

Evaluation of an Appearance-Preserving Mesh Simplification Scheme for Configura AB

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Upphovsrätt

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1 Introduction

The rendering of meshes (a collection of polygons describing a surface) is one of the main activities in computer graphics (usually, a collection of meshes; a so called scene description). In many cases, these meshes are very detailed, and require a large amount of polygons to fully describe a surface. This is problematic, since the rendering time of a scene depends on the number of polygons it has. Therefore, it is important to reduce the number of polygons in a mesh as much as possible. This is especially true in video games, where the scene needs to be rendered in real-time. However, if the number of polygons are reduced too much, it will degrade the visual quality of a mesh, giving a progressively flatter surface than intended and removing small surface details. This destroys the intended *geometrical appearance* of the mesh.

1.1 Motivation

While the geometrical appearance of a mesh is important, it is not the only factor which gives the final appearance of a mesh when rendering. According to *Cohen et al.* [2], both the surface curvature and color are equally as important contributors. *Textured appearance* will be used as the common name for these since surface properties are usually specified with a texture map.

In computer graphics, the process to reduce the number of polygons in a mesh based on some metric is called a *mesh simplification algorithm*, as seen in *Talton's survey* [18] in the field. Historically, these have been mostly concerned with minimizing the geometrical deviation of a mesh when applying it. Somewhat recently, methods for minimizing the texture deviation when simplifying a mesh have also appeared. They attempt to reduce the texture deviation and stretching caused when removing polygons from a mesh, as described in *Hoppe et al.* [8].

By simultaneously taking into account the geometrical and texture deviation, one can preserve the *visual appearance* of a mesh when simplifying it. If polygons can be removed without affecting this appearance significantly, the rendering time can be reduced for “free”.

1.2 Aim

The aim of this thesis is to first perform a literature study of mesh simplification algorithms that preserve the visual appearance of a mesh. A suitable solution will then be integrated as a preprocessing step in *CET Designer's* graphics pipeline. *CET Designer* is a space planning

software developed by the company *Configura AB* (see Section 1.5 for a more detailed description). Considering the visual appearance when simplifying a mesh will enable Configura to generate better *Level of Detail* (LoD) meshes for speeding up their rendering time. Currently, Configura only takes into account the geometrical deviation when simplifying, with no regard for the textures (e.g. diffuse or normal) on top of the mesh.

1.3 Research Questions

1. What alternative *mesh simplification schemes* exist that *preserves the appearance* of a mesh?
2. Which of these alternatives would be appropriate to integrate into Configura's software?

1.4 Delimitations

Since the thesis is done on a time limit a comparison of multiple mesh simplification schemes taking the appearance into account is not feasible. Therefore, one mesh simplification algorithm will be chosen to be implemented and evaluated. The choice will be based on a study of algorithms that can be found in the literature.

1.5 Background

This thesis was requested by Configura AB, a company in Linköping which provides space planning software. Their main product, *CET designer*, lets companies plan, create and render 3-D office spaces (among other things). These scenes can have a large amount of polygons that need to be rendered in real-time for customers to evaluate their creations in CET designer.

To allow larger scenes to be rendered with higher frame-rates (e.g. needed when exploring environments in *Virtual Reality* (VR), to prevent motion sickness), it would be beneficial to reduce the amount of polygons as much as possible. The meshes in these scenes usually have textures applied to them, and it is therefore important to keep the quality as high as possible.

While Configura already has a mesh simplification in their pipeline, it only accounts for surface simplifications, and does not take into account the texture appearance that might be degraded when applying mesh simplification. Hence, the given task was to integrate a new mesh simplification scheme that takes into account texture quality when simplifying a mesh.



2 Theory

Since several mesh simplification algorithms are being considered, Section 2.1 gives a brief overview of the most notable schemes found in previous work. A more detailed explanation of the algorithms can be found in Sections 2.2 to 2.4.

Afterwards, in Section 2.7, the different metrics that can be used to measure the appearance preservation after a simplification has been done is discussed. This will later be used to evaluate the solution empirically by giving a concrete metric for the amount of appearance deviation.

Finally, in Section 2.8, the methods and common practices for measuring performance of an algorithm are discussed. Based on existing industry practices, we show how to measure the computation time and memory usage of the algorithms. Since these measurements can be noisy, statistical methods will need to be used to truthfully answer our research questions.

2.1 Related Work

Some different approaches have been presented in the literature to solve the problem of simplifying a mesh. Early solutions focused on the geometrical error which is enough in many cases, but in the case of a mesh with appearance attributes this may give a poor result. Other solutions have been presented that takes the attributes into account to give a better appearance of the mesh. This section will give a brief overview of the simplification algorithms that can be found in the literature.

According to *David Luebke's survey* [14] on the subject, mesh simplification is a technique which transforms a geometrically complex mesh (with a lot of polygons) to a simpler representation by removing unimportant geometrical details (reducing the number of polygons). It does this by assuming that some meshes are small, distant, or have areas which are unimportant to the visual quality of the rendered image. For example, if the camera in a scene always faces towards a certain direction, then removing details from the backside of a mesh won't affect the final rendered result, since they will never be seen by the camera anyway. Reducing the number of polygons allows meshes to use less storage space and need less computation time.

There are many mesh simplification algorithms, as can be seen in *David Luebke's survey* [14], each presenting a new approach with their own strengths and weaknesses. The first scheme is due to *Schroeder et al.* [17] in 1992, called *mesh decimation*. It was meant to be used to simplify meshes produced by the marching cubes algorithm, which usually gives unneces-

sary details. It works by making multiple passes through the meshes' vertices, and deleting vertices that do not destroy local topology and are within a given distance threshold when re-triangulated.

Besides *decimation-based methods*, such as the aforementioned mesh decimation scheme, there exists another class of simplifiers based on *vertex-merging mechanisms*. According to Luebke [14], these work by iteratively collapsing a pair of vertices (v_j, v_k) into a single vertex v_i . This will also remove any polygons which were suspended by (v_j, v_k) . The first collapse scheme is due to Hoppe *et al.* [9], which shows an *edge collapse* of $e_{ji} = (v_j, v_i) \rightarrow v_i$ as in Fig. 2.1 (a). There exist other schemes, such as *pair contraction* in Fig. 2.1 (c) where vertices within a distance t are allowed to be merged. These don't tend to preserve the local topology of the original mesh, and instead focus on a more aggressive simplification.

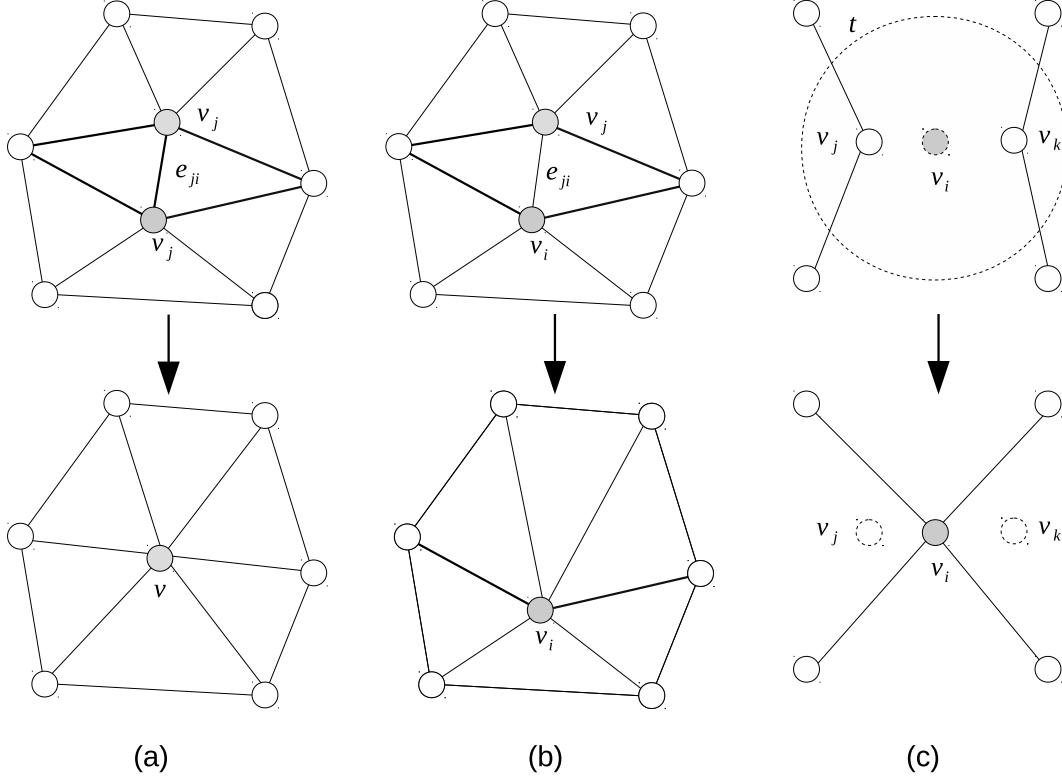


Figure 2.1: (a) edge collapse, (b) vertex removal, and (c) pair contraction

Quadric Error Metrics (QEM), due to Garland and Heckbert [4] performs edge collapses to provide a provably optimal simplification. In each iteration, an edge is collapsed $(v_j, v_i) \rightarrow \mathbf{v}$ and \mathbf{v} is re-positioned at the position which gives the lowest possible geometrical error. Hoppe [8] also perform edge collapses but he tries to minimize an energy function. The edge with the lowest estimated energy is chosen for the collapse.

Focusing on minimizing the geometrical error during simplification works well for many meshes. But in the case of a mesh with appearance attributes such as color, normals, and texture coordinates the result may be poor. A common way to solve this is to use a metric which does not only take the geometry, but also the appearance attributes into account.

Cohen *et al.* [2] defines a new *texture deviation metric* which takes three attributes into account: Surface position, surface curvature, and surface color. These attributes are sampled from the input surface and the simplification is done with edge collapses and vertex removals.

Sander *et al.* [15] uses the texture deviation metric together with a *texture stretch metric* to better balance frequency content in every direction all over the surface.

An extended more general version of the QEM is presented by *Garland and Heckbert* [3] where the metric can be used for points in n -dimensional space. Thus, when the color is considered each vertex would be represented by a 6-dimensional vector. Another version of QEM by *Hoppe* [7] base the attribute error on geometric correspondance in 3D rather than using points in n -dimensional space.

Image-driven simplification defined by *Lindstrom and Turk* [13] captures images from different angles of the mesh. The distance between images of the mesh before and after an edge collapse are used to guide the simplification.

2.2 Appearance-Preserving Simplification

In order to preserve the appearance of a model when it is simplified, *Cohen et al.* [2] defines a *texture deviation metric*. This metric takes three attributes into account: Surface position, surface curvature, and surface color. To properly sample these attributes from the input surface, the surface position is decoupled from the color and normals stored in texture and normal maps, respectively. The metric guarantees that the maps will not shift more than a user-specified number of pixels on the screen. This user-specified number is defined as ϵ .

Approximation of the surface position is done offline with simplification operations such as edge collapsing and vertex removals. At run-time, the color and normals are sampled in pixel-coordinates with mip-mapping techniques. Mip-maps are a pre-calculated sequence of images with progressively lower resolution. Here the decoupled representation is useful since the texture deviation metric can be used to bound how much the mapped attributes value's positions deviate from the positions of the original mesh. This guarantees that the sampling and mapping to screen-space of the attributes is done in an appropriate way.

Before any simplification can be made, a parametrization of the surface is required in order to store the color and normals in maps. If the input mesh does not have a parametrization, it is created and stored per-vertex in texture and normal maps. Next, the surface and maps are fed into the simplification algorithm which decides which simplification operations to use and in what order. The deviation caused by each operation is measured with the texture deviation metric. A *progressive mesh* (PM) with error bounds for each operation is returned by the algorithm, which can then be used to create a set of LOD with error bounds. Using the error bounds, the tessellation of the model can be adjusted to meet the user-specified error ϵ .

2.3 Quadric-Based Error Metric

Mesh simplification with *Quadric Error Metrics* (QEM), due to *Garland and Heckbert* [4], is based on the vertex merging paradigm. It provides a provably optimal simplification in each iteration, by collapsing the edge $(v_j, v_i) \rightarrow v_i$ and re-positioning it at \mathbf{v} , which gives it the lowest possible geometrical error. By assigning a matrix \mathbf{Q}_i for each vertex v_i , one can find the error $\Delta(\mathbf{v})$ introduced by moving v_i to \mathbf{v} . $\Delta(\mathbf{v})$ is the sum of squared distances from \mathbf{v} to the planes \mathbf{f}_k in v_i 's neighborhood N_i (all polygons around v_i as in Fig. 2.2).

Since $\Delta(\mathbf{v})$ is quadratic, finding a \mathbf{v} which gives a minimal error is a linear problem. The best position $\bar{\mathbf{v}}_i$ for v_i after a collapse $(v_j, v_i) \rightarrow v_i$ is a solution to Eq. (2.1).

$$(\mathbf{Q}_j + \mathbf{Q}_i)\bar{\mathbf{v}}_i = \begin{bmatrix} 0 & 0 & 0 & 1 \end{bmatrix}^\top. \quad (2.1)$$

$$\Delta(\mathbf{v}) = \mathbf{v}^\top \mathbf{Q}_i \mathbf{v}, \quad \mathbf{Q}_i = \sum_{\mathbf{f}_k \in N_i} \mathbf{f}_k \mathbf{f}_k^\top. \quad (2.2)$$

By storing the $\Delta(\bar{\mathbf{v}}_i)$ for every valid collapse $(v_j, v_i) \rightarrow v_i$ in a min-heap, the least cost collapse on the top of the heap can be done in each iteration, removing a vertex in each step. This is repeated until either a user-given vertex count $|\mathcal{V}|$ is reached or until some error threshold ϵ .

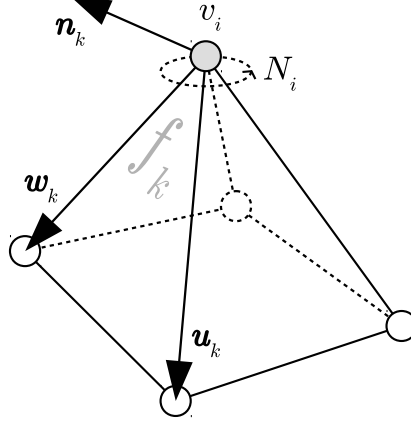


Figure 2.2: depiction of one of the planes f_k in the neighborhood N_i of the vertex v_i . It has a normal \mathbf{n}_k ; found by the $\mathbf{w}_k \times \mathbf{u}_k$ of its edges.

The results by *Garland and Heckbert* [4] show that QEM can reduce the simplification error by up to 50 % in comparison to a naïve scheme where $\bar{\mathbf{v}}_i = (v_i + v_j) \div 2$ and $\Delta(\mathbf{v}) = \|\mathbf{v} - v_i\|$. They also argue that QEM gives higher-quality simplifications than *vertex clustering* and that it is faster than *progressive meshing* (which we also present later).

A general version of QEM was later presented by Garland and Heckbert [3] where vertices can be placed in n -dimensional space. This makes it possible to, for example, include the color of the surface in the computation. Each vertex is treated as a vector $v \in \mathbb{R}^n$. Thus, when the color is considered each vertex will be represented by a 6-dimensional vector $v = [x, y, z, r, g, b]^\top$. The first three values is the spatial coordinates and the last three values will be the color. The same thing can be done with for example texture coordinates where each vertex would be represented by a 5-dimensional vector $v = [x, y, z, s, t]$ where s, t is the 2D texture coordinates.

The original version of QEM used a 4x4 homogeneous matrix Q_i for the computations. A more convenient notation is used in the general version. A face in the original model defines a plane which satisfies the equation $\mathbf{n}^\top \mathbf{v} + d = 0$ where \mathbf{n} is the face normal and d is a scalar. The squared distance of a vertex to a plane is given by

$$D^2 = (\mathbf{n}^\top \mathbf{v} + d)^2 = \mathbf{v}^\top (\mathbf{n}\mathbf{n}^\top) \mathbf{v} + 2d\mathbf{n}^\top \mathbf{v} + d^2 \quad (2.3)$$

D^2 can now be represented as the quadric Q

$$Q = (\mathbf{A}, \mathbf{b}, c) = (\mathbf{n}\mathbf{n}^\top, d\mathbf{n}, d^2) \quad (2.4)$$

$$Q(\mathbf{v}) = \mathbf{v}^\top \mathbf{A} \mathbf{v} + 2\mathbf{b} \mathbf{v} + c \quad (2.5)$$

where $Q(\mathbf{v})$ is the sum of squared distances. This representation performs matrix operations on 3x3 matrices instead of 4x4 as in the previous notation. This increases performance when, for example, performing matrix inversions.

The overhead of the higher dimensional quadrics is not extreme according to Garland and Heckbert. However, when using this with colors, normals, and texture coordinates some caution is needed. Colors may need to be clamped and normals needs to be normalized to unit length.

Garland and Heckbert have assumed that the properties vary continuously over the whole surface. However, if we want to for example apply a texture to a cylinder there will always be a seam where the ends of the texture meets. All vertices along this seam needs to be duplicated since they would require two different texture coordinates. The authors suggested having boundary constraints that would maintain the seam. However, in the case where a

mesh have a corresponding texture atlas where each face have a specific part of the texture this might not work. The solution suggested by the authors is to allow multiple quadrics for each vertex, but, this is not yet implemented.

Hugues Hoppe [7] also uses QEM for meshes with appearance attributes. Instead of calculating the distances to hyperplanes as Garland and Heckbert, Hoppe base the attribute error on geometric correspondance in 3D. A point p is projected onto a face in \mathbb{R}^3 rather than a plane in a higher dimension and then both the geometric and attribute error is computed. According to the author this gives a better result compared to Garland and Heckberts general QEM.

2.4 Progressive Meshes

Hugues Hoppe [8] introduced the *Progressive Mesh* (PM) representation as a scheme for storing and transmitting arbitrary polygon meshes. An abitrary mesh \hat{M} in PM form is defined by a sequence of meshes M^0, M^1, \dots, M^n with increasing accuracy of the original mesh $\hat{M} = M^n$. Only the most coarse mesh M^0 is stored together with records of *vertex splits* that is used to refine M^0 into the more detailed meshes. A vertex split will transform M^i the more detailed mesh M^{i+1} and an edge collapse transforms M^i to the coarser mesh M^{i-1} .

To construct a PM the edge collapses of the original mesh needs to be determined. Multiple possible algorithms for chosing those edge collapses is presented by Hoppe [8], some with high speed but low accuracy and some more accurate but with lower speed. A fast but maybe not so accurate strategy is to choose the edge collapses at random but with some conditions. Another more accurate scheme is to use heursitics. According to Hoppe, the construction of a PM is supposed to be a preprocess, Therefore, the author chose an algorithm that take some time but is more accurate.

Hoppe based the simplification on the previous work *Mesh Optimizatoin* [9] where the goal is to find a mesh that fits a sets X of points $x_i \in \mathbb{R}^3$ with a small number of vertices. This problem is defined as a minimization of the energy function.

$$E(M) = E_{dist}(M) + E_{spring}(M) + E_{scalar}(M) + E_{disc}(M)n \quad (2.6)$$

Distance energy $E_{dist}(M)$ measures the sum of the squared distances from the points to the mesh. *Spring energy* E_{spring} is used to regularize the optimization problem. *Scalar energy* E_{scalar} measures the accuracy of the scalar attributes of the mesh. The last term, E_{disc} measures the geometric accuracy of the discontinuity curves (e.g creases). All legal edge collapses is placed in a priority queue where the edge collapse with lowest ΔE (estimated energy) is on the top of the queue. After a transformation is performed, the energy of the neighboring edges is updated.

Given an arbitrary mesh, *Sander et. al* [15] presents a method to construct a PM where a texture parametrization is shared between all meshes in the PM sequence. In order to create a texture mapping for a simplified mesh, the original mesh's attributes, e.g normals, is sampled. This method was developed with two goals taken into consideration:

- *Minimize texture stretch:* When a mesh is simplified the texture may be stretched in some areas which decrease the quality of the appearance. Since the texture parametrization determines the sampling density, a balanced parametrization is preferred over one that samples with different density in different areas. The balanced parametrization is obtained by minimizing the largest texture stretch over all points in the domain. No point in the domain will therefore be too stretched and thus making no point undersampled.
- *Minimize texture deviation:* Conventional methods use geometric error for the mesh simplification. According to the authors this is not appropriate when a mesh is textured. The stricter texture deviation error metric, where the geometric error is measured according to the parametrization, is more appropriate. This is the metric by *Cohen et al.*

[2] explained in Section 2.2. By plotting a graph of the texture deviation vs the number of faces, the goal is to minimize the height of this graph.

Cohen et al. [2] stored an error bound for each vertex in a PM. *Sander et al.* [15] instead tries to find an atlas parametrization that minimizes both texture deviation and texture stretch for all meshes in the PM.

2.5 Mesh parametrization

In order to apply, for example, a texture to a mesh each vertex is given a texture coordinate. This problem of finding a mapping between a surface (mesh) and a parameter domain (texture map) is called parameterization. Given a triangular mesh Hormann et al. [10] refers to the mapping problem as mesh parameterization. According to Hormann et al. there exists a one-to-one mapping between two surfaces with similar topology. Thus, a surface that is homeomorphic to a disk can be mapped onto a plane, i.e. a texture. If a mesh is not homeomorphic to a disk it has to be split into parts which are homeomorphic to a disk. These parts can then be put onto the same plane and only one texture is needed.

2.6 Multiple attributes for a vertex

A vertex of a mesh often have a properties associated with it such as texture coordinates, color, and normal. A common way of texturing a model is to use a texture atlas where each triangle of the mesh is assigned a specific part of the texture. Since a texture is in a 2-dimensional domain a mesh parameterization needs to be performed. In many cases the mesh needs to be cut somewhere which will create seams. The vertices along this seam would require two sets of texture coordinates and this will create a discontinuity. In Fig. 2.3 a cylinder is unwrapped to 2D which creates a seam. All vertices along the seam will have two sets of texture coordinates (s, t) , one with $s = 0$ and a second with $s = 1$.

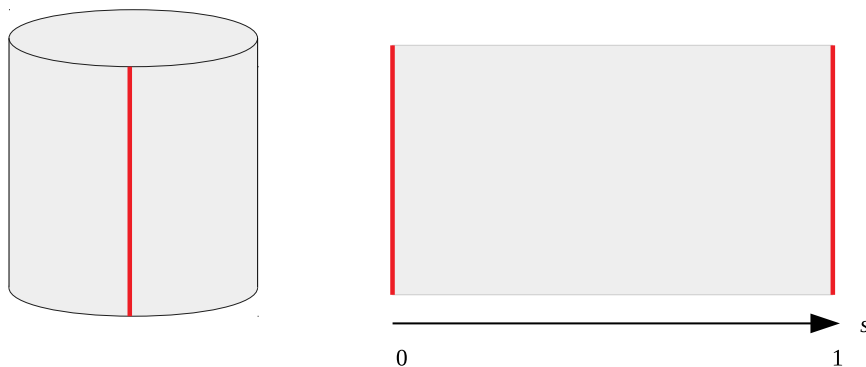


Figure 2.3: Unwrapping a cylinder. Vertices along seam (red line) require two texture coordinates

Hugues Hoppe [6] presents a mesh representation where each face adjacent to a vertex can have different appearance attributes. The attribute values is associated with the corners of the faces instead of the vertices. A *corner* is defined by Hoppe as a tuple $\langle vertex, face \rangle$. The attribute values at a corner defines the value that should be used for face f at vertex v . Corners with the same attributes and adjacent vertex are stored in a *wedge*. The wedge has one or more corners and each vertex will be divided into one or more wedges. This representation is useful for simplification of meshes with discontinuities in their attribute fields. Discontinuities could result in a simplified mesh where adjacent faces have been separated which introduces new holes in the mesh.

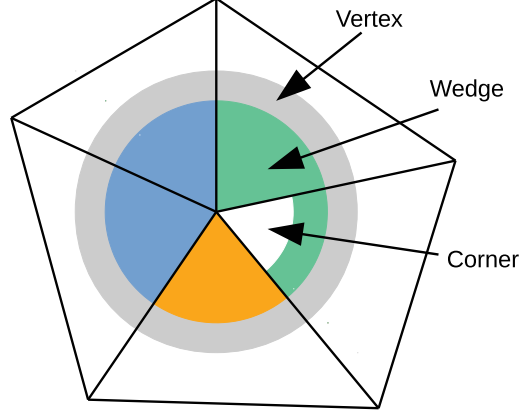


Figure 2.4: Vertex with wedges

2.7 Metrics for Appearance Preservation

Previously in Sections 2.2 and 2.4, the metrics texture deviation and texture stretch have been defined. But to measure more exactly how much the visual appearance of a simplified mesh deviate from the original mesh another metric would be better. *Lindstrom and Turk* [13] defines *image-driven simplification* which captures images from different angles of the mesh. The difference between the images of the original and simplified mesh are computed in order to measure how well the appearance is preserved. This metric is more general and can be applied to all simplification algorithms since it only compares the original mesh to the simplified mesh.

The *image metric* is defined as a function taking two images and gives the distance between them. To measure the distance the authors use root mean square of the luminance values of two images Y^0 and Y^1 with dimensions $m \times n$ pixels. It is defined as:

$$d_{RMS}(Y^0, Y^1) = \sqrt{\frac{1}{mn} \sum_{i=1}^m \sum_{j=1}^n (y_{ij}^0 - y_{ij}^1)^2} \quad (2.7)$$

To evaluate the quality of the simplified mesh the authors capture images from 24 different camera positions. The positions are defined as the vertices of a rhombicuboctahedron which can be seen in Fig. 2.5. Two sets of l images $Y^0 = Y_h^0$ and $Y^1 = Y_h^1$ with dimensions $m \times n$ is rendered and the RMS is then computed as:

$$d_{RMS}(Y^0, Y^1) = \sqrt{\frac{1}{lmn} \sum_{h=1}^l \sum_{i=1}^m \sum_{j=1}^n (y_{hij}^0 - y_{hij}^1)^2} \quad (2.8)$$

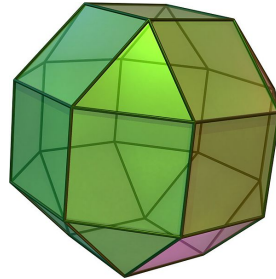


Figure 2.5: Rhombicuboctahedron with 24 vertices which is used as the camera positions. (Rhombicuboctahedron by Hellisp / CC BY 3.0)

2.8 Measuring Algorithmic Performance

According to *David Lilja* [11, p. 4], there are three fundamental techniques that can be used when confronted with a performance-analysis problem: *measurement*, *simulation* or *modeling*. While the book concentrates on evaluating computer performance, these techniques can also be applied when evaluating different algorithms. Measurement would be to actually execute the implemented algorithm and simultaneously gather interesting statistics (e.g. how long it took to finish and how much memory was needed), and use this to compare the algorithms. While modeling would be to analytically derive an abstract model for the algorithm (e.g. the Big \mathcal{O} worst-case running time and memory), and see which of them has a lower complexity.

Since not all of the algorithms in Section 2.1 have an analytical model derived by the authors, and also because the algorithms are to be evaluated in a real system, only the problems inherent to the measurement approach will be considered. One of the problems with doing measurements of a real system (a program running on a computer in this case), according to *David Lilja* [11, p. 43], is that they introduce noise. This noise needs to be modeled to be able to reach a correct conclusion, such as determining if algorithm A is faster than algorithm B. One way of doing this, according to *David Lilja* [11, p. 48], is to find the confidence interval of the measured value, by assuming the source's error is distributed according to some statistical distribution (like the Gaussian or the Student t-distribution). The confidence interval $[a, b]$ when assuming the source's error is t-distributed, can be found as shown below. Where n tests are taken (giving $n - 1$ degrees of freedom), with a significance level of α (usually 5 %).

$$a = \bar{x} - t_k \frac{s}{\sqrt{n}}, \quad b = \bar{x} + t_k \frac{s}{\sqrt{n}}, \quad t_k = t_{1-\alpha/2, n-1} \quad (2.9)$$

One common mistake, according to *Schenker et al.* [16], when using confidence intervals to determine if e.g. an implemented algorithm A is faster than B, is the use of the overlapping method to reach conclusions. If two confidence intervals *do not* overlap, then the result is provably significant (that is, algorithm A is either faster or slower than B). However, the converse is not true, if two intervals *do* overlap, then no conclusions can be reached since the result could be either significant or not significant.



3 Method

Now that the theoretical groundwork has been laid out, we describe in Section 3.1 how the solution was implemented into Configura’s graphics pipeline and then show how to evaluate it in Section 3.2.

3.1 Implementation

In this section an explanation of how the mesh simplification scheme was implemented is given. Some problems that were encountered during the implementation is also presented as well as how they were solved.

3.1.1 Handling seams

To be able to apply a texture to a mesh a mesh parameterization is needed that maps vertices to texture coordinates. If the mesh is not homeomorphic to a disk it is split into parts which will introduce seams. Vertices along these seams is duplicated which enable us to have multiple texture coordinates. However, this is a problem during simplification and will likely make the mesh tear in the seams as seen in Fig. 3.1a. Welding duplicate vertices removes the seams and our tearing problem goes away. This, however, does not work good for textured meshes since we can no longer have discontinuities which results in the seam shown in Fig. 3.1b. Vertices that share the same attributes are safe to remove though.

The mesh representation by Hoppe [6] allows vertices to have multiple attributes associated with it. As explained in Section 2.6 the corners of a face defines the attribute value that should be used for that face.

Finding duplicate vertices

A fast method to find vertices that occupy the same space in 3D is to use a hash map. It is an associative container that is organized into buckets that contains the elements. Search, insert, and removal of elements have on average constant time complexity but in the worst case linear. If a key maps to the same bucket as another key it will be put in a collision chain in the same bucket. The time complexity will in that case be linear on the number of elements in that bucket.

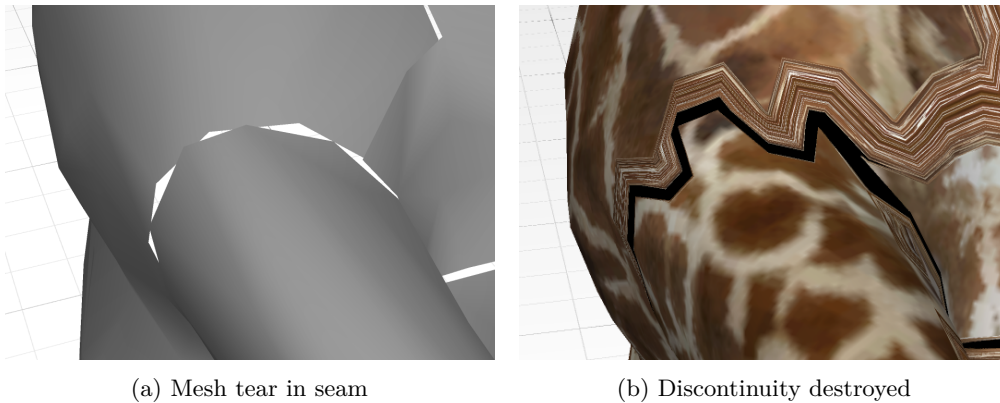


Figure 3.1: Problems in the seams of a mesh

To get fast search and insert a hash function with few collisions is important. The hash function that is used at Configura can be seen in listing 3.1. This hash of a 3-dimensional vector is a combination of the x, y, z coordinates. The hashes of x and y is also rotated i.e. bits are circular shifted, to get fewer collisions.

```

bool eq(float a, float b) {
    return abs(a - b) < precision;
}

int hash(float z) {
    if (eq(z, 0.0)) return 0;
    float r = floor(z/precision);
    int* p = (int*)&r;
    return rotateRight(p[0], 4);
}

int hash(vec3 p) {
    return (rotateRight(hash(p[0]), 8) +
            rotateRight(hash(p[1]), 4) +
            hash(p[2]));
}

```

Listing 3.1: Hashing 3D point

Extracting all *unique* vertices in a mesh can be done with the aforementioned hash map. This is done by iterating through all the vertices and inserting them into the hash map. If the map already contains a vertex we have found a duplicate and it will not be inserted. After the iterations the map will only contain unique vertices and the next step is to update the triangles to map to the new vertices. This is an easy task since when the vertices are inserted into the hash map they will be associated with an index. Therefore, we only have to iterate through the triangle indices and update them with the new indices. (See listing 3.2).

```

void removeDuplicates(vector<vec3>& vertices ,
                     vector<int>& triangles) {
    unordered_map<vec3, int> indices;
    vector<vec3> newVertices;

    for (vec3 v : vertices) {
        if (!indices.count(v)) {
            indices.emplace(v, newVertices.size());
            newVertices.push_back(v);
        }
    }

    vertices = newVertices;

    // Remap triangles to the new vertices
    for (int i=0; i<triangles.size(); i++) {
        int index = triangles[i]
        vec3 z = vertices[index];
        int newIndex = indices[z];
        triangles[i] = newIndex;
    }
}

```

Listing 3.2: Removing duplicates

Vertices with multiple attributes

To handle vertices with multiple unique attributes the `removeDuplicates` listing 3.2 function require some modification. A simple solution is to associate each 3-dimensional vector with an array of indices. Thus, vertices can be associated with multiple texture coordinate indices. A vertex will only be removed if it is in the same place as another vertex with the same texture coordinates. However, if the texture coordinate is unique the vertex index will be added to the end of the list associated with the spatial coordinate.

This association can then be used to create vertices divided into one or more wedges. This kind of vertex will hereafter be called *multi-vertex* to distinguish it from the real vertices. For each vertex, a wedge will be created containing the vertex index and then put in an array. A multi-vertex will contain indices to this array of wedges.

3.1.2 Quadric-Based Error Metric

As a rule, the original mesh will be given as an ordinary triangle mesh (a so called “triangle soup”), which is not suitable for applying the QEM algorithm (since the local neighborhood information isn’t available). Instead, we convert this triangle soup to a half-edge mesh. This allows easy manipulation of the local neighborhood of the mesh, which is precisely what is needed when doing an edge collapse or when calculating the error quadrics of a given vertex.

After doing this, the implementation basically follows the theoretical framework to the letter, where the least-cost edge is chosen to be contracted from the min-heap. Lastly, this edge is collapsed and then the remaining “hole” is simply (but with a few special cases...) linked back together so that the local neighborhood of the vertex still qualifies as a closed manifold.

3.1.3 Solving linear equation systems

A very common task during the simplification is to find the optimal position for a vertex after an edge collapse. As mentioned in Section 2.3, this is done by solving the linear equation system $Av_{min} = b$ where v_{min} is the optimal position. In the original version of the QEM the optimal solution is obtained by finding A^{-1} . If the matrix A is not invertible one of the vertices on the end points of the edge is chosen to be the new position.

In MixKit, the inverse of a matrix is found using Gaussian elimination with partial pivoting. The method is fast but it was noted that in many cases it fails to find the inverse of the matrix. This leads to many fallbacks to the endpoints which may give bad results for vertices with multiple attributes.

In order to have a higher rate of found solutions to the linear equation systems the linear algebra library *Eigen*¹ was used. This library contains numerical solvers, some more accurate and some with higher speed. First, the solvers finds a decomposition of A and then the decomposition is used to find a solution. The choice of a solver is a tradeoff between speed and accuracy. A fast but also with decent accuracy is a solver using LU decomposition with partial pivoting and is a good candidate for the optimization problem.

3.1.4 Parallelization with OpenMP

During initialization a quadric is created for each multi-vertex. The quadric for a face is then applied to the three corners of the face. The face quadric calculations are independent of each other and gives a good opportunity for parallelization. A relatively easy way to get parallelization on the CPU is to use *OpenMP*. The simplicity can be seen in listing 3.3 where the iteration of faces have been made parallel. Now the work of computing face quadrics is shared between multiple threads which would increase the performance. Since the vertices belong to multiple faces multiple threads could try to modify the vertex quadric concurrently. Therefore, this section is made critical meaning that the code can only be executed by one thread at a time.

```
#pragma omp parallel for
for (int i=0; i<face_count(); i++) {
    Face& f = model->face(i);

    Quadric Q();
    compute_face_quadric(f, Q);

#pragma omp critical
    {
        quadric(f[0]) += Q;
        quadric(f[1]) += Q;
        quadric(f[2]) += Q;
    }
}
```

Listing 3.3: Parallelization with OpenMP

Parallelization during the simplification is not as easy since the edge collapses are done iteratively. The min-heap is updated after each iteration meaning that the edge costs change. Therefore, the choice of an edge to collapse is dependent on the previous step, thus, parallelization is not possible.

However, after a collapse the costs of the edges in the local neighborhood need to be updated, i.e. update cost and compute optimal position. These edges do not depend on each other and therefore the computations can be done in parallel.

¹eigen.tuxfamily.org

3.1.5 Volume preservation

Collapsing edges and moving vertices may change the local shape of the mesh being simplified. This can result in a loss of volume and will affect the appearance. According to Lindstrom and Turk [12], moving a vertex v_0 to v sweeps out a volume which can be described as a tetrahedron with vertices (v, v_0, v_1, v_2) as seen in Fig. 3.2. The volume of this tetrahedron is the change in volume that the new vertex position v would give.

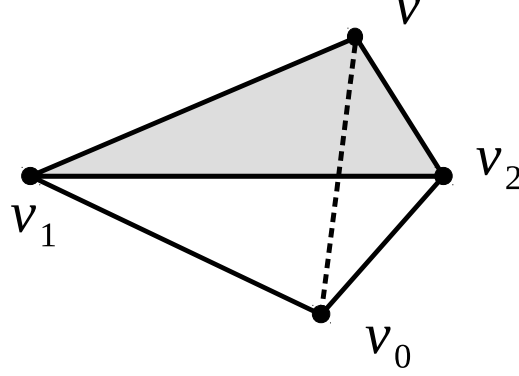


Figure 3.2: Tetrahedral volume

Given four vertices (v, v_0, v_1, v_2) of a tetrahedron the volume can be calculated with the left hand side of Eq. (3.1). If this volume is zero there is no local change in volume and therefore no global change in volume, hence, the right hand side is set to zero.

$$\left\| \frac{(v - v_0) \cdot ((v_1 - v_0) \times (v_2 - v_0))}{6} \right\| = 0 \quad (3.1)$$

Eq. (3.1) can be rewritten as

$$\frac{area}{3} \mathbf{n}^\top \mathbf{v} - \frac{area}{3} \mathbf{n}^\top \mathbf{v}_0 = \mathbf{g}_{vol}^\top \mathbf{v} + d_{vol} = 0 \quad (3.2)$$

where v_0 is a vertex of face (v_0, v_1, v_2) , \mathbf{n}^\top is the face normal, and v is the new vertex position. This will give a linear constraint that can easily be added to the system of linear equations, thus, increasing its dimension by one.

$$\begin{bmatrix} \mathbf{A} & \mathbf{g}_{vol} \\ \mathbf{g}_{vol}^\top & 0 \end{bmatrix} \begin{bmatrix} \mathbf{v}_{min} \\ \gamma \end{bmatrix} = \begin{bmatrix} -\mathbf{b} \\ -d_{vol} \end{bmatrix} \quad (3.3)$$

3.1.6 Improving Texture Atlas

Trying to keep the seam during simplification improves the quality of the resulting mesh. However, when a mesh is heavily simplified it is hard to keep the geometry and often gives a bad result. Removing the seam constraint gives a better geometry but now there is another problem. Since the seam is not kept we could get texture coordinates that lies outside the defined areas of the texture atlas. A common color in this area is black but it depends on what the texture artist chose.

One way of finding valid pixels is to first create a mesh where vertices are defined by the texture coordinates, i.e. $v = (s, t, 0)$ where s , and t are the texture coordinates. This creates sheets lying in the same plane where empty areas will be locations that are not defined in the texture atlas. By casting rays towards the sheets the empty areas can be detected. The origin of the rays will be based on the pixel locations but translated in the direction of the normal to

the plane. They will then be casted straight down towards the sheets and if they hit anything we have found a valid pixel.

Given some scattered data, Gortler et al. [5] present a way of filling in the empty areas based on the given data. This is done by using a image pyramid containing images of decreasing resolution. The lower resolution images is used to fill in the empty areas of the higher resolution images. The algorithm works in the two phases *pull* and *push* hence it is given the name *pull-push*.

Pull

The first level $r = 0$ of the pyramid is the input image and level $r + 1$ have half the size of level r in each dimension. Each pixel have a data value x_i^r and weight w_i^r . The pull phase starts at level 0 and recursively computes the values of the next level according to Eqs. (3.4) and (3.5) where \tilde{h} is a gaussian filter. \tilde{h} blends the neighboring pixels with an applied weight according to Fig. 3.3 which will give a blurred image. At the first level valid pixels is assigned a weight of 1 and invalid pixels a weight of 0. This will make sure that the valid pixels will not be changed.

$$w_i^{r+1} = \sum_k \tilde{h}_k \min(w_k^r, 1) \quad (3.4)$$

$$x_i^{r+1} = \frac{1}{w_i^{r+1}} \sum_k \tilde{h}_k \min(w_k^r, 1) x_i^r \quad (3.5)$$

| | | | |
|---|---|---|---|
| 1 | 2 | 2 | 1 |
| 2 | 4 | 4 | 2 |
| 2 | 4 | 4 | 2 |
| 1 | 2 | 2 | 1 |

Figure 3.3: Interpolation of pixel values in pull phase

Push

The lower resolution images generated in the pull phase are used in the push phase to fill in empty pixels in the higher resolution images. The weights that was computed for each pixel in the pull phase are used to determine how the pixel values will be blended. A lower weight means that the color will mostly be influenced by the lower resolution pixels. Higher weights means that the current pixel color will influence the most.

The first step is to calculate temporay values tx and tw according to

$$tw_i^r = \sum_k h_k \min(w_k^{r+1}, 1) \quad (3.6)$$

$$tx_i^r = \frac{1}{tw_i^r} \sum_k h_k \min(w_k^{r+1}, 1) x_i^{r+1} \quad (3.7)$$

The current values x^r and w^r are then blended with the temporary values according to

$$x_i^r = tx_i^r(1 - w_i^r) + w^r x_i^r \quad (3.8)$$

$$w_i^r = tw_i^r(1 - w_i^r) + w^r \quad (3.9)$$

What neighboring pixels to blend with is determined by the pixel's location within its superpixel. For example, the top-left subpixel of the middle pixel is blended with the top-left, top, middle, and left pixel as can be seen in Fig. 3.4. These pixel values are weighted by 1, 3, or 9, depending on their location.

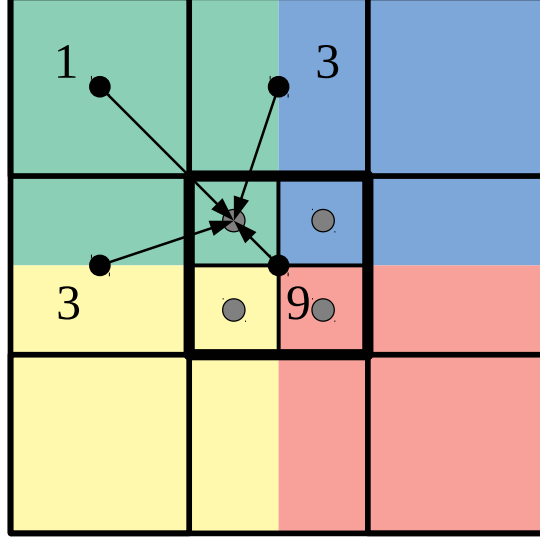


Figure 3.4: Interpolation of pixel values in push phase

Pixels at the edges of the texture needs special treatment since some neighboring pixels are missing. There exist multiple solutions to this problem such as ignoring pixels, using the value of the closest pixel, mirroring values, or wrapping around to the opposite side. Textures are often wrapped when used and therefore the wrapping seams like a good solution.

3.2 Evaluation

An evaluation of the appearance of meshes simplified by the implemented simplification scheme was performed. In this section the the models and metrics used for the evaluation is presented.

3.2.1 Models

Four LoD:s are usually used by Configura and they are defined by triangle density ($\#triangles/area$). The four levels are super ($5000\ triangles/m^2$), high ($1000\ triangles/m^2$), medium ($200\ triangles/m^2$), and low ($50\ triangles/m^2$) and these will be used for the evaluation. Configura have textured models of humans and a subset of them have been selected to be used in the evaluation. The triangle counts lies around 15000 but smaller models with about 10000 and larger models with about 30000 triangles are also included.

3.2.2 Appearance Preservation

In order to compare how well the appearance is preserved for different LoDs the image metric described in Section 2.7 can be used. The main idea is to render multiple images of both the original and simplified mesh from a set of camera positions defined by the vertices of a rhombicuboctahedron (Fig. 2.5). A RMS of all the pixel values of the images is then simply the error that the simplification introduced. The authors [13] measured difference in luminance but other metrics, such as Euclidean distance of the RGB colors, can be used.

Another common approach for measuring the difference between two meshes is to use the *Hausdorff distance*. Cignoni et al. [1] first defines the distance between a point p and a surface S as

$$e(p, S) = \min_{p' \in S} \|p' - p\|$$

A one-sided distance between two surfaces S, S' is then defined as

$$E(S, S') = \max_{p \in S} e(p, S')$$

This distance is not symmetric and depends on which surface you start the measurement from, meaning that $E(S, S') \neq E(S', S)$ in some cases. Finally, the Hausdorff distance can be obtained by taking the maximum of the distances in both directions. A mean distance between the surfaces can be obtained by uniformly sample points on both surfaces, measuring their Hausdorff distance, and then dividing by the number of sampled points.

How many points to sample depends on the size and shape of the meshes being compared. For the meshes used in the evaluation 10000 points on each mesh seemed to give a stable estimate of the error introduced by the simplification.

The sampling of a point on a mesh can be done in two steps: First, randomly pick a triangle of the mesh, then pick a random point on the chosen triangle. A triangle can simply be picked by uniformly choose a random triangle index. A random point on a triangle can be picked by using barycentric coordinates. As can be seen in listing 3.4, two random numbers s, t between 0 and 1 are chosen. The sampled point is then a convex combination of the vertices (v_0, v_1, v_2) of the triangle. The condition $s + t \leq 1$ must be fulfilled, therefore, s and t are randomized until the condition is met.

```

do {
    float s = random(0,1);
    float t = random(0,1);
} while (s + t > 1)

point v = (1 - s - t)*v0 + s*v1 + t*v2;

```

Listing 3.4: Sampling point on triangle by using barycentric coordinates

3.2.3 Volume preservation

Since the volume of a mesh is affected by simplification a way to measure the volume is needed. *Zhang and Chen* [19] introduce a way of measuring the volume of a manifold mesh using tetrahedrons. A tetrahedron have 4 vertices, therefore, they can be created by using the vertices of a triangle and the origin. As explained in Section 3.1.5 the volume of a tetrahedron can be calculated with Eq. (3.1). Not taking the absolute value of the equation gives the *signed volume* which is used by Zhang and Chen. As can be seen in Fig. 3.5 triangles with a normal facing the origin gets a negative volume and triangles facing away from the origin get a positive volume. By taking the sum of all the tetrahedrons, constructed from the triangles and the origin, the volume contained within the triangles is obtained. As said before this only works if the mesh is manifold.

$$V_i = \frac{v_0 \cdot (v_1 \times v_2)}{6} \quad (3.10)$$

$$V_{total} = \sum_i V_i \quad (3.11)$$

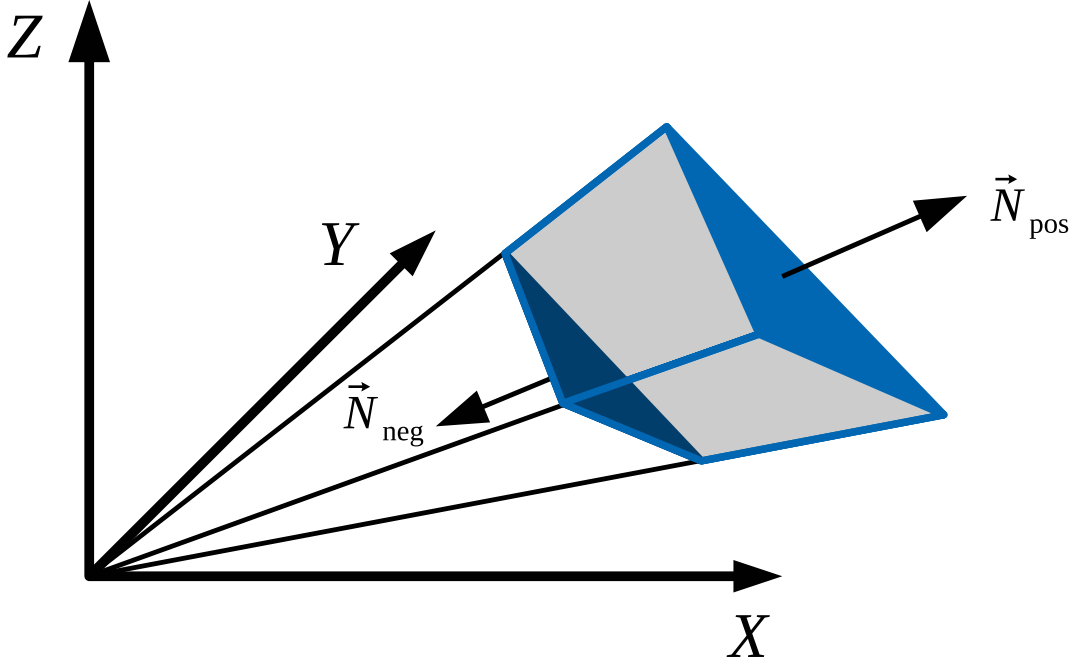


Figure 3.5: Illustration of mesh volume computation

3.2.4 Execution Time

A simple parallelization with OpenMP have been implemented with the goal of decreasing the computation time. In order to see how much the computation time is reduced it was measured for multiple runs of the simplification scheme using the office woman model. Measurements was made for the four LoD:s super, high, medium, and low and the number used threads was from 1 to 8 threads.

To account for noise the measurements of the execution time is performed several times. From the collected data the mean \bar{x} and standard deviation s can be calculated. The confidence interval $[a, b]$ fo the execution time can be found by the equations shown in Section 2.8 with $\alpha = 0.05$.

4 Results

In this chapter the results of the thesis is presented. First, results collected using multiple metrics for mesh appearance are presented. Afterwards, a comparison of the execution time using different numbers of threads is given. Finally, simplified models generated to be used as LoD:s as well as the new improved texture atlas is presented.

4.1 Luminance error

RMS luminance error was computed by rendering multiple images of a model from different camera positions as explained in Section 2.7 and can be seen in Fig. 4.1. Four LoD:s are presented where *super* have the most amount of triangles and *low* have the least amount of triangles. The error was measured for different settings of seam and volume preservation to determine what setting would give the best result. Nine different models with triangle counts between 10000 and 30118 was used in this evaluation. For each model the RMS luminance error was computed for all LoD:s. A mean of the RMS was then obtained and is presented together with a 95% confidence interval in Fig. 4.1.

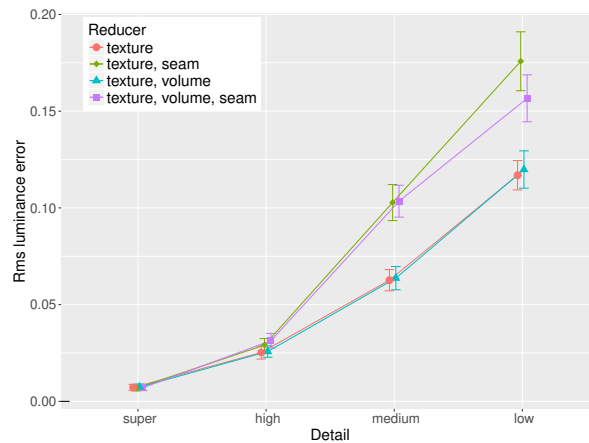


Figure 4.1: Rms luminance error

4.2 Geometric and Color Error

To see how the geometry and color of a model is affected by simplification, points were sampled on the surface of the simplified mesh and the original mesh. The distances from the sampled points on one mesh to the closest points on the other mesh can then be used to measure the distance between the meshes as well as the color difference. This is described in more detail in Section 3.2. Both the RMS and the maximum error was measured for different settings of seam and volume preservation with the *office woman model* and the values are plotted in Fig. 4.2. Note that the x-axis and y-axis have a logarithmic scale.

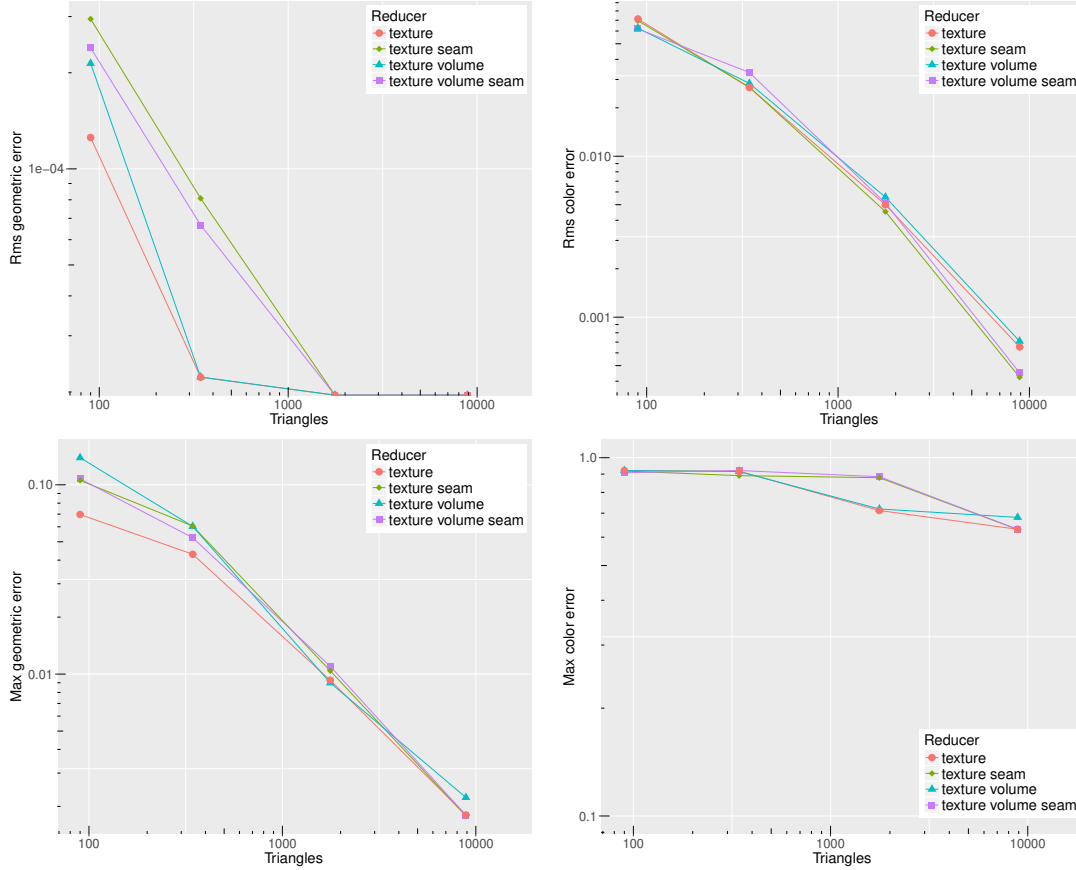


Figure 4.2: Office woman geometric and color error

4.3 Volume Preservation

When simplification is performed the volume of the mesh may be reduced. How much the volume of a simplified mesh differ from the original mesh is therefore plotted in Fig. 4.3. Reduction was made with four configurations of texture, volume, and seam considerations for nine models. The mean difference in volume is plotted together with a 95% confidence interval.

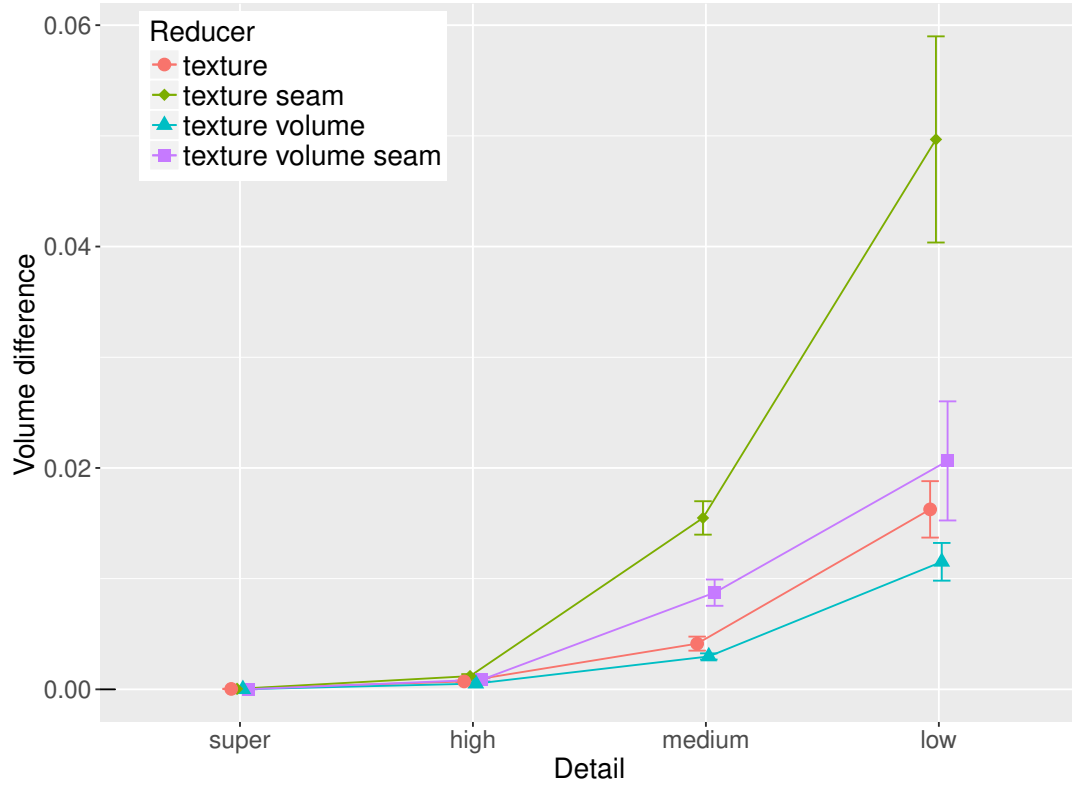


Figure 4.3: Mean difference in volume

4.4 Execution time

Four LoD:s were generated with the mesh simplification scheme multiple times. The mean execution time in milliseconds for different number of threads running in parallel is plotted in Fig. 4.4 with a 95% confidence interval.

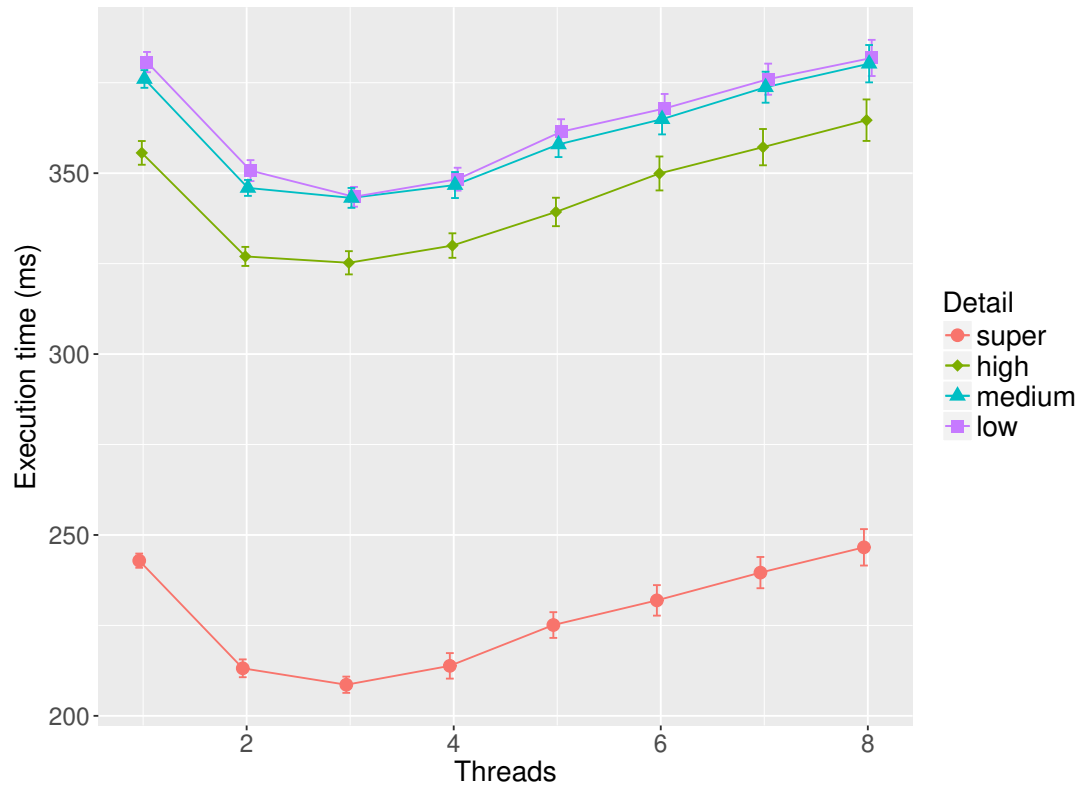


Figure 4.4: Mean execution time when using multiple threads

4.5 Improved Texture Atlas

A pull-push algorithm was implemented in order to improve the texture that is used by a mesh since undefined areas may be seen when applied to a simplified model. Given a texture (Fig. 4.5a), rays are casted for each pixel in order to generate a black and white image that distinguish valid pixels from invalid pixels. Valid pixels get a white color and invalid pixels a black color as seen in Fig. 4.5b. Pixels with a corresponding black pixel will be filled in by the pull-push algorithm. This will result in the texture seen in Fig. 4.5c where all the empty pixels have been filled in.

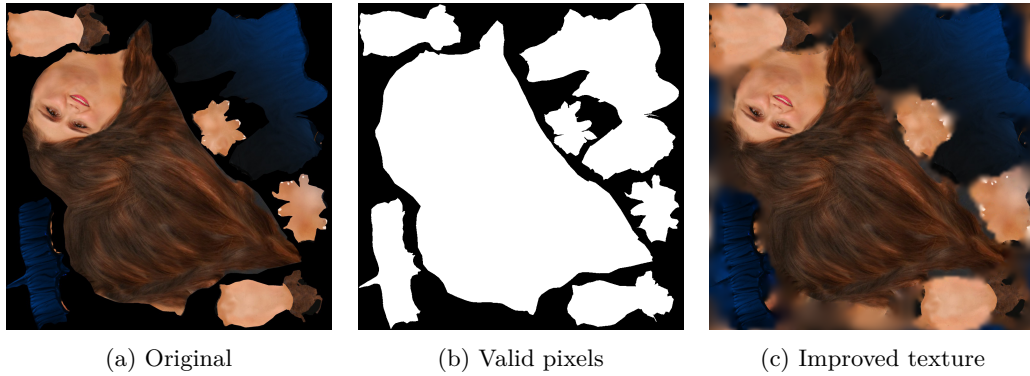


Figure 4.5: Filling in empty pixels in the texture atlas

Simplification of the office woman model introduced black areas on the legs where the original seam used to be (Fig. 4.6a). Trying to improve the appearance by applying the new improved texture results in the model shown in Fig. 4.6b.



Figure 4.6: Comparison between original and improved texture

4.6 Comparison of LoD:s

To compare how different LoD:s are affected by the simplification the office woman model have been rendered after simplification. The original model has 14996 triangles and the LoD:s super, high, medium, and low have 8886, 1768, 344, 90 triangles respectively. Renderings of the LoD:s have been created both with equal distance from the camera and with the camera placed at the distance where they would actually be used which can be seen in Figs. 4.7 and 4.8 respectively. When creating these LoD:s with the simplification algorithm the seam and volume was not considered, only the texture.



Figure 4.7: Office woman LoD:s at equal distance



Figure 4.8: Office woman LoD:s at their corresponding distance



5 Discussion

This chapter provides a discussion on the work. First, a discussion of the results is given in Section 5.1. Afterwards, in Section 5.2 the used method is discussed.

5.1 Result

5.1.1 Luminance Error

When simplifying a mesh to be used for LoD super and high, considering the seam or the volume does not affect the rms luminance error much as can be seen in Fig. 4.1. At the high level the graphs start to diverge but the confidence intervals overlap which means that we can not say with any significance that any setting is better than another. However, for medium and low, considering the seam gives a worse result than not considering it.

Not allowing all edge removals in the seam constrains the simplification and this affects the final geometry. Geometry that differs a lot from the original will give a high luminance error. This occurs since in some areas of the rendered images the background is rendered where the mesh used to be. In this case the background was white leading to a high difference of the images.

Ignoring the seam for now, if the volume is considered the error becomes slightly larger but not with any significance. Not considering the volume may be a better choice since the optimization problem would be less constrained and could be solved faster.

5.1.2 Color and Geometric Error

To further investigate when the seam and volume should be considered points was sampled on the surfaces of the mesh. A comparison of this can be seen in Fig. 4.2.

If we first look at the geometric error the two highest LoD:s have a geometric error close to zero for all settings. For the other two lower levels we can see, just as discussed in Section 5.1.1, that the seam preservation give a worse result. According the graphs of the geometric error the best setting would be to only consider the texture.

When looking at the color error the difference is small between the settings. However, the rms color error for the super LoD is lower when the seam is considered. Therefore, considering

the seam may give a better result for the super and high LoD since the geometric error was small.

5.1.3 Volume Preservation

Fig. 4.3 shows how the volume of meshes is affected by different configurations of texture, seam and volume preservation. Just as discussed in previous sections the configuration affect the result for the two highest LoD:s very little. By looking at the figure we can see that the volume constraint indeed keep the volume better. Considering the seam gives a larger difference in volume but it is kept better if the volume is also consider. The best configuration if one wants to keep the volume is to only consider the texture and the volume.

5.1.4 Execution Time

By looking at Fig. 4.4 we can see the difference when using multiple threads. Parallelization was only added to the initialization phase of the simplification since it did not have that many dependent operations. A gain in speed can be noticed by just using one more thread. The total execution time is only decreased by about 30 ms which is only a decrease of 12%.

For all four LoD:s the curves are similar. The similarity is expected since the same initial computations is performed for all levels and no parallelization is performed during the simplification phase.

The fastest execution time is obtained when using between 2 to 4 threads. Using more threads seem to increase the execution time. This could be because the threads have to wait for each other to write to the quadric matrices. In the implementation only one thread at a time can write which is not desireable.

5.1.5 Improved Texture Atlas

As we have seen from the graphs the seam gives a bad result in terms of luminance error and geometric error. But, when the seam is not considered undefined areas of the texture may appear just at the seam. This can be seen in Fig. 4.6a where where black areas have appeared on the legs of the model.

Using the pull-push algorithm to fill in missing pixel values results in a new texture that gives a better result in the seams. As can be seen in Fig. 4.6b almost all the black areas have disappeared from the legs. However, on the left leg a small hint of black can be seen. By looking at the new texture we can see that there still remains some black areas just at the seam bound.

5.1.6 Comparison of LoD:s

Looking at the four LoD:s of the office woman model in Fig. 4.7 we can see how the different levels are affected by simplification. The super and high have not changed very much the the appearance is still good. One can see that the silhouette of the high LoD is not as round as the super LoD. For medium the effect of the simplification is clear and even more for the low LoD where we can clearly see the triangles.

When looking at the LoD:s from the distance where they would actually be used the edgy silhouette is harder to distinguish.

5.2 Method

5.2.1 Implementation

A very simple parallelization of the initial phase of the simplification was implemented with OpenMP, but as discussed in Section 5.1.4 only a small speedup was gained. When using more than 4 threads only increase the execution time since only one thread can write at a time. In order to reduce the time waiting for write access a solution could be to make it possible for the threads to have there own private set of quadric matrices. When all threads have finished their computations, a reduction operation could be performed that combine all versions of the matrices. This would let the threads write freely without having to wait for another thread to finish writing.

5.2.2 Evaluation

The models that was used in the evaluation all had approximately the same number of triangles. Since all the meshes were textured models of humans their shape were also similar, meaning that only a small portion of models are covered by the evaluation. It would be interesting to see how the simplification scheme performs on other models, especially models with more triangles.

When comparing the execution time of using different number of threads a mean execution time was computed. The number of samples collected per thread and detail pair was 120. Since the confidence intervals are narrow we can be confident that the sampled mean execution time is close to the real mean execution time. Therefore, the sample size seem to be large enough.



6 Conclusion

In this final chapter the conclusions of the thesis is given.



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