

International Journal of Image and Graphics
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MESH COMPARISON USING ATTRIBUTE DEVIATION METRIC

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Received 3 June 2002
Revised 5 December 2002
Accepted 4 November 2002

We propose a mesh comparison method using a new attribute deviation metric. Considered meshes contain geometrical and appearance attributes (material color, texture, temperature, etc.). The proposed deviation metric computes local differences between attributes of two meshes. Mesh comparison assessment can be done easily and quickly using this metric. The techniques proposed are applicable in a number of ways - e.g. 3D matching and registration - and the example described in the paper is the simplification of a surface by iteratively reducing its complexity according to an error metric. Results are presented showing the success of the algorithm through comparisons with other measures and with three different simplification algorithms.

Keywords: mesh; attribute; assessment; deviation; simplification; quality.

1. Introduction

Current computer graphic tools allow design and visualization of more and more realistic and precise 3D models. These models are numerical representations of both the real and imaginary worlds. Acquisition and design techniques of 3D models (modeler, scanner, sensor, etc.) usually produce huge data sets containing geometrical and appearance attributes. Geometrical attributes describe shape and dimensions of the object and include data relative to a point set on the object surface. Appearance attributes describe object surface properties such as colors, texture coordinates, normal vectors, etc. High quality meshes usually contain a high number of vertices and faces that cause non interactive rendering or high storage space. In recent years results have been presented in order to reduce the mesh complexity either by merging/collapsing elements or by re-sampling vertices. Mesh simplification algorithms use different error criteria to measure the fitness of the approximated

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surfaces. Usually, these algorithms do not return measures of the error introduced while simplifying the mesh. Therefore, a mesh comparison tool would be useful to characterize mesh simplification algorithms.

In this paper, we present a mesh comparison method based on a new attribute deviation metric. This assessment allows one to compute local differences between the attributes of two meshes. The primary advantages of our method are:

- *Generality*: the method manages meshes containing geometric features as well as other surface attributes such as material colors, texture, temperature, radiation, etc. Moreover the measurements are independent of the viewpoint and the attribute type.
- *Locality*: assessments are done for given points on the mesh surface. Assessment resolution can be increased by a surface sampling method.
- *Applications*: the method is suitable for numerical models from real scenes and for synthetic models. This mesh comparison method can be used for many applications: mesh simplification, reverse engineering (comparison between a CAD model and a numerical model of the real object), mesh segmentation, mesh processing algorithm characterization, etc.

In Section 2, we review the related work on mesh difference metric. In Section 3, we present the attribute deviation metric used for mesh comparison. Algorithms used for the implementation of the proposed mesh comparison method are summarized in Section 4. Results on mesh simplification quality are presented in Section 5.

2. Review of Related Work

Complex meshes are expensive to store, transmit, and render. A lower level of detail can be obtained by simplifying the mesh (reducing the number of vertices and faces). In most cases, the simplified surface is therefore different from the original surface. Many simplification algorithms use their own error metric to guide the simplification process. Cignoni *et al.*¹ has presented an overview of the techniques used to evaluate the error introduced by the mesh simplification process.

2.1. Simplification algorithms and error metrics

Many algorithms use geometric measurements of distance or curvature. Schroeder *et al.*² use a vertex-to-plane distance as decimation criterion. Reddy³ employs a function based on curvature to guide the simplification process. Klein *et al.*⁴ apply an error metric based on the Hausdorff distance. Ronfard *et al.*⁵ use two energy functions: local tessellation error and local geometric error. Guézic⁶ utilizes a tolerance volume as an error bound measure. Rossignac⁷ uses an error bound metric based on distances to supporting planes. Lindstrom *et al.*⁸ use a volume metric.

These algorithms simplify the geometry and ignore the distortion caused to other surface attributes (colors, texture, normals, etc.). Figure 1 shows results of an

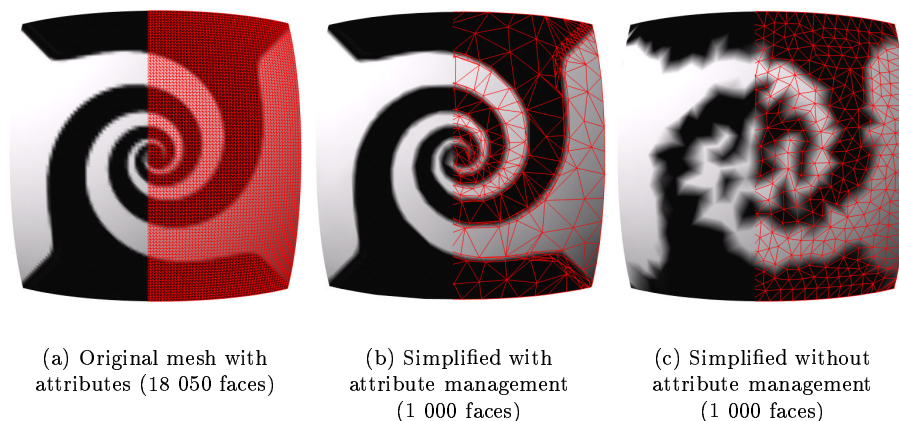


Fig. 1. Mesh simplification example. The simplification algorithm used in (b) manages appearance attributes, and the algorithm used in (c) does not.

example of mesh simplification algorithms. Figure 1(a) shows the original mesh. The algorithm used in Figure 1(b) manages appearance attributes, while the algorithm used in Figure 1(c) does not. We see clearly in the last figure that the mesh aspect is highly deteriorated.

Thus, more complete algorithms are needed to manage mesh attributes during the simplification process. Hoppe⁹ uses three energy functions to preserve surface geometry, scalar attributes and discontinuity curves. Instead of using an error measure, Cohen *et al.*¹⁰ propose a geometric construction, called simplification envelopes, to minimize the surface deviation. Garland *et al.*^{11,12} use a quadric error metric based on the computation of vertex-to-plane distances. Hoppe^{13,14} has improved the last technique for meshes for appearance attributes.

Toubin *et al.*^{15,16} have presented a method for analysis and simplification of numerical models coming from real scenes with several appearance attributes (temperature, luminance, etc.). Analysis of these models is done with the quincunx wavelet transform. This technique allows the extraction of geometric and appearance data considered as important information. Thus the original model is simplified in order to conserve these data. After what have been developed by Toubin, we have looked for an error metric to assess the conservation of the important information. Currently there is no tool to assess simplification error introduced on appearance attributes. We have previously presented a simplification quality assessment for appearance attribute^{17,18}.

2.2. Geometric error

Cignoni's *et al.* "Metro tool"¹⁹ allows the measurement of mesh simplification algorithm quality as a geometric error between the original and the simplified meshes.

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This error is reported directly on the mesh, which allows the visualization of the local error. The software also returns numerical values such as the mean error. The quality measurement is based on the point-to-surface distance.

Given a point p and a surface S , the point-to-surface distance $e(p, S)$ is defined as:

$$e(p, S) = \min_{p' \in S} d(p, p') \quad (1)$$

where $d(p, p')$ is the Euclidian distance between two points in \mathbb{R}^3 . The Metro tool is commonly used. However it can only measure the geometric error and does not manage meshes with appearance attributes.

2.3. Texture deviation

Geometric data simplification introduces a modification of texture coordinates. Thus, the texture is applied differently on the simplified mesh than on the original one, which generates a modification of the texture aspect on the simplified surface. This alteration of aspect is called: *texture deviation*. Cohen *et al.*²⁰ proposed a measurement of this deviation to guide the simplification process.

Cohen defines an application $F_i(p) = (u, v)$ that gives the texture coordinates (u, v) associated to the point p on the surface S_i . This application allows one to go from geometric space to parametric space. The inverse application $F_i^{-1}(u, v) = p$ that gives the point p on the surface S_i with the texture coordinates (u, v) is also defined. Given two meshes M_a and M_b , their respective surfaces S_a and S_b , and a point $p_i \in S_a$, the texture deviation $T(p_i, S_b)$ between p_i and S_b is defined as:

$$T(p_i, S_b) = d(p_i, F_b^{-1}(F_a(p_i))) \quad (2)$$

The texture deviation is the distance between a given point on S_a and the point on S_b with the same texture coordinates. The measurement of texture deviation is suitable to guide a simplification process, but results show that it is not suitable for assessing simplification quality (see Section 5).

3. Mesh Comparison

Different shape matching methods have been proposed in the literature^{21,22,23,24}. The most famous mesh comparison metric is the Hausdorff distance, which gives a global comparison between two meshes. This method is not suitable in our case because we desire to highlight mesh regions sensitive to the simplification process. Thus, we need to develop a local comparison assessment.

Attributes are considered as vectors in Euclidian space defined on all points of the mesh. So a point is represented as an array composed of n attribute vectors $(\mathbf{a}_1, \dots, \mathbf{a}_n)$ with \mathbf{a}_i an attribute vector. We define an application $\mathbf{f}_i(p) = \mathbf{a}_i$ that gives the attribute vector \mathbf{a}_i of attribute i associated with the point p . The mesh comparison method proposed in this paper is based on the difference assessment between mesh attributes.

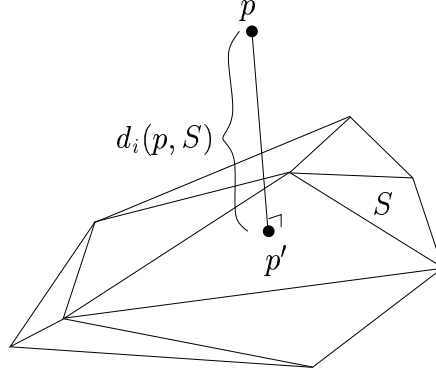


Fig. 2. Attribute deviation metric. The deviation $d_i(p, S)$ is the distance of the attributes i between a point p and a surface S . The point p' is the nearest point to p on the surface S .

3.1. Attribute deviation metric

Given a surface S and a point $p \in \mathbb{R}^3$, the deviation $d_i(p, S)$ between the attribute i of the point p and the surface S is defined as:

$$d_i(p, S) = \| f_i(p) - f_i(N_S(p)) \| \quad (3)$$

with $N_S(p) = p'$ the nearest point to p on the surface S . The attribute deviation $d_i(p, S)$ is the distance from the attribute i of the point p to the attribute i of the nearest point to p on the surface S . In the case of several points on the surface S having the same distance to the point p , the attribute deviation is the minimum distance between the attribute i of p to the attributes i of the nearest points to p on S . The attribute deviation metric scheme is presented in Figure 2.

3.2. Deviation assessment

Given two meshes M_a and M_b , their respective surfaces S_a and S_b , and a set P of points $\{p_j \mid p_j \subset S_a \text{ and } j = 1, \dots, m\}$, the deviation $D_i(M_a|_P, M_b)$ of the attribute i between $M_a|_P$ and M_b is defined as:

$$D_i(M_a|_P, M_b) = \{d_i(p_j, S_b) \mid j = 1, \dots, m\} \quad (4)$$

The deviation between two meshes uses the attribute deviation metric (Eq. 3). Mesh M_a is called the *reference mesh* and is restricted to a point set taken on its surface. These points constitute the measurement points for the attribute deviation metric.

3.3. Discussion

Attribute deviation assessments allow one to highlight local differences between two meshes. Note that this assessment is guided by the geometrical correspondence between the meshes (the nearest point on a surface to a point on the other surface).

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Also note that attribute deviation assessment is not symmetric. It is computed from a point set defined on the reference mesh surface. If the meshes are inverted, results may be different. In practice, an average of both deviations $D_i(M_a|_{P_a}, M_b)$ and $D_i(M_b|_{P_b}, M_a)$ is considered. Results are often different but relatively close.

As part of mesh simplification algorithm quality assessment, geometric deviation assessment is the main measurement, because mesh simplification is essentially geometric. Deviation assessment of the other attributes can be used to quantify aspect modifications due to the simplification process. After an important simplification (90% or more reduced faces), we usually note important local deviations of appearance attributes.

Note that Eq. 4 requires two meshes where one is sampled with a point set taken on its surface. So we may take points only in regions of interest. Measurement points may be vertices of the reference mesh or points taken on the mesh surface. The measurement resolution can be increased using a surface sampling algorithm (for example to compute deviation inside faces).

4. Algorithm Summary

Our mesh comparison method is based on the attribute deviation metric. For each point on the first surface, the nearest neighbors on the second surface are found, and deviations between them are measured. Performances of this method depend on algorithms implied in the different operations (nearest neighbor search, face sampling, etc.).

For a given point, the nearest point is computed efficiently by evaluating point-to-surface distances. A regular grid of square cells is built, covering the bounding box of both meshes^{25,26}. Each cell contains a list of all vertices included in the cell and all faces intersecting the cell. This technique allows one to quickly find the nearest point on a surface for a given point. Note that the nearest point could be a vertex or a point on an edge or a point on a face.

We have developed a fast algorithm to sample a triangular face. This algorithm is based on the scan conversion algorithm^{27,28}. The face sampling is performed in 3D space. In order to maintain the best accuracy, there is no 2D projection. This algorithm allows the generation of uniformly distributed points on a triangle in 3D space (see Figure 3).

Given a face $f = (A, B, C)$, we define a local reference (\vec{u}, \vec{v}) as:

$$\vec{u} = \frac{\vec{AB}}{\|\vec{AB}\|} \cdot \Delta \quad \vec{v} = \frac{\vec{AC}}{\|\vec{AC}\|} \cdot \Delta \quad (5)$$

where Δ is the sampling step. The reference (\vec{u}, \vec{v}) is defined on the plane formed by the face f . We generate horizontal scan lines parallel to \vec{u} and vertical scan lines parallel to \vec{v} . Scan line numbers are defined as:

$$n_u = \frac{\|\vec{AB}\|}{\Delta} \quad n_v = \frac{\|\vec{AC}\|}{\Delta} \quad (6)$$

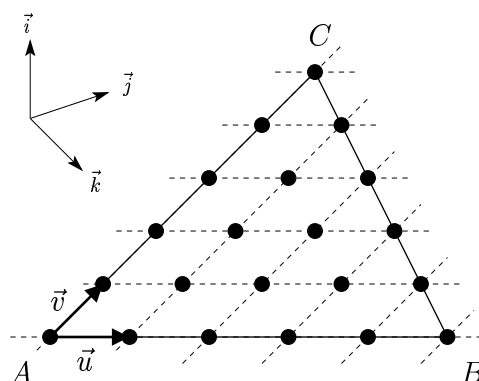


Fig. 3. Face sampling scheme.

The number of points per horizontal scan line can be determined by incremental computation using the slope of edge BC . With this sampling method, attributes can be easily computed for all samples using Phong interpolation²⁷. In order to obtain visual results of measured deviations on these points, a deviation image is created for every face. Deviation values are coded according to a color scale. Images built for every face are packed in a standard, regular texture. We use the packing algorithm proposed by Cignoni²⁹ to build this texture.

5. Experimental Results

We have developed a mesh comparison software called MeshDev based on the attribute deviation metric presented above. This software is freely available online^a. It requires two meshes as input, and returns numerical and visual comparison results. Numerical results contain characteristics of both meshes and statistics of the assessed deviation, and visual results allow one to highlight high deviation regions.

| | Mesh M_a | Mesh M_b | Deviation | |
|----------|------------|------------|-----------|---------|
| Vertices | 46 870 | 2 806 | Minimum | 0.00013 |
| Faces | 93 752 | 5 624 | Maximum | 0.4933 |
| Area | 22 090 | 22 124 | Mean | 0.0398 |
| | | | Variance | 0.00085 |

Table 1. Example of numerical results returned by MeshDev software.

Table 1 shows an example of numerical results returned by MeshDev software. The left box shows mesh characteristics. The right box shows statistics related to

^a<http://meshdev.sourceforge.net>

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the measured deviation. More other statistical results can be given by MeshDev software.

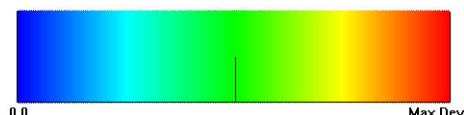


Fig. 4. Color scale used for visual representation of measured deviation.

Visual results are constructed by coloring the reference mesh according to the measured deviation. Figure 4 shows the color scale used: blue represents minimum deviation, green represents medium deviation and red shows maximum deviation.

Figure 5 shows visual results of geometric and attribute deviations computed using MeshDev software. In this figure we compare the attribute deviation metric to Cohen's texture deviation measurement (see Section 2.3). Figure 5(a) shows the original mesh (3 972 faces). Figure 5(b) represents the simplified mesh (69 faces) with low texture distortion. Figure 5(c) represents the simplified mesh on which we have applied high texture distortion. Figure 5(d) shows the geometric deviation measured between the original and the simplified mesh. With low texture distortion, Cohen's measurement gives the same visual result as the geometric deviation (see Figures 5(d) and 5(e)). Nevertheless, both measurements cannot be numerically compared. The attribute deviation metric returns only the effective texture deviation (see Figures 5(e) and 5(f)). With high texture distortion, Cohen's measurement returns deviation values in regions where there is no distortion (see Figure 5(g)). Attribute deviation metric gives more precise results than Cohen's measurement (see Figure 5(h)). If there is no texture distortion, Cohen's measurement indicates a deviation coming from strictly geometrical distortion.

In our experiments, we used three simplification software programs:

- *QSlim*^b: software developed by Michael Garland based on a quadratic error measurement^{11,12}.
- *Jade*^c: software developed by *Italian Visual Computing Group* based on a global error measurement³⁰.
- *ProgMesh*^d: software developed by *Paralelo* based on the progressive meshes from Hughes Hoppe⁹.

Figures 6 and 7 show visual results obtained with MeshDev software on a mesh simplified by these three simplification software programs. The deviation representation is normalized for each mesh, so visual comparisons are not possible. We have

^b<http://graphics.cs.uiuc.edu/~garland>

^c<http://vcg.iei.cnr.it/enhadecimation.html>

^d<http://www.paralelo.com.br>

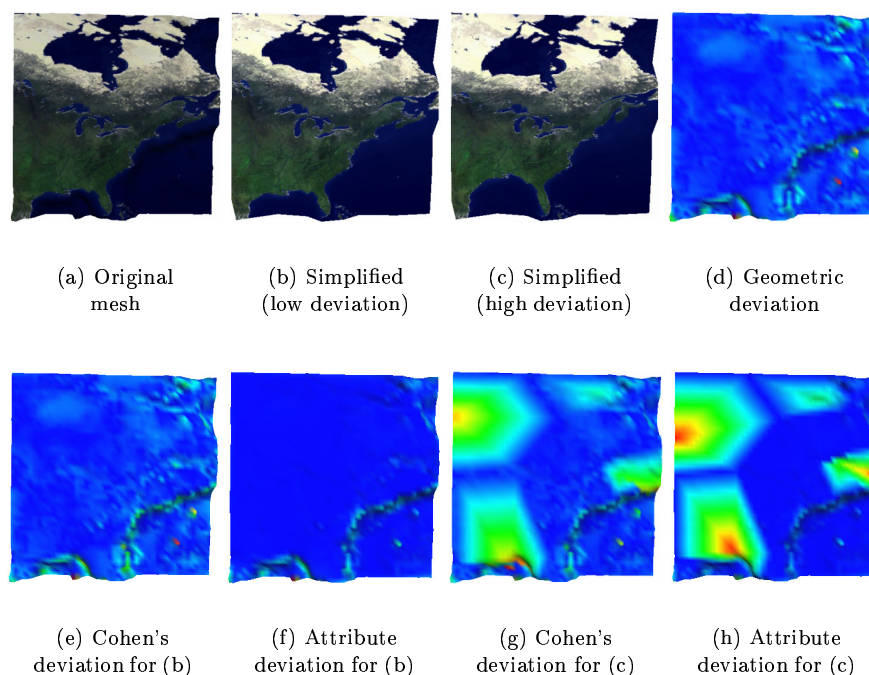


Fig. 5. Comparison between Cohen's measurement in (e) and (g) and the attribute deviation metric in (f) and (h) (the considered attribute is the texture coordinate).

chosen the normalized representation of deviations to highlight all measured values for each simplification algorithm. Figure 6 shows results of the geometric deviation and Figure 7 shows results of the attribute deviation in which the attribute considered is the surface normal (vertex normals are estimated by simply averaging face normals in the vertex neighborhood). *QSlim* generates a low deviation on the entire mesh but we find that there are some regions with high deviation (see Figures 6(a) and 7(a)). *Jade* generates medium deviation on the entire mesh (see Figures 6(b) and 7(b)). This algorithm simplifies the mesh by bounding the global error. *ProgMesh* generates low and medium deviation on the entire mesh (see Figures 6(c) and 7(c)).

Figure 8 represents the graphs of numerical results obtained from the simplified forms of the previous mesh. Simplified meshes are made using the three above cited software packages. Figure 8(a) shows the mean geometric deviation. Figure 8(b) the mean attribute deviation where considered attribute is the normal. These graphs confirm remarks made above. *QSlim* software obtained the lowest mean deviation in all cases. This software perfectly manages appearance attributes during the simplification process and generates low deviation.

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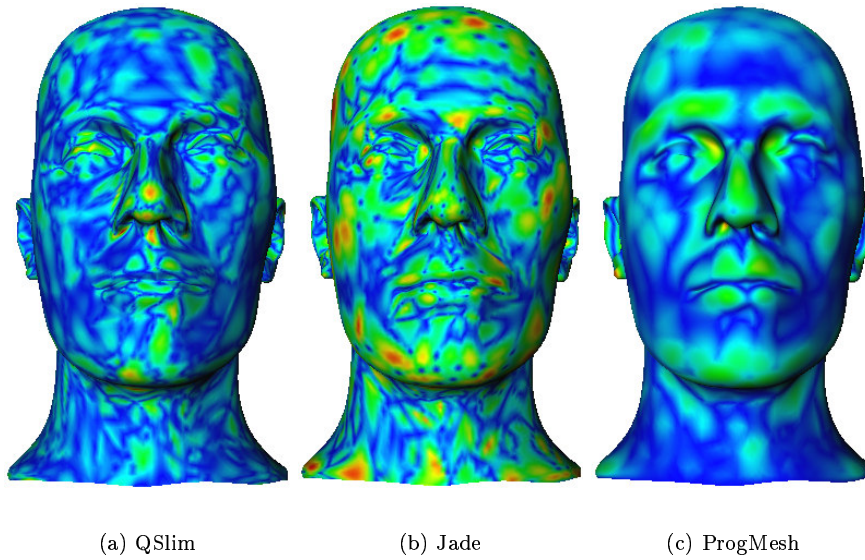


Fig. 6. Geometric deviation assessment for three different simplification algorithms.

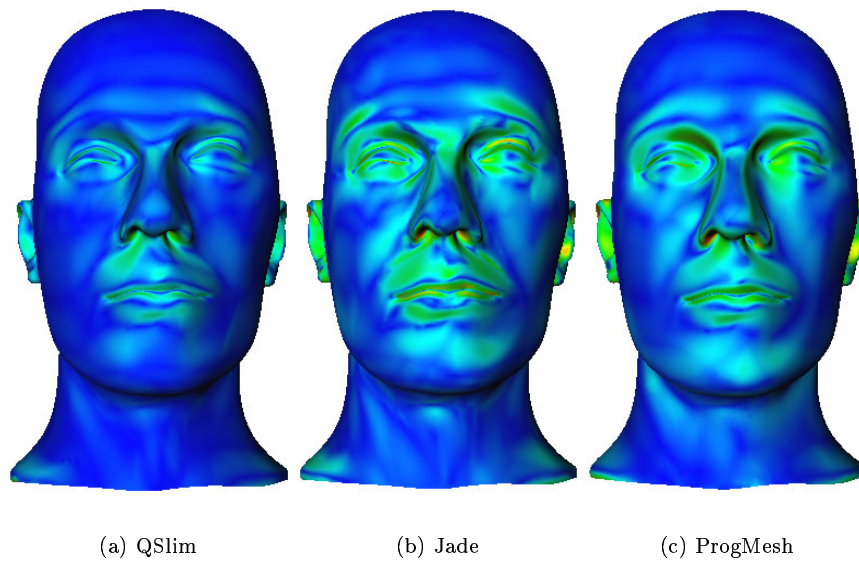


Fig. 7. Attribute deviation assessment for three different simplification algorithms (the considered attribute is the surface normal).

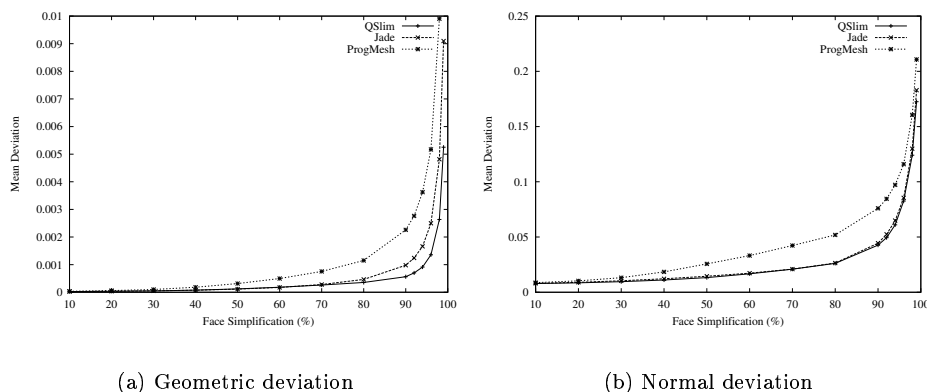


Fig. 8. Comparison between three mesh simplification algorithms.

6. Conclusion and future work

We have presented the attribute deviation metric for approximating local differences between two meshes. This metric was used to build a mesh comparison program. The local measurement allows one to precisely view regions with high deviations. This is a great advantage compared to other methods that return global comparison. Geometric deviation is useful to assess shape differences. Deviation assessment of other attributes is efficient to assess appearance modifications.

Since the attributes are considered as vectors in Euclidian space, measurements in the real attribute space (such as RGB space for colors) would be more appropriate. Other metrics can be added to the attribute deviation metric (e.g. tessellation quality) in order to get a more general mesh comparison tool.

Acknowledgements

This work was made in collaboration with the IRIS Lab^e (University of Tennessee). The authors acknowledge David Page^f, Yiyong Sun^g, Andreas Koschan, Mongi Abidi and Tadeusz Sliwa^h for their help.

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