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Specialized 3D Meshes: Variations in Mesh Structures in Heritage Databases

Markus Sebastian Bakken Storeide; Colourlab, Department of Computer Science, Norwegian University of Science and Technology; Gjøvik, Norway
Sony George; Colourlab, Department of Computer Science, Norwegian University of Science and Technology; Gjøvik, Norway

Abstract
Mass 3D digitization of heritage objects is today heavily encouraged by various institutions. This is in an effort to measure and document objects for the future, use them for visualization and dissemination, and open up for the analytic tools that are available for 3D meshes. However, the structure required of a mesh depends heavily on the application, and the data might vary significantly based on the digitizing institution, object characteristics, and acquisition workflow.
In this work, we sample 3D data stored in several major open-access databases for 3D heritage data and analyze the content. We take a close look at sampled mesh structures by computing various graph metrics, check some integrity measures, and evaluate their possible future use. Finally, we provide an overview of the use cases and interoperability of the meshes depending on results from the mesh structure analysis.

1. Introduction
High-fidelity 3D models of tangible objects have a plethora of use cases within the field of cultural heritage [1]. Results of digitization processes are mathematical representations of tangible objects, and can have various levels of approximation and data formats depending on the data acquisition workflow.
However, determining how to generate high-quality 3D data without over-complicating the process is still up for debate and under development. For example, Europeana's publishing guide for 3D content [2] notes that the quality of the data depends on many factors, such as vertex numbers and applied post-processing methods, but does not provide **specific** requirements or guidelines. Other guidelines have similarly diffuse requirements to not limit the digitization process too much [3,4,5,6]. Historically, this diffuse approach led to the creation of the London Charter, which was an incentive to ensure the use of computer-based visualization and methodologies for CH are conducted with robust scientific and technical discipline [7]. This study evaluates if this standard has been maintained in terms of data quality.

2. Related Work
The open-ended nature of 3D digitization has resulted in the creation of great volumes of heterogeneous data, as different institutions and workflows generate data for various applications. What format and approximation level the data is in therefore depends on the application, as there is currently no acquisition workflow that is optimized for all applications. We can as such describe the heterogeneous data apparent in heritage data repositories as *specialized*, with limited possibility for overlap between the possible applications due to the differences in the mesh structures.

Digitization of objects by means of 3D scanning is primarily a computer science and engineering field, which has developed several metrics to evaluate the objective metrological quality of a scanned object [8]. Furthermore, several mathematical measures exist on how to interact with Riemannian manifolds [8], which share many similarities to 3D meshes. However, these metrics are not commonly used in interdisciplinary application fields. Detailed evaluations of the objective, mathematical quality of 3D meshes are therefore rarely integrated in digitization processes.

Nonetheless, there is a significant international push to digitize CH using 3D metrology for documentation and preservation purposes. As a result of all of these incentives, concerns about the inoperative nature of the 3D cultural heritage field, similar to what caused the creation of the London Charter in 2006, and the urge for mass digitization of 3D data for cultural heritage are happening concurrently. Therefore, as a result of this severally varied conducted digitization process without established guidelines, we risk that great amounts of acquired data is rendered impractical, incomplete, or unusable for many purposes.

3. Methodology

In this work we evaluate sample data from some of the most prominent databases for 3D heritage data [10], namely Europeana, Open Heritage 3D, Morphosource, and tDAR. These repositories all host data provided by different aggregators, and have different requirements for publishing.

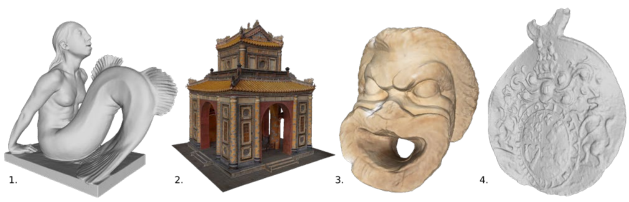

FIGURE 1- EXAMPLES OF TESTED OBJECTS: 1. EUROPEANA_2, 2. OH3D_2, 3. MORPHOSOURCE_3, 4. TDAR_2

First, we give our impression on the general usability of the repositories, discussing the ease of accessing the data, clarity of the metadata and paradata, and general impressions. From each repository, we evaluate 5 randomly selected meshes, resulting in great variation in the characteristics of the digitized tangible objects. The number of meshes evaluated are planned to be increased in future work. We limit this investigation to triangulated meshes and not point clouds, but evaluate several data formats.

Some sample objects can be seen in Figure 1 and the number of vertices (v), edges (e), and faces (f) can be found in Table 1.

Secondly, we evaluate the characteristics of the 3D data by computing several metrics to evaluate its integrity, topology, and geometry. We begin by assuring three integrity conditions: *Watertightness* ($\mathcal{WT}$) which assure that the mesh has a continuous surface, *orientability* ($\mathcal{O}$) which confirms that the inside and outside is clearly defined, and *manifoldness* ($\mathcal{M}$) which is a measure of vertex, edge, and face ambiguity. For many applications, the $\mathcal{WT}$ condition is not required to be true. However, violations to this condition often signify missing parts of a mesh, and makes analysis of the data less straightforward and predictable.

Second, we evaluate the topological complexity or "holes" by the Euler-Poincare Characteristic (χ) [11]. This measure was not designed to detect holes in the structure of the mesh, but rather the topological structure. For example, a doughnut has one hole, which would result in χ value of 0, while a sphere has no holes and would have a χ value of 2. Higher or negative values signify a greater topological complexity within the mesh, such as several topological holes or irregular geometry. However, when computing the characteristic for a mesh, a hole in the structure is still counted as a hole, meaning that we cannot distinguish between topological holes and violations for the $\mathcal{WT}$ condition. X also provides no spatial information about potential errors, meaning that one must look at specific structural elements of the mesh. Therefore, finally, we evaluate some geometric characteristics of the meshes with selected graph metrics [12]. These measures are borrowed from graph theory and provide insights to the connectivity and geometric representation of the 3D structure. We compute, evaluate and provide the numbers for the Aspect Ratio (AR), skewness (γ), dihedral angle (φ), edge lengths ($e_{(\mathcal{L})}$), triangle volumes ($t_{(\mathcal{V})}$), vertex valence ($\mathcal{V}_v$), and vertex connectivity ($\mathbb{C}_v$).

Europeana				**Open Heritage 3D**			
Nr.	v	e	f	**Nr.**	v	e	f
1	148.770	446.304	297.536	**1**	1.263.463	3.790.765	2.526.258
2	979.323	2.937.987	1.958.658	**2**	350.325	1.050.418	699.805
3	24.999	75.000	50.000	**3**	254.146	753.874	499.999
4	1.353.953	3.587.914	2.232.414	**4**	1.502.124	4.501.487	2.999.252
5	123.559	370.689	247.126	**5**	496.624	1.491.432	993.499
6	250.009	750.004	499.998	**6**	465.184	1.400.602	933.355
7	35.500	98.315	63.008	**7**	25.430	75.632	49.993
8	90.000	270.000	180.000	**8**	498.405	1.496.946	997.483
9	90.012	270.000	180.000	**9**	555.201	1.653.293	1.099.632
10	491.590	1.474.686	983.122	**10**	1.502.124	4.501.467	2.999.252
Morphosource				**tDAR**			
Nr.	v	e	f	**Nr.**	v	e	f
1	1.651.758	5.005.503	3.337.756	**1**	70.293	210.645	139.813
2	6.741.168	20.223.504	13.482.336	**2**	612.186	1.836.549	1.224.362
3	249.890	749.709	499.806	**3**	259.539	777.951	518.413
4	1.116.207	3.348.621	2.232.414	**4**	511.043	1.532.564	1.021.517
5	776.476	2.133.287	1.358.653	**5**	277.344	823.592	546.137
6	1.321.882	3.571.968	2.249.893	**6**	182.879	548.631	365.754
7	4.443783	11.982.238	7.544.025	**7**	24.670	73.634	48.566
8	3.856.014	10.340.088	6.485.385	**8**	162.910	488.023	325.116
9	2.782.803	7.149.654	4.370.976	**9**	299.997	899.991	599.994
10	12.731.502	38.194.500	25.463.000	**10**	203.005	608.353	405.349

TABLE 3- MESH STATISTICS OF TESTED OBJECTS FROM HERITAGE REPOSITORIES.

The metrics AR, γ, and φ, are used to evaluate the structure of the triangles in the mesh, where the optimal values are 1, and 0.5 for the aspect ratio and skewness respectively. Dihedral angle does not have an optimal value, but an ideal representation features smooth transitions, therefore low dihedral angle, for each triangle. Valence and connectivity are used in conjunction with these prior metrics to evaluate a vertex' importance in the mesh, and its susceptibility to visualization and computation errors. Valence measures how many faces the vertex participates in creating, and connectivity measures how many adjacent vertices it is connected to via an edge. High values for both of these measures usually signify higher values for AR and γ, which should be avoided. In a manifold mesh, valence and connectivity should have the same value. A visualization of all the metrics can be seen in Figure 3. Both the edge lengths and triangle volumes were normalized by the objects' bounding box as to compare all the meshes to each other. This combination of triangle- (AR, γ, φ, $e_{(\mathcal{L})}$, $t_{(\mathcal{V})}$), and vertex characteristics ($\mathcal{V}_v$, $\mathbb{C}_v$) provides good insights to the structure of the mesh, and allows for several statistical evaluations. For this work, we primarily consider the triangle congruence and surface variation.

4. Results & Discussion

An overview of the results so far are presented in Tables 2 and 3, and the whole dataset and code will be uploaded and available on Zenodo for the full paper. The tables present what percentage of the tested objects returned true values for the integrity conditions, the χ characteristic for each tested object, as well as the most significant values from the graph metrics across the tested objects from each repository.

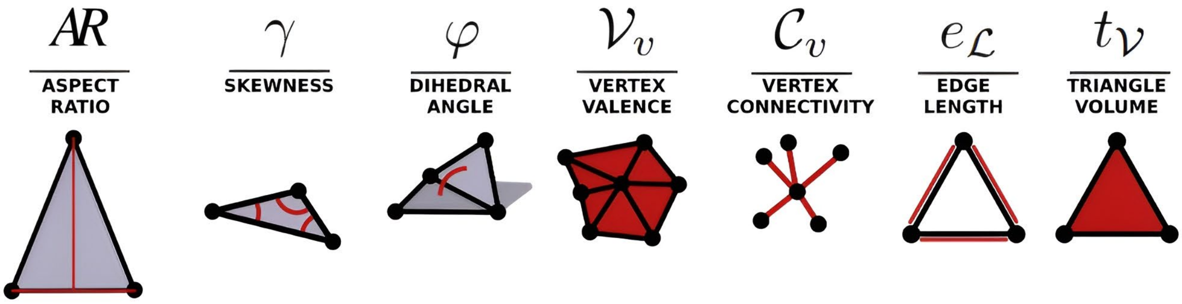

FIGURE 2 – VISUALIZATION OF TESTED GRAPH METRICS.

Interacting with the repositories proved to give quite varied experiences, due to the differences in how they host the data and present metadata. For example, several models published in Europeana were found to be deleted when attempting to download them by visiting the host website. This is the only repository we tested that does not host the models directly, but rather works by embedding 3D viewers from other databases. Validating the data and acquiring the metadata therefore proved more challenging than for other repositories, as each host website had a different format. Differently, Open Heritage 3D works by sending you a download link for the selected dataset, but also this failed to arrive at several occasions. Comparatively, Morphosource and tDAR allow for downloading straight from their websites. Another weakness with sampling from these repositories was that some of them, while featuring many 3D objects, mostly consist of data generated from a few institutions. Typically, these institutions use the same acquisition and processing method, meaning that the data will have many similar characteristics. A higher sampling rate of these repositories would therefore not introduce much new data or give a better picture of the possible mesh variations between institutions. Future work with other sampling methods could improve upon these data, but as digitization of CH is still set to increase in the future, the data volume from different institutions would also increase. A study of this nature should therefore be repeated regularly to document the characteristics of the 3D data of CH.

Values for the integrity conditions and graph metrics were also quite varied, corresponding to our hypothesis of the heterogeneous data apparent in heritage repositories. Complex applications like 3D-printing, high-resolution rendering, structural analysis, and simulation require that all integrity conditions are true, which occurred very rarely in the data. The applicability for most of the data available in these repositories is therefore questionable. For the graph metrics, both extremely high and low values were observed, meaning that most of the meshes have severe structural faults. To use a 2D image metaphor, this would mean that some of the pixels have different sizes, are oriented in a different way, or overlaps into other pixels. The image would in this case have a great deal of ambiguity, and produce erroneous results in subsequent analysis. The results for the integrity measures of the tested meshes can be seen in Table 2, and the graph metrics in Table 3.

Characteristics like low variance in triangle-characteristics and

Europeana		Open Heritage 3D	
Integrity	*Percentage*	**Integrity**	*Percentage*
$\mathcal{WT}$	10%	$\mathcal{WT}$	10%
$\mathcal{O}$	90%	$\mathcal{O}$	70%
$\mathcal{M}_v$	70%	$\mathcal{M}_v$	20%
$\mathcal{M}_e$	90%	$\mathcal{M}_e$	70%
$\mathcal{M}_f$	10%	$\mathcal{M}_f$	0%
χ	2, -6, -1, -42591, -4, 10, 51, 0, 12, 29	χ	313, 414, 3981, -7,-110, -1493, 429, -343, 4793, 2498
Morphosource		**tDAR**	
Integrity	*Percentage*	**Integrity**	*Percentage*
$\mathcal{WT}$	20%	$\mathcal{WT}$	0%
$\mathcal{O}$	70%	$\mathcal{O}$	100%
$\mathcal{M}_v$	60%	$\mathcal{M}_v$	60%
$\mathcal{M}_e$	60%	$\mathcal{M}_e$	100%
$\mathcal{M}_f$	30%	$\mathcal{M}_f$	10%
χ	-3, 15, -13, 0, 208, 61, 2, 0, -42, 9	χ	383, 5, 333, 285, 4276, 2, 381, 352, 0, 331

TABLE 2 – RESULTS OF TESTED INTEGRITY METRICS.

vertex connectivity further valorize the digital object, and lead to less unpredictability in subsequent analysis. If any or all the integrity conditions are false, the mesh can still be used for visualization. However, how a rendering software will interact with the ambiguous surface often leads to unpredictable errors and glitches in the visualization. For visualization the graph metric values also have less significance, as the perceptual quality of the mesh can still be high while the objective quality is low [13].

5. Future Perspectives

In this work we have evaluated some mesh characteristics of sampled 3D data from some of the most prominent heritage data repositories, and discussed how the various characteristics might affect the usability of the meshes. The tested meshes span a great variety in shape and size, and proved to have a significant difference in both integrity measures and metric values. The available data in heritage depositories are therefore not all applicable for many of the use-cases and analytical tools available for 3D meshes. In a future publication, the authors analyze these data in more rigorous statistical detail, documenting how they relate to specific semantic features to provide further insights to how the mesh characteristics matter.

Efforts like the 3D4CH Competence Center [14] and the ECHOES [15] projects which are currently being established might provide more in-depth structures and guidelines for processing 3D content for heritage applications. However, we deem that the existing guidelines are still lacking in detailed information about mesh structures and topology and how this can affect the processing workflow and the usability of the resulting meshes.

Europeana					Open Heritage 3D				
Metrics	min	$mean$	max	σ	**Metrics**	min	$mean$	max	σ
AR	1	1.5644	67633	0.303	AR	1	3406	$\gg$	10206
γ	ε	0.509	1.999	0.102	γ	ε	0.621	1.998	0.068
φ	ε	0.0005	0.726	0.012	φ	ε	0.001	1.570	0.004
$\mathcal{V}_v$	1	3.919	37	2.185	$\mathcal{V}_v$	1	5.974	25	0.039
$\mathcal{C}_v$	2	4.219	37	1.852	$\mathcal{C}_v$	1	5.986	25	0.026
$e_{\mathcal{L}}$	0.0002	0.166	73.807	0.303	$e_{\mathcal{L}}$	ε	0.160	4.591	0.143
$t_{\mathcal{V}}$	ε	0.046	24.921	0.123	$t_{\mathcal{V}}$	ε	0.018	4.105	0.030
File Formats		.obj, .ply, .stl			**File Formats**	.obj			
Morphosource					**tDAR**				
Metrics	min	$mean$	max	σ	**Metrics**	min	$mean$	max	σ
AR	1	0.022	1.222	0.040	AR	1	1.695	1008	0.843
γ	ε	0.523	1.998	0.0921	γ	ε	0.387	1.999	0.137
φ	ε	0.064	1.570	0.081	φ	ε	0.0009	0.514	0.0022
$\mathcal{V}_v$	0	6	51	0.024	$\mathcal{V}_v$	1	5.974	14	0.034
$\mathcal{C}_v$	0	6	51	0.024	$\mathcal{C}_v$	1	5.987	14	0.018
$e_{\mathcal{L}}$	ε	0.137	2.143	0.199	$e_{\mathcal{L}}$	ε	0.330	5.109	0.259
$t_{\mathcal{V}}$	ε	0.022	1.222	0.040	$t_{\mathcal{V}}$	ε	0.077	8.544	0.083
File Formats		.obj, .ply, .gltf			**File Formats**	.obj			

TABLE 3 – RESULTS OF TESTED GRAPH METRICS.

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Author Biographies

Markus Sebastian Bakken Storeide is a PhD candidate in Computer Science at the Colourlab. Norwegian University of Science and Technology (NTNU). His PhD project regards information extraction from mesh geometry and information enrichment of multimodal data.

Sony George, PhD is an Associate Professor at the Colourlab, Norwegian University of Science and Technology (NTNU), Norway. His research interests include color imaging, multi/hyper spectral imaging, imaging applications in cultural heritage. He has been involved in several national and EU projects related to cultural heritage imaging, including H2020 MSCA CHANGE-ITN and PERCEIVE.