent sliver triangles, very often a mesh needs triangles with different size and shape to preserve the smoothness of the silhouettes. For example, the approximation of the hoof surface in (b) is better than the one shown in (a), because of the presence of smaller size and irregular triangles. As a result of the spring energy constraint many critical short edges are removed by PM. Therefore, in terms of visual quality, QEM is preferable.

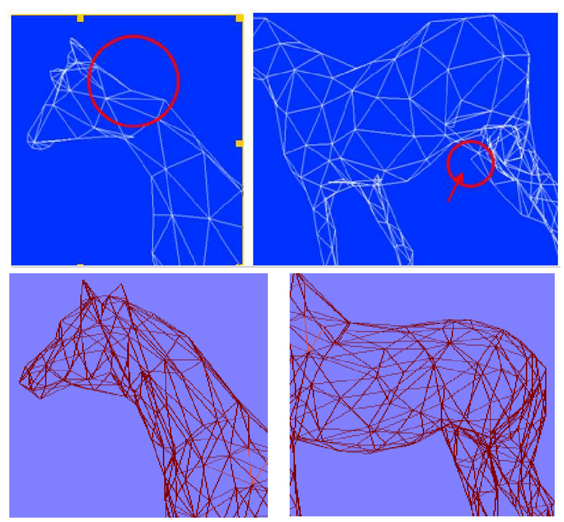


Figure 9: (Top) A simplified horse mesh composed of 700 faces, generated by the PM algorithm, shows noticeable degradation of visual quality. (Bottom) Corresponding mesh surface generated by the QEM algorithm shows smoother silhouettes.

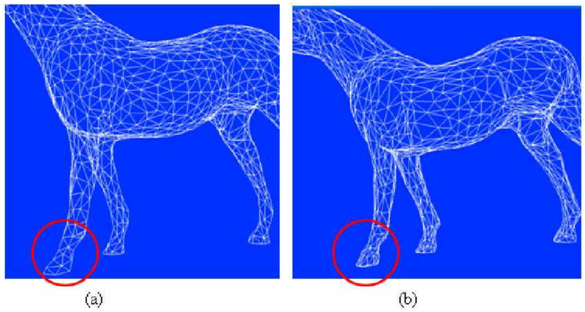
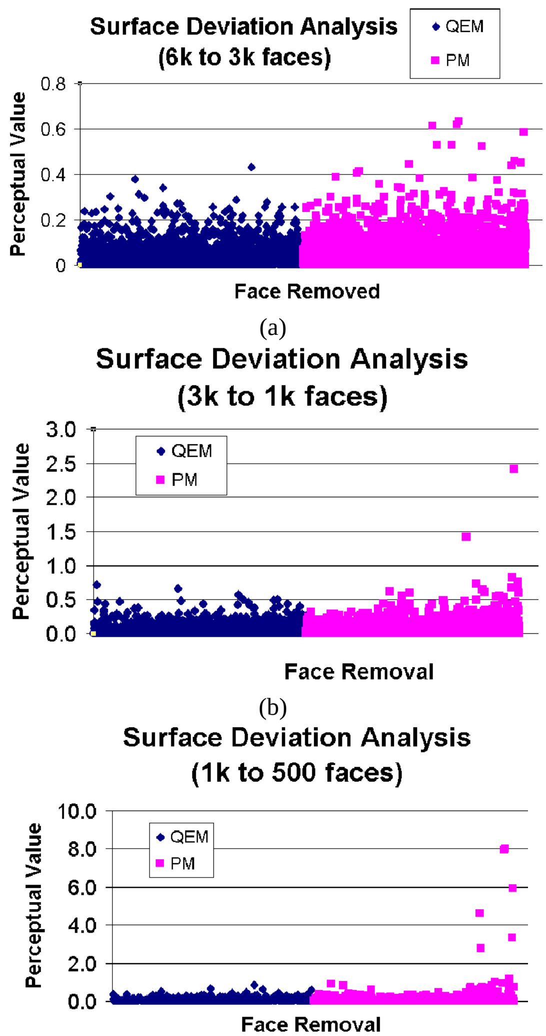


Figure 10: A simplified horse mesh composed of 3,000 faces generated by the PM (a) and QEM (b) algorithm.

4.5. JND analysis



(c)

Figure 11: A comparison between QEM and PM with respect to the visual impact generated by removing a sequence of faces. Based on the perceptual values computed, QEM generates a smaller surface deviation on average and gives a smoother simplified surface.

A visual analysis can only be performed after the LODs have been generated. In case of unsatisfactory visual quality, it will be too late to regenerate and redisplay to the viewers. By applying our JND analysis, the expected visual quality can be predicted beforehand, and thus better quality LOD can be generated if necessary, depending on the available resources. To verify whether the JND analysis is consistent with the visual analysis, we computed the perceptual values of a 3D object. For each face removed, the perceptual value was recorded (Figure 11). For each of the QEM and PM technique, the graph from left to right shows a sequence of triangle faces removal. The results from QEM (left/blue) and PM (right/pink) are reported.

There are two observations one can conclude from the resulting graphs:

1) In general the simplified meshes generated by QEM have better visual quality than those generated by PM as demonstrated by the smaller deviation from the original 3D mesh surface. Table 2 shows the statistics derived when simplifying a horse mesh. QEM has smaller average, standard deviation, and maximum values.

Table 2: A comparison between QEM and PM: Statistics of the perceptual values generated when simplifying a horse 3D mesh.

Faces	From 6k-3k	From 3k-1k	From 1k-500
QEM			
Mean	0.038796	0.060189	0.092833
Std dev	0.045587	0.076118	0.104457
Max	0.432001	0.711911	0.870905
PM			
Mean	0.068318	0.086274	0.233991
Std dev	0.07227	0.116368	0.729989
Max	0.631635	2.406617	8.026027

2) In the visual analysis, the simplified meshes from QEM and PM do not show significant difference when 3,000 faces are removed from the 6,000 faces mesh. This can be explained by the low average perceptual values – which do not generate significant visual impact (Figure 11 (a)). When reducing the faces from 3,000 to 1,000, PM has a number of obvious artifacts denoted by the isolated pink squares with comparative high perceptual values (Figure 11 (b)). When reducing from 1,000 to 500 faces, the artifacts created by PM are more prominent, and at *the same time the simplified mesh generated by QEM also shows more noticeable visual degradation; more perceptual values are above the JND threshold of 10% (Figure 11 (c)).*

We can conclude that the predication result from the JND analysis is consistent with the visual analysis result in Section 4.4. Thus, the JND analysis is a reliable method to evaluate and compare the performances of different simplification techniques.

5. Conclusion and Future Work

In this paper, we proposed a perceptual analysis technique, based on the JND methodology, to evaluate the performance of simplification algorithms. Although mesh simplification has been discussed extensively in the literature, there is no systematic method to compare and measure the efficiency of simplification algorithms taking human perception into consideration. Our approach integrates quantitative with perceptual analysis to compute the expected visual quality of a simplified mesh, so that better quality level-of-detail can be generated based on the available resources. We applied our analysis on the PM and QEM simplification techniques. Experimental results show that the analysis performed is consistent with the visual analysis. The proposed perceptual analysis can therefore be used to evaluate the performance of simplification algorithms. To compare the performance of two simplification algorithms, perceptual values are sufficient. When predicting the resulting visual quality of a 3D mesh after a set of faces is removed, cumulated perceptual values have to be computed.

As explained in our earlier research [4], during simplification SSF groups surface structures of similar dimensions in adjacent scales (Convergence feature), and thus mesh refinement and resources utilization can be more efficient. In future work, we will apply the JND analysis to other simplification techniques to detect their convergence features, and compare with SSF.

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