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Statistical Evaluation of 3D Manifolds Shape Retention During Simplification Stages

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Abstract
Simplification of 3D meshes is a fundamental part of most 3D workflows, where the amount of data is reduced to be more manageable for a user. The unprocessed data includes a lot of redundancies and small errors that occur during a 3D acquisition process which can often safely be removed without jeopardizing is function. Several algorithmic approaches are being used across applications of 3D data, which bring with them their own benefits and drawbacks. There is for the moment no standardized algorithm for cultural heritage. This investigation will make a statistical evaluation of how geometric primitive shapes behave during different simplification approaches and evaluate what information might be lost in a HBIM (Heritage-Building-Information-Modeling) or change-monitoring process of cultural heritage if each of these are applied to more complex manifolds.

Keywords: *3D Imaging, quality evaluation, cultural heritage, digitization, HBIM*

1. Introduction
Collecting 3D for documentation, analysis, visualization, and dissemination is a very common practice in the cultural heritage (CH) sector. Various scanning methods like LiDAR, photogrammetry, or structured light [1], all provide a 3D point cloud that is processed into a triangulated 3D mesh, but often provide more data than necessary. This includes noise, but also redundancies and errors that must be removed during a simplification stage. The simplification approach will introduce changes to the data, and must therefore be monitored so that it does not remove important features of the object. For CH objects, this is especially important as small tangible changes in the surfaces or construction of the object might put it at risk, and must therefore be documented properly so the correct conservation work can be done. Selecting the optimal simplification approach based on object geometry is therefore an important step in digitizing the objects, but there exists little guidance on how to apply these algorithms and what effects they might have.

In prior reviews of simplification approaches they have utilized objects of different shapes and sizes for a global evaluation of the effect of different algorithms [2,3], but which tells us little about how the algorithms handle different segments of the total mesh. Investigations on local geometry have also been done [4], but is different from investigating segmented areas that feature a similar geometric characteristics as a part of a larger mesh. We define these areas as if they can be reduced to geometric primitives like spheres, planes, or cubes.

To statistically evaluate the effect of simplification algorithms on geometric primitives we have selected a few of the most common algorithms and applied them to modeled primitive objects. These primitives are often segmented parts of full CH objects. This is done in order to have a clearer understanding of how the algorithms affect different types of geometries, instead of applying it to 3D scans of complex CH objects that feature all of these geometries at once. While the investigation is set to evaluate data created from a 3D scanning process, we have chosen to model the analyzed shapes in a 3D software. This was done to have ground truth reference to compare the simplified versions of the data to, and to avoid the possible inaccuracies or tool biases of a proprietary or custom scanner. We also extend our shapes to include slightly more complex manifolds than pure primitives like spheres and cubes, introducing wavy patterns and rugged surfaces onto otherwise uncomplicated shapes. This is done to strain the method somewhat, and include further features that are common on large heritage objects but would not necessarily be described as a geometric primitive. This includes geometric features like angles, curves, and points. A benefit with these features is that they can be easily measured on the different object to evaluate the effect of the simplification. With this knowledge, we will be able to further analyze their behavior on more complex 3D manifolds to see if the same effect remains.

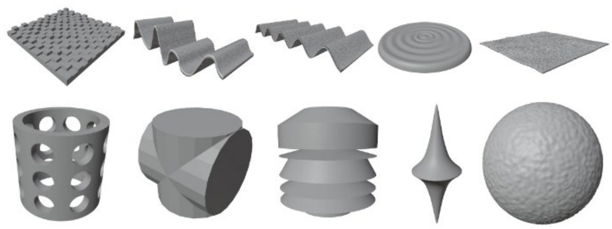

Fig. 1: *3D Objects Used.*

For our process we make use of 10 baseline objects processed through 5 algorithms at 16 stages each, resulting in 800 variations of the objects.

2. Related Works
As applications of 3D meshes and point clouds has become more commonplace, the need for some comprehensive metric of quality in 3D meshes has emerged. Several studies have reviewed the quality in 3D digitization of CH [5,6], and found that there is a great variation in the features of 3D objects. The

discussion on how to develop tools to evaluate this and what parameters to analyze are still ongoing. While there currently exists several metrics for evaluation the quality of 3D meshes, none of them are fully appropriate for HBIM or other desired documentation practices. Perceptual metrics [7–13] provides a good measure of how visible the geometry of a 3D object is to a human observer, with applications for computer graphics in creative and entertainment industries. These are most often based on psychovisual observer experiments.

Some parametric measurement tools are available and commonly used, like Metro [14,15], but still leaves gaps in the data it reports that would be necessary for an objective quality metric based on predetermined thresholds. What this data might be and what thresholds they have based on different applications is still an ongoing area of research, but the active use of the Metro software is an indicator of the desire for a parametric evaluation tool in processes that utilize 3D meshes, including CH.

2.1. Psychovisual Approaches

Prior evaluation of 3D meshes and point clouds are predominantly perceptual based, targeted to applications in creative industries. Measurement of quality in 3D is often defined as how easily we can perceive that the 3D object is made from a high number of flat surfaces, or the perceptual saliency of the number of polygons on the geometry. This however provides no parametric evaluation of the object, and are based on observer studies.

Often in these studies, they provide observers with either 2D renders of the 3D object, or limited 3D viewing of them [16]. Additionally, they conduct experiments with simple or well-known geometry, like spheres [17] or the Stanford-bunny [18,19]. In addition to only being based on perception, the technology and assets used in these experiments might be outdated compared to modern ones. The texture resolution was found spanning from 64x64 pixels at the lowest to 512x512 pixels at the highest [20]. Similarly, model resolution might be limited compared to modern scans. We do not believe this reflects the quality of objects currently available in the field, both cultural heritage and computer science, thus limiting the application of results from prior investigations. Common modern resolutions for texture are 2K, 4K or 8K, and model resolution spans into millions of polygons.

2.2. Parametric Approaches

To make 3D scans useful for HBIM we need to transform 3D point cloud data into Industry Foundation Class (IFC) formats via an automatic shape recognition process, converting the large arrays of coordinates into simplified geometry that represents the buildings overall shape. In such a process, microsurfaces are discarded and only broad geometric features are of interest. Commonly, either an aggressive simplification approach [21] or a rebuilding approach using primitives [22] are utilized. As the surfaces of the objects are decimated to such an extent, they can only provide global information about the object at a very low 3D resolution, and are therefore unusable when documenting very small geometric characteristics in the manifold.

Rugged surfaces or objects with a lot of organic geometry might be sensitive to over-segmentation using the primitive rebuilding approach, where noise is still kept in the model to include surface features of sizable importance. However, the objective of simplifying the model would also be jeopardized if this segmentation is not limited. Setting the threshold for such a limitation is therefore a case-by-case event, and would require an statistical evaluation of the point cloud as well as an evaluation by an expert before applying any primitive rebuilding.

3. Method

The 10 baseline objects used for this investigation is designed to be easy to measure, and the have specific unique features. Objects were modeled with a high subdivision level, with polygons being as congruent as possible. All meshes are then triangulated with introduced noise in their topology to imitate the result of a 3D-scan. This noise introduces no geometric error higher than 0,0001 units in relation to the object bounding box, and is therefore a safe way of changing the topology of an object without losing geometry. Each object is then simplified by each algorithm in 16 stages, with a triangle reduction rate of 5,625% at each stage. This results in a linear decrease in triangle counts down to a reduction of 90% at stage 16.

3.1. Simplification Algorithms

Simplification of 3D data, either point clouds or meshes, is a nearly unavoidable step in digitizing tangible objects. Objects must be sampled, filtered, and reduced in order to remove redundant data and be more manageable for an end-user. There are currently several different algorithms that are commonly used for automating this process, all of which take different approaches in reducing the geometry of an object. We have utilized several toolboxes and softwares to implement 5 of the most common of these algorithms:

Decimation [23] iteratively removes vertices in a mesh based on an evaluation of optimal local geometry. It can also be applied to edges and faces. Implemented with Open3D.

Vertex Clustering [24] takes vertices in close proximity to each other and clusters and merges them into a single vertex.

Object Name	Vertices	Edges	Polygons	B.B Diag	Max Poly Surface	Min Poly Surface	...
SMB (Baseline)	16812	50430	33620	15.018574	0.006	0.004	...
SMD1	15984	47710	31727	15.018574	0.006	0.004	...
SMD2	15037	44872	29836	15.018574	0.006	0.004	...
...	...	...	...	...	...	...	...
SMD16	1713	5073	3361	14.970101	1.2	0.02	...

Table 1: *Some of the values extracted from the objects*

Surrounding polygons are then re-triangulated. Implemented with Open3D.

Quadric Error Metrics [25] utilizes a plane equation of a given triangle to estimate the ideal location of vertices. Implemented with Meshlab.

Coplanar facets merging [26] looks at planar divergence between polygons and merges them if they are above a certain threshold. Implemented with Blender.

Edge Collapse [27] finds pairs of vertices that are close together and collapses the edge between them. This creates a new vertex at the halfway point between the two original vertices. Implemented with Blender.

Note that many of these algorithms has been developed further since the original papers.

To evaluate the difference introduced by the simplification stages we have developed a workflow that analyzes several measurable values of the objects, utilizing common toolboxes like Meshlab [28], Open3D [29], Blender [30] and CloudCompare [31] in a Python environment. We analyze the objects both as point clouds, and as triangulated meshes to make use of the normal vector of each polygon.

First, various object variables are extracted from the 3D objects; including poly-count, vertex-count, triangle sizes, bounding-box diagonal, etc. An example table listing a few of these variables can be found in Table 1.

These values are used in the evaluation basis of the objects, comparing them to the values provided by measuring the differences between the original object and the simplified versions. Two distances of the difference in the point clouds are measured: Hausdorff Distance and Chamfer Distance:

Hausdorff Distance 1 samples either the original or the simplified mesh, and reports the max, mean, and RMS distance from one object to the other. This is interpreted as the error of the object as seen in Table 2.

$$d_H(X,Y) = \max sup_{x\in X} d(x,Y), sup_{y\in Y} d(X,y) \quad (1)$$

Chamfer Distance 2 takes the nearest neighbour correspondence of two point clouds and sums the square distances between them. Reports values as seen in Table 3.

$$d_{CD}(X,Y) = \sum_{x\in X} min_{y\in Y}\|x-y\|_2^2 + \sum_{y\in Y} min_{x\in X}\|x-y\|_2^2 \quad (2)$$

Including these distances allows us to evaluate the differences in the meshes in several different ways, as we use the Chamfer distance to measure from vertices, and Hausdorff distance from polygon faces. The objective is to chart the different vertices and faces contribution to the overall geometry of the manifold, and how these are changed or removed during the different simplification approaches. How well each of the algorithms retain features like curves, flat surfaces, and angles working from the same baseline geometry provide us with good estimations on how they interact with 3D manifolds.

4. Results and Discussion

Early results on the test objects show that the nature of a 3D manifold reacts differently to varied simplification approaches, and that accuracy results can be vastly different based on algorithm selection.

An obvious difference could be seen when using the Decimation algorithm. While the 'Uniform' object had clusters of larger errors around the peaks and valleys, the 'NonUniform' object had a more uniform distribution of errors. Visualized in Figure 2.

Errors were therefore more common but less drastic for the 'NonUniform' object, while the only geometric difference between the two objects were the height variation in the peaks and valleys. Topological differences will be further investigated if they differ greatly between the two objects. The Uniform object had more similar behavior to the 'NonUniform' when applying the Edge Collapse algorithm. So while both objects feature a linear decrease in polygons, increase in maximum and mean error is very different and seemingly unrelated to features like curvature in the case of these objects. We expect that this relation can be found in the object topology.

Object Name	RMS	B.B Diag Baseline 0	B.B Diag Simpl	Max	Mean	Min	*n* face samples
SMD1	0.000650	15.018574	15.018574	0.009218	0.000161	0.000000	33620
SMD2	0.001370	15.018574	15.018574	0.013218	0.000465	0.000000	33620
SMD3	0.002337	15.018574	15.018574	0.020793	0.000966	0.000000	33620
...	...	...	...	...	...	...	...
SMD16	0.024435	15.018574	14.970101	0.100776	0.020085	0.000001	33620

Table 2: *Values provided by Metro using the Hausdorff Distance.*

Object Name	B.B Diag Baseline 0	B.B Diag Simpl	Chamfer Distance Sum	*n* vertex samples
SMD1	15.018574	15.018574	0.0000462	16812
SMD2	15.018574	15.018574	0.0000982	16812
SMD3	15.018574	15.018574	0.0001382	16812
...	...	...	...	...
SMD16	15.018574	14.970101	0.0045262	16812

Table 3: *Values provided using the Chamfer Distance.*

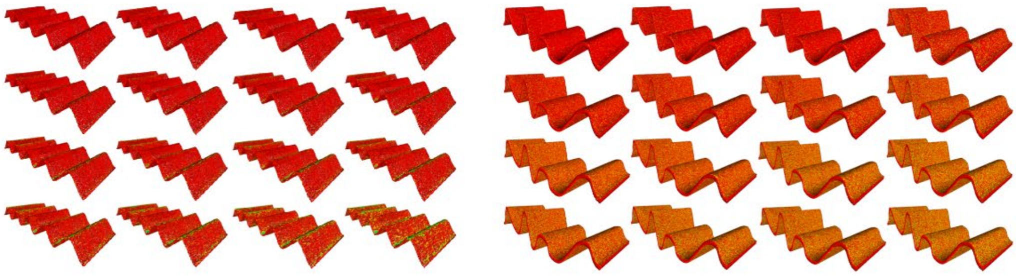

Fig. 2: *Metro Error Visualization. Left: Uniform Object. Right: NonUniform Object. Red = Low Error, Green = High Error*

5. Future Work

Our investigation so far has shown that geometries behave very differently when subjected to different simplification algorithms, and that several variables can be analyzed to evaluate this difference. However, more data is required to map the effect of the algorithms more accurately on geometric features. Subsequently we want to apply the method to scans of CH objects that has features similar to these primitives, to see if the patterns observed here are visible when working with more complex 3D manifolds. Object materials of CH with certain geometry can introduce difficulties when attempting to reduce a point cloud to primitives, without including the variation in algorithm results as investigated here. Example materials are rough stone walls, wooden beams with cracks in the longitudinal grain, or patterned surfaces like tiled rooves. Such materials and surfaces cannot be easily simplified into a geometric primitive without losing defining characteristics, thereby reducing the usefulness of the final HBIM models. Simplification must therefore be stopped before the error rises over a certain threshold, which we hope our study can provide.

Several steps that are not included in this investigation will be added in future work. Additional research will be done by introducing small deviances in the primitive objects, to see how much effect this has on the simplification process. Additionally, we want to run the models through the previously mentioned metrics, to contextualize our results to different approximations of visual quality, including parametric and perceptual. This will also visualize if perceived error corresponds to measured error.

Many other evaluation approaches that are not explored here might also be added in the future for a more comprehensive framework. Earth Mover's Distance and Energy Optimization algorithms might be an interesting approach to explore in the future, in addition to a signal to noise ratio when working with 3D scans. The long-term objective is to develop the framework into a full toolbox where users can input their own objects to get an evaluation of the error, as a step towards developing a quality metric for 3D CH objects.

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