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Short Paper

Streamlining the preparation of scanned 3D artifacts to support digital analysis and processing: the GRAVITATE case study

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Abstract

Digitally acquired 3D models of cultural assets are not always ready for further processing. Sometimes, the digital surface presents geometric or topological defects that may hinder downstream surface analysis algorithms. Furthermore, the high resolution meshes provided by acquisition might pose complexity issues to the processing afterwards. Preprocessing models can be a tedious and sometimes manual work. We present the processing needs for a set of cultural artifacts in the framework of the GRAVITATE project and describe a fully automatic procedure to fix and adaptively simplify 3D models of cultural interest.

CCS Concepts

•***Computing methodologies*** → *Computer graphics; Shape modeling;*

1. Introduction

Nowadays, digitization technologies offer plenty of solutions to acquire digital copies of cultural heritage artifacts, from high-end laser scanning to low-end apps that turn smart phones into portable 3D scanners [Rem16]. At the same time, 3D modelling and processing are now mature enough to offer a wide spectrum of software tools that could support quantitative analysis, classification, comparative reasoning on stylistic features. While the technology is ready, what are the needs of upcoming software systems that will assemble state-of-the-art methods in computer graphics and geometry processing in toolboxes that support the digital analysis and study in cultural heritage domains?

In this paper we address this question, in the context provided by the ongoing GRAVITATE Project [PWM*16] whose goal is to set up a workbench of tools and services to aid archaeologists in studying fractured objects, leveraging on geometry and semantics to reason about possible *re-assembling* of shards, *re-unification* of pieces likely belonging to the same object and *re-association* of fragments across distributed collections.

To reach this challenging objective, a large set of tools need to be integrated and algorithms must be deployed to analyze, describe, index and compare individual fragments, as well as parts or groups of fragments. The algorithms cover therefore a wide range of tasks, and each of them come into play with its own computational performances and requirements on the representation of the digital model. On the other side, fragments are typically digitized by laser scanning or photogrammetry and are made available mostly as triangle meshes. Every step of the digitization pipeline can introduce errors and defects in the surface. Such defects are typically holes, due to self-occlusions determined either by the shape of the object along some acquisition directions or by the material properties (e.g. reflectance), and geometry or connectivity errors, like outliers in the point cloud or overlapping triangles. Fixing such defects is usually a manual and tedious post-processing work, but is necessary if shape analysis has to be applied to the models. Tools such as curvature estimation, faceting (identification of fracture region, inner and outer faces), thickness distribution, are useful to describe and compare fragments, but need the mesh to exhibit some good properties, in order to be properly navigated without ambiguities about adjacent elements (vertices, edges or faces). Furthermore, the digitization might produce very high resolution models that are hardly tractable for intrinsically heavy computations (e.g., geodesic measurements on the surface). However, simplification must be adaptive, that is, remove mesh elements that do not smooth away salient surface features, even if tiny details, because they are crucial for answering archaeological questions. Our objective and contribution is to provide archaeologists a ready-to-use package that performs two main operations: cleaning the input mesh from any defect that could hinder geometric analysis, and adaptively simplify the models up to three different model sizes that can fit the needs of the different analysis algorithms. The whole pipeline is a sequence of operations that are transparent to the user and completely automatic.

1.1. The case study

The GRAVITATE case study regards a set of terracotta figurative statues discovered in the XIX century in Salamis, on the island of Cyprus, and dating back to the seventh - early sixth century BC [KKF91]. These statues are highly fragmented and distributed across many collections, notably at the Cyprus Museum, the British

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Museum in London, the Ashmolean in Oxford and the Fitzwilliam in Cambridge. Furthermore, shards are cracked, faded and eroded.

The digital scans of the fragments have been acquired by the Cyprus Institute using diverse technologies: photogrammetry and 3D scanning (Breuckmann 3D Scanner with structured light and a NextEngine Desktop 3D Scanner). The complete repository had 647 files in PLY format, including complete meshes but also raw data (single or multiple range images not yet aligned in a unique reference system) or partially processed data (registered scans not yet meshed or meshes consisting of multiple connected components). Colour information was generally available, but not for all models.

The complete models appeared as high resolution triangle meshes; their size ranges from about 46000 triangles to 27 million triangles. However, from the surface quality point of view, many meshes presented defects that visualization could cope with, but that could compromise the efficacy of shape analysis algorithms. Some of the defects were outliers in the point cloud, due to the scanning phase, and some geometric or topological inaccuracies were also introduced by the reconstruction pipeline.

Concerning surface quality, a well-formed 3D model is typically required to be bounded, closed, rigid, regular and such that its boundary surface (the mesh in our case) is 2-manifold [ACK13]. In particular, requiring the surface mesh to be manifold excludes degenerate, dangling and isolated elements, intersections occurring out of elements' extrema and multiply-connected vertex neighborhood. However, in our case study we do not require the mesh to be closed, in order to maintain when possible the original data, which might be incomplete, without introducing new data, not validated by the archaeologists.

Concerning mesh resolution, a higher sampling ensures an impressive visual quality but also poses performance-related issues when designing the architecture of the GRAVITATE system. While modern web technologies now allow to include 3D graphics functionalities into Web applications easily, the memory load delegated to the browser for a high resolution mesh would likely throw an error or cause a crash. For these reasons, GRAVITATE implemented a hybrid dual-client solution, in which a part of the 3D graphics functionalities would be offered through the web-based client, using low resolution models, while another part through a dedicated desktop client, using high resolution models. Functionalities that would belong to the web-based client would be for example the simple visualization of the 3D models for exploration purposes and the semantic search. Functionalities belonging to the desktop-based client would be those belonging to the manipulation category, such as the semantic annotation of regions of interest or the computation of geometric features. The two clients synchronize seamlessly during the session (more details can be found in [CRS17]. Also, the intrinsic computational complexity of some algorithms (e.g. the space search for mating two fragments) invokes low or medium resolution on the desktop client as well. To derive lightweight versions of the full resolution meshes, however, we must cope with the accuracy of the simplified mesh in regions of high frequency detail. Indeed, the Salamis statues exhibit very interesting 3D patterns on their outer surface, which appear for instance as tiny circular or fish-bone incisions. Such fine-grain features are easily lost if a greedy decimation method is applied to reduce the model dimensions. Instead, we need an adaptive simplification tool, able to dismiss non salient vertices first (see Figure 1).

2. Available free tools

We started considering free softwares available for carrying out the twofold task of cleaning and simplification. In particular, the following software were tested: Meshlab, CloudCompare, Netfabb, Vorpalite, ReMESH, MeshFix. Many of the above tools have capabilities to check geometry and connectivity, repair defects, and simplify the mesh, but no one has turned out to be the best fit for our specific requirements. In fact, since we have to process a large number of 3D models, we need to devise a pipeline of operations to be performed possibly automatically.

Meshlab [CI] has functions to check the presence of non-manifold vertices and edges; it also provides functionalities to solve specific geometric and topological issues but does not suggest a cleaning pipeline. This leaves the user to decide which sequence of functions to apply, but there is no guarantee that the n-th cleaning step does not introduce new problems. For instance, the user loads a mesh and runs the check for non-manifold edges: the result is that all edges are manifold. Then, the user checks for self-intersecting triangles and finds some cases. So, runs the removal of intersecting triangles, which leaves holes in the mesh. Finally, filling the holes can cause non-manifold edges to appear. In addition, the software was not able to process big models (test case: 20/30 Million of points on hardware with PCI Desktop with 16 GB CPU i7, Nvidia Geforce 580gtx video card).

Netfabb [Aut] treats models for 3D printing and, as such, if focussed on closed models (no boundary edges). The main repair functions therefore target orientation and closure (hole filling and triangle flipping); it is also possible to repair degenerate faces. These operations can be done automatically (in the pro version) through a script, which the user can edit to choose the sequence of operations. Self-intersections can be treated only if the shape has no holes. The free version is 32bit and does not allow to handle big models (not greater than one million vertices).

CloudCompare [Clo] works essentially on point clouds so it is not directly applicable to the purpose. It can simplify vertices as a point cloud and can give an estimate of the error between the original and simplified model in terms of point clouds - not of surfaces - between the initial and the simplified model (chamfer).

Vorpalite (Geogram) [INR] seems to smooth tiny details during simplification. However, the function has a few parameters (e.g., anisotropy, gradation, refinement, sharp edges) and possibly a better tuning of the parameter could provide better simplification for our purpose. In particular, the sharp edge parameter is likely to maintain feature lines but unfortunately it is declared as an advanced parameter and in the documentation it was not completely clear how to use it.

ReMESH [Attc] provides the Check Geometry feature that allows you to evaluate and correct topological issues. Similarly to the Meshlab GUI, the user has to manually fix the several issues that may arise with no guarantee to generate other issues during the process. It has adaptive simplification capabilities but can handle models of limited dimension.

Meshfix [Attb] [Att10], without graphical interface, can handle large models. The software allows to automatically obtain a guaranteed clean model, but with no control on the hole patching, which closes all the boundaries. Furthermore, it does not perform simplification, which should be done afterwards.

Also MeshLab provides a scripting facility, to launch a set of operations without interaction through the GUI. This should allow the management of huge models. However, it is not easy to set the proper pipeline / parameters and guarantee the cleaning without a check.

3. Method

In order to get a clear idea of the quality and variability of models in the repository, we implemented a simple diagnostic tool to analyze each model. The file format in the case study is PLY (Polygon File Format). So, we parse the PLY header first, and check encoding (ascii or binary), number of vertices, presence of color property, presence of face elements. Note that, if the face element is absent, this means the corresponding object is actually a point cloud without a mesh representation. If faces are present, the mesh is loaded and analysed to get information about the number of boundaries and the number of shells. We use the ImatiSTL library [Atta] to load the ply file and get these information.

After running the diagnostics, it became evident that 146 models out of the whole 647 were point clouds, and among the meshed models 225 comprehended more than ten shells (up to hundred shells: these were unmerged scans). Eventually, We restricted our set to 241 models, i.e., those that are meshed, have less than 10 shells and have colour information. The size distribution of these selected models ranges from 28 to 1.5 million points with an average of 10 million vertices. We proceed following the MeshFix approach; however, we need to adapt the pipeline in mainly two ways to meet the specific requirements of our case study. We will call the pipeline devised to meet the GRAVITATE requirements *GraviFix*.

Firstly, we want to keep all the holes that were present in the original model, since the archaeologist prefers to have holes where data could not be captured instead of mixing "real" data, coming from acquisition with interpolated data, introduced for completion. Conversely, MeshFix fills all the holes at an early stage, and proceeds filling holes as soon as they are created by removing degeneracies and intersecting faces. Therefore, we remove the main hole filling step from the pipeline and implemented a new version of the cleaning procedure, which keeps original holes but fills those due to the cleaning of local degeneracies.

Secondly, we introduce a simplification phase to obtain versions of each model with different size, so that each shape can be processed efficiently by downstream services depending on the complexity. In our case study, the Salamis fragments will undergo several operations to support archaeological research: previewing on the web, surface analysis, faceting, annotation, mating to name a few. In our vision, low resolution models in the order of 50K vertices can be used to give a 3D preview of the corresponding model on a web interface without loosing interactive rate. The mating algorithm needs a denser mesh in order to find reliable point correspondences between two fragments, but the trade-off with the computational complexity must be taken into account: due to the huge number of possible combinations to be tested, we agreed on a size of approximatively 100K vertices for this procedure. We also provide a quite high resolution model of 1 million points, along with the full resolution, cleaned model.

Thirdly, we provide feedback on all the operations performed to process a model: a detailed log with timings and details of each routine, and a string of fixed syntax, encoding the mesh properties and how they change during the process. The log will be analyzed to derive performance statistics in future implementations.

3.1. Implementation

We detail here the sequence of operations performed by GraviFix.

Model load. The PLY file of an original model is loaded using available methods from the ImatiSTL library [Atta] also used by MeshFix. As MeshFix, our tool expects objects to have a single connected component; isolated patches are considered a meshing error. The algorithm then tries first to join components whose boundaries are closest in terms of Euclidean distance. Remaining components are simply removed to keep the one with maximum area only.

Geometry and topology check. Using library methods, we check any condition that can compromise the mesh quality. The geometry, namely the position in the 3D space of elements, is checked to guarantee the absence of coincident elements (e.g., different vertices with the same 3D coordinates, overlapping triangles) or degenerate ones (e.g., a triangle with aligned vertices, that is, with null area). The topology check verifies that the connectivity relations about elements are correct. In particular, the procedure looks for null, isolated or duplicated elements, missing or coincident bounding elements.

Native boundaries tagging. Since the cleaning procedure deletes problematic mesh elements creating small holes that are later filled, we tag original boundary edges at this stage. Later on, boundaries consisting of tagged edges will not be filled. ImatiSTL provides facilities to mark mesh elements.

Mesh cleaning. This is the core of the process, where mesh defects are actually resolved. We follow the iterative loop of MeshFix which removes degeneracies first; removing degenerate triangles produces holes in the mesh. While MeshFix at this stage fills all the holes, GraviFix keeps those marked as original boundaries. Then, triangles intersecting out of common vertices or along common edges are removed. After removal, again only newly introduced boundaries are closed. The clean operations are iterated until either no more degeneracies and intersections are found or the max number of iterations is reached. (a maximum of 10 iterations are currently allowed). If the model has been successfully cleaned, it is saved as *filenameclean.ply*. Otherwise, a warning is raised.

Simplification. At this stage, the model has been fixed and saved. Now an error-driven simplification is applied in order to achieve the best trade-off between point density and quality of the surface. We

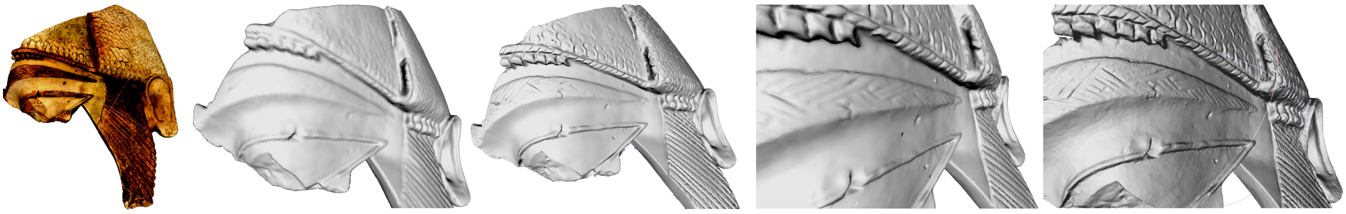

Figure 1: *Examples of small scale features on Salamis fragments and simplification behaviour. From left to right: original model; simplification with CloudCompare (108367 vertices; maximum error to the original: 0,42% of the bounding box diagonal), with Vorpalite (105384 vertices, maximum error 0,5%), with Meshlab (103613 vertices, maximum error 0,023%) and GraviFix (100000 vertices, maximum error 0,015% of the bounding box diagonal).*

implemented a simplification that follows [GH97] based on an iterative edge-collapse operation performed on minimum error edge. The edge collapse removes at each step one edge and one vertex. Several choices can be done about the position of the remaining vertex: We choose to keep the one between the original vertices with lowest error. This guarantees that vertices at low resolution are always present also in the higher resolution and original meshes. This might ease further operations over the model, e.g., annotation transfer among different resolution of the same artefact for documentation [SSM17]. The simplification is repeated at most three times, for models having more than 1 million points; models with less than 50000 points will not be simplified at all.

After each simplification, it is necessary to check once more the model quality, since simplification might introduce new errors. If necessary, the cleaning is repeated after each simplification before saving the output model.

4. Results and Conclusions

The GraviFix tool has been launched on the 241 selected models of the GRAVITATE Repository; according to the diagnostics, 99 models out of 241 needed cleaning. GraviFix successfully fixed the 99 models and simplified all the models in approximatively 40 hours, on a Xeon 8 core 2GHz machine. Clean models were simplified as described in section 3. The adaptive simplification successfully maintains as much as possible the surface detail features (see Figure 2). The output log strings (one for each processed model) build up a lookup table to get an overview of the overall operations and partial outcomes, to be further analyzed to get performance statistics in future developments. In spite of the time taken to clean and simplify models, the process has been fully automatic. With respect to other softwares, GraviFix discharges the user from the selection of which functions to run, in which sequence, and with which parameters.

Acknowledgements

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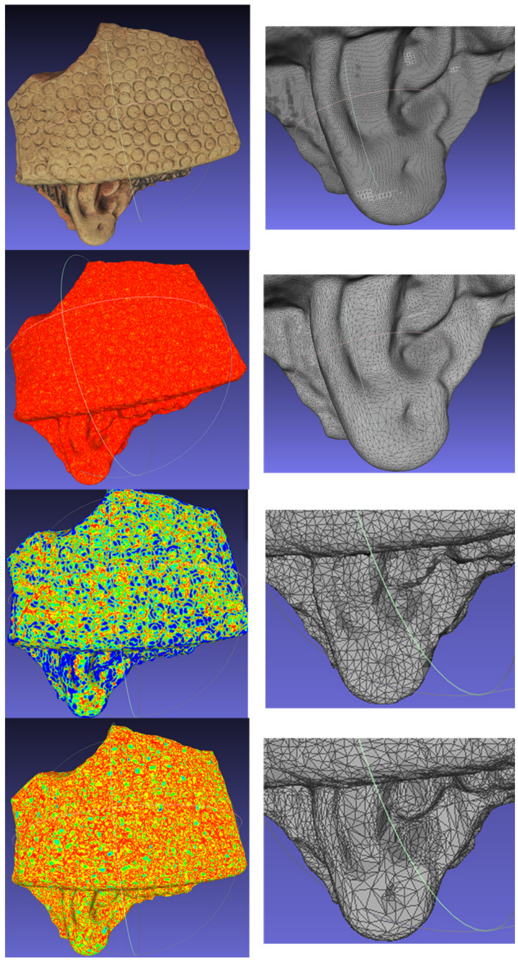

Figure 2: *from top to bottom: original mesh; cleaned model; simplification at 50K vertices with GraviFix; model simplified at 7783 vertices with Meshlab; model simplified at 7783 vertices using our approach. The right column shows the error of the meshes with respect to the full-resolution, cleaned model. The error increases from red to green to blue areas.*

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