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A dashboard for the analysis of tangible heritage artefacts: a case study in archaeology

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Abstract

Digital manipulation and analysis of tangible cultural objects has the potential to bring about a revolution in the way classification, stylistic analysis, and refitting of fragments are handled in the cultural heritage area: 3D modelling, processing and analysis are now mature enough to allow handling 3D digitized objects as if they were physical, and semantic models allow for a rich documentation of many different aspects of artefacts or assets of any complexity, as well as of contextual information about them.

In this perspective, the paper presents the ongoing development of a software workbench which integrates several tools that can be used, combined, and customized to provide scientists with a working environment to process and analyse digital assets. The general objective is to exemplify the potential of new platforms to work on digital models beyond the simple rendering and visualization of assets. In particular, the paper presents the design of the workbench – the Dashboard – which reflects the analysis of the requirements gathered in a specific community of archaeologists and curators: the functionalities included in the case study target mostly the ReUnification, ReAssembly and ReAssociation of fragmented or dispersed cultural assets.

CCS Concepts

•***Computing methodologies*** → ***Shape analysis;*** •***Human-centered computing*** → *Interactive systems and tools;* •***Applied computing*** → *Archaeology;*

1. Introduction

Nowadays photogrammetry and 3D scanning techniques are widely adopted in Cultural Heritage (CH) and several collections of historical artefacts have been digitised and made available for different purposes. The classical application is the visualisation of the artefacts themselves in virtual catalogues, museums or even interactive environments mainly to provide the general public with a more effective consumption of Cultural Heritage.

Nevertheless, the potential of computer vision and computer graphics methodologies to support the humanistic research has recently become more evident. Indeed, 3D modelling, processing and analysis are now mature enough to allow handling 3D digitized objects as if they were physical, and then conducting specialised qualitative and quantitative analyses to assist researchers in the field.

Moreover, the availability of knowledge allows for a digital and extensive documentation of many different aspects of complex assets as well as of contextual information about them. Bringing geometric and semantic modelling together is the next challenge towards a real *digital heritage science*.

The paper discusses a case study where the integration of tools for geometry- and semantics-driven analysis of digital artefacts is realized to support research in archaeology. The context is particularly interesting, as most of the archaeological objects discovered in a survey are not in an optimal preservation state. Artefacts are usually fragmentary, eroded and broken, documented with traditional archaeological texts describing the content of the fragments verbally, and therefore mostly qualitatively. This makes the archaeological research challenging in cataloguing such pieces first , and in reassembling them afterwards. The process is even harder considering that pieces of historical importance may be dispersed across different collections, which might hinder the possibility to complete a reassembly or limit the scope of a historical study. What if, instead, researchers could rely on quantitative data together with descriptive ones, to document, classify and retrieve fragments?

In this context, the paper describes the design of the workbench, named *Dashboard*, which reflects the analysis of the requirements gathered in a specific community of archaeologists and curators, originated by the project GRAVITATE [PWM*16]. The general objective of the project is proposing an innovative approach to the study of heritage artefacts, which includes virtual reconstruction, classification and morphological analysis, steps that nowadays are limited by access to physical items and the impossibility to re-unite them physically, either because they are stored in various museums or because physical refitting fails. The project is currently developing a smart platform to support professionals in Cultural Her-

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itage, which is based on shape and semantic analysis techniques applied to 3D models derived by the reconstruction from 3D scanners. The ongoing development of the *Dashboard*, the front end of the platform, is a challenging case study which will demonstrate the value of the integration of several tools that can be used, combined, and customized to provide scientists with a working environment to process, analyse and document digital assets.

There are several approaches in the literature tackling crucial problems of virtual reconstruction and classification/retrieval of digital artefacts, but none of the proposals covers the challenges in the comprehensive way the project aims to do. A pioneering project was the Stanford's Digital Forma Urbis Romae [KTN*06], whose goal was the digitalization and then virtual reconstruction of eroded fragments; moreover, an on-line database including all the documented fragments was set-up for research purposes. Content-based retrieval and exploration was not considered in this project and the annotation of fragment features was performed manually and meant to support only the reconstruction task. Oppositely, the EROS-3D project [GCJ*07] focused on dataset navigation and global matching, targeting only the content-based classification and search of artwork 3D models and no reassembly issues. In particular, a set of global descriptors for 3D models, partially broken and eroded, has been proposed, but colour information was not taken into account. The work proposed by Yu and Hunter [YH13] is closer to the approach presented in this paper. Actually, they proposed a system supporting the user in documenting relationships between multiple 3D digital representations of museum objects using web-based annotation tools. The annotation scheme and procedure follow a standardized format (by adopting W3C recommendations) but the annotation task is manual. The user is able to select areas of interest on a 2D image or 3D model and label them according to the terms of an ad-hoc ontology. Few measures are automatically computed (i.e. distances, areas, volumes), while all the relationships between parts are coded only semantically. Consequently, the semantic aspect is the core here, whereas the geometric one is only drafted.

The design of the *Dashboard* focuses on research challenges related to the ReUnification, ReAssembly and ReAssociation of artefacts. We define *ReUnification* as the process of discovering parts of the same object held in different collections and evaluate if and how they could fit together; *ReAssembly* as the process of digitally recreating an historical artefact by the set of its fragments; and *ReAssociation* as the process that allows researchers to look for new understanding and insights into the movement and links between different communities on the basis of similar artefacts found in different locations. We will call *ReX* tasks the aforementioned activities and the platform intends to support them in an extensive and (semi)automatic manner.

The paper is organised as follows. In Section 2 the specific objectives of the dashboard are outlined together with the identification of the targeted users; a synthesis of the user requirements will be given, which have been translated in geometric functional requirements of the platform. In Section 3, the design of the dashboard will be detailed, distinguishing the different components and the related functionalities. Finally, Section 4 concludes the paper with the future work.

2. Analysis of the user requirements

The role of the dashboard is to specify and implement the functionalities needed to support actively users in the interaction with a rich visual context in the exploration of fragments, assets, or collections in ReX workflows.

Similarity evaluation is the key concept underlying such tasks. Indeed, it entails the ability to reason, in a computational setting, about several and diverse object properties which may relate to geometric attributes (e.g., spatial extent, aspect), to colourimetric properties (e.g., colour, texture), to specific traits that fragments exhibit (e.g., decorations), or to metadata documenting the artefacts. Comparing shapes and reasoning about the similarities of their relevant features is crucial not only for ReAssembly problems; it also enables classification or stylistic analysis, as well as track changes in techniques, tools or materials that were associated with the production, decoration, or use of an artefact.

Our approach consists in integrating the geometric modality with a semantic description of the 3D artefacts, with a particular emphasis on the computational analysis of 3D fragment, which is a specific area where the digital setting may support a safer and enhanced manipulation of fragile and precious artefacts.

On the one hand, semantic annotations are used to document the physical and abstract characteristics of the fragments, and semantic reasoning is used to induce relationships between them. In this way, similar cultural heritage artefacts can be identified and matched, and more abstract relationships among objects, such as provenance, historical association, geographical origin or style can also be discovered, thus adding to historical knowledge such as migratory or trading patterns in different periods of history.

On the other hand, geometric similarity comes into place. It has been broadly explored in the computer graphics community and many approaches have been proposed according to different applications (see, for example, [PPY*16, BCBB16]). In the context of the ReX tasks, shape similarity has specific connotations. In ReAssembly, it corresponds mainly to the concepts of *complementarity* and *compatibility*. Complementarity is due whenever a user is focussed on the ReAssembly of various fragments. Nevertheless, it is not sufficient since most of the pieces are missing, eroded or broken (see Figure 1). Then, compatibility has to be taken into account to find correlations between non perfectly matching fragments. In the ReAssociation task, shape similarity relates to different features or properties, such as 2D and 3D patterns (e.g. decorations and reliefs).

In the following subsections, the users of the dashboard will be identified and the outcomes of the requirement phases will be discussed. In the light of those, we have proposed digital tools based on similarity, which aim to:

- Interact with the geometric and semantic data in a combined way;
- Share research hypotheses among users by expressive documentation;
- Provide quantitative measurements of 3D fragments to make research and documentation accurate and reliable.

Figure 1: *Examples of pairs of complementary fragments of the Salamis collection*

2.1. Identification of the users

The user requirements were collected in a double form: with both online questionnaires and face-to-face interviews. An online questionnaire was prepared and made it available on the project website in order to gather feedback outside the consortium. In parallel, face-to-face interviews to experts belonging to CH institutions with different roles have been organised in order to understand where semantic and geometric analysis come into place in the ReX workflows.

Four key roles for the usage of the dashboard emerged during the requirement phase: *researchers* in archaeological sciences, *curators*, *conservators* and *illustrators*.

Researchers are interested in understanding the archaeological context of a set of objects retrieved in a survey. The context may include economical, social and cultural aspects. They are mainly focussed on ReAssociation of artefacts, answering to research questions such as "In which era and where was an object created?" or "Where else similar objects were found?".

Curators take care of maintaining the records of digital catalogues and presenting the collections to the public. They prepare exhibitions by selecting a theme and collecting the artefacts to be displayed: in other words, such pieces share a similarity in terms of semantics or shape (ReUnification/ReAssociation). Objects involved in the ReUnification may belong to collections of different museums.

Conservators are in charge or restoring broken artefacts. They are given fragments belonging to the same object (ReUnification) and their task is to reconstruct them (ReAssembly), often using similar pieces to approximate the shape and the artistic style of the object under investigation.

Illustrators assist curators by producing graphical representations of the research under study, doing visual interpretation and extrapolation; illustrators' work is also a support for archaeological hypotheses. They sketch up the shape of a reconstructed object/environment, starting from the shape of the available fragments and trying to complete it in a plausible way according to the suggestions of the curator. Moreover, they usually takes advantage of all the contextual information (metadata) about the fragments to look for similar objects in digital and physical catalogues, and consult books. Illustrators consider valuable the capability of measuring digitally artefacts and compare them quantitatively.

Interviews and questionnaires to these categories of users led to the definition of a series of user requirements pertaining the semantic and the morphological aspects. In this paper we will concentrate on the second ones.

2.2. User requirements related to geometry

The primary use case under investigation in the project consists of terracotta figurative statues from the port of Salamis on the island of Cyprus [Kar91]. These statues are highly fragmented and distributed across many collections, notably at the Cyprus Museum, the British Museum in London, the Ashmolean in Oxford and the Fitzwilliam in Cambridge. The digital dataset consists of around 267 3D triangulated models derived from 3D scans, documented according to the International Council of Museums' (ICOM) Documentation Committee's (CIDOC) Conceptual Reference Model (CRM) and whose records are exposed as Linked Open Data [NOR*16].

The geometric information the user of the dashboard interact with is generally a set of properties that refer to the physical aspect of fragments, such as shape, colour, or decorations. The interactions range from simple graphical interactions with the digitized fragments to issues related to the processing of the digital model itself. They also include more sophisticated analyses to support semantic enrichment for both the ReX tasks and a richer documentation.

Surprisingly, the digitization process still poses issues related to the reconstruction of a good geometrical approximation of the physical object (3D meshes in our case) and requires an accurate pre-processing phase. The digitization quality is an important factor for visualizing a faithful representation of the real object, and also to extract realistic measurements from it: point cloud alignment problems, holes, dangling faces and edges are still tricky issues for a CH scientist. Adaptive techniques to process geometry and colour together in order to obtain high-resolution 3D meshes are needed. Being the focus of the research on 3D analysis, such requirement has been considered as a pre-processing step aimed to create a high quality 3D repository.

Regarding the graphical interaction, users want to manipulate interactively the digital model as if it was the physical one. This entails being able to visualize each piece alone, or in groups, zooming in and out to visually explore the features of the fragment, rotating or adjusting the fragment position in a proposed assembly. A quick response is considered valuable.

Structuring conveniently the fragments is also important. Most of the reasoning done by users implies a distinction between the external, internal and fracture parts of the fragments. We named these areas "facets": the *external* facet often contains painted or relief decorations; the *internal* facet may give some insight on the crafting technique used by the sculptor, and the *fracture* facet, which indicates the lateral area where the fragment is broken, may help the conservator to find complementary fragments that can be reassembled together. The platform should support the pre-processing of all fragments so that the facets are properly identified before further analyses.

Another important requirement for any ReX activity is the possibility to discriminate between fragments and fragment features, according to the dimensions expected of the reconstructed physical object.

A key and recurrent requirement relates to effective methodologies to asses the similarity among fragments in order to group fragments which possibly belong to the same object (ReUnification for ReAssembly). In this context, similarity involves both strictly geometric aspects (e.g. the thickness or the curvature of the external facet), colours, or any kind of decoration, and semantic ones (e.g. metadata). Clustering should be driven by any of these aspects, as well as a combination of them. Additionally, a support should be offered to pre-align fragments in order to highlight any possible feature continuity, as well as presenting to the users fragments in their likely true orientation (e.g. a nose has a canonical orientation, and the fragment visualization should conform to it).

The use cases provide a varied set of examples of queries dealing with similarities between fragments valuable for each ReX task. Therefore, the system should integrate a variety of methods implementing 3D content-based retrieval (e.g. finding similar 3D shapes, finding similar coloured decorations, finding similar anatomical features). Similarity-based reasoning can guide both searching a specific known target and an unconstrained search which allows the user to explore the repositories. The identification of the features characterising the reliefs, the decoration and the morphological characteristics of the artefacts is a basic step for the definition of effective similarity measures.

Finally, as the core of ReAssembly, algorithms able to detect semi-automatically all possible and plausible matching between fragments should be developed. The user intervention for acceptance or for adjustments would be preferable.

2.3. Geometric functional requirements

The user requirements described in the previous section have been revised and re-formulated into a series of functional requirements for the dashboard application, which we grouped according to their scope:

- *ReAssembly*: software services whose aim is to find and evaluate a possible match between fragments or a possible reconstruction path;
- *Annotation & analysis*: functionalities whose goal is to enrich the knowledge and documentation of fragments; typically, both software services that help analysing a fragment and storing the analysis results in a structured manner are included;
- *Selection*: functionalities whose goal is to help users to retrieve fragments/assets on which further actions have to be carried out. Browsing, searching, navigating are examples of this class;
- *Visualization*: modalities of visualization of 3D data as well as textual or conceptual data or information needed during the processes;
- *Publishing*: set of functionalities supporting the users in the finalization of any new finding and its sharing with other users/communities.

Regarding ReAssembly, different approaches have been proposed [HFG*06, BTFD*08, SF16, PSA*17] but the problem cannot be considered solved. Actually, some approaches consider essentially 2D objects such as frescos [BTFD*08, SF16], while other exploits either the presence of all the fragments composing the object [HFG*06] or some special symmetries and construction lines, as in architectural contexts [PSA*17].

In the case study presented in this work, the challenge consists in free-form, eroded and broken fragments, including many missing pieces. Therefore, a first ReAssembly workflow to be included in the dashboard would find initial clusters of fragments by the following criteria: (i) aligned *painted patterns*, (ii) aligned *relief patterns*, (iii) *fracture complementarity*. Another ReAssembly workflow has been considered in the dashboard, based on the definition of a digital "template" model. Often, conservators and illustrators have already in mind the overall shape of the object that they want to reconstruct, and rely on canonical representations (e.g. illustrations and images on catalogues) to find an approximate placement of the available pieces. Analogously, a virtual mannequin has been envisaged, which encapsulates the knowledge about the statues of the user study, including possible constraints about the size of the various anatomical features.

One of the basic functionality of the category of Annotation & Analysis is the *semi-automatic detection of facets* on 3D meshes, which would really help the work of the experts, being tedious and time-consuming if performed manually. This is a complex problem and a solution is available only for specific classes of objects [PSA*17]. Then, it is reasonable to provide a manual correction of the output of the developed algorithm.

The *automatic feature detection* is another class of shape analysis algorithms that would support users in the investigation of the fragments. We distinguished three types of features that may be helpful in the CH area:

- Morphological features (partial on complete);
- Coloured/painted features on the external facet;
- Reliefs and patterns on the external facet;
- Manufacturing patterns in the internal facet.

Here again, a *manual selection tool* has been planned to correct the possible imprecise output of the algorithms included.

Another set of functionalities that the users considered relevant for their activity is the *geometric characterization*, intended as the capability of computing and visualizing specific measures of the fragment; they may be either basic values (e.g lengths, areas, volume) or describe the general behaviour of the surface by scalar fields (e.g. mean curvature [CSM03], CIELAB representation [AKK00]).

Geometric characterisation and feature identification can be used either per se or as part of the whole 3D part-based annotation process. Basically, *fragment annotation* is the process of linking a piece of geometric information (the whole fragment or a part) to additional information, either textual or symbolic. In the current context, the annotation is created through a controlled vocabulary defined by experts of the archaeological context, which describes the characteristic elements of the statues and the pottery originated in Salamis. The annotation pipeline that will follow the approach presented in [BAC*16], although a different application domain

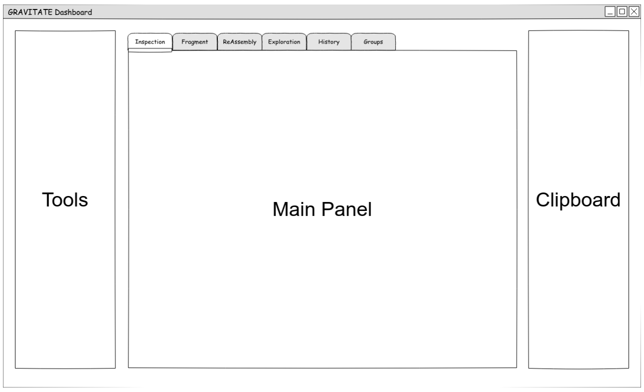


Figure 2: *The main elements of the Dashboard: Tools, Main Panel, Clipboard*

was tackled there. Thanks to annotation, the user is able to make the information persistent, and shareable to other experts. Once an annotation has been added to the 3D model, it is then possible to perform SPARQL queries on the annotated parts, such as "find all objects containing (parts of) a head whose diameter is 10 cm".

Regarding selection functionalities, we have included functionalities for metadata search, that is SPARQL queries to access the knowledge base and retrieve the information. In combination with textual queries, we have considered computational methods to evaluate the similarity among fragments, according to their geometric appearance, colour, decorations and textures.

Visualisation regards all the classical interaction with 3D data and the visualisation of semantic data, such as metadata and the partonomy scheme. The visualisation of the annotated part on the 3D model has been also included.

Finally, publishing pertains the functionality to create the documentation of the pipeline followed to devise the new findings and the groups of artefacts constituting the new finding itself to be shared among different users of the platform.

3. Design of the dashboard

The dashboard has been designed modularly, offering different *views* focused on specific tasks to be performed; the user is free to switch view at any time, since the dashboard does not impose any pre-defined workflow.

The main window is organized in three main sections (see Figure 2):

- The *tools* on the left; each view has a set of common tools and others that are specific for each view;
- The *main panel*, which occupies the central space of the window; it is different for each view;
- The *clipboard*, on the right: it is a fixed space where the user can temporarily store the items of interest for the current session, or even between sessions. The content of the clipboard is always the same, regardless of the view the user has selected.

In the current design of the dashboard, six views have been conceptualized:

- **Inspection view**: the default view to examine the context and appearance of one or more artefacts in the repository; for each artefact, the corresponding 3D object is displayed along with its metadata. It offers basic graphical interaction functionalities;
- **Fragment view**: the view devoted to the morphological and quantitative analysis, and part-based annotation of a single artefact;
- **ReAssembly view**: the specialised view for ReAssembling an object that has been found fragmented in multiple pieces;
- **Exploration view**: the view for exploring a large repository of multiple collections, using metrics combining geometric and semantic similarity, and a graphical layout designed to facilitate the ReAssociation task;
- **History view**: the view for reviewing the workflow provenance of the actions performed through the dashboard. Such provenance can be used to document the findings achieved in the platform;
- **Groups view**: the view where new groups of objects can be created and saved as "new findings".

The dashboard has been designed so that each view has its own tools. There is, however, a set of default tools, which are common to all the views: they are the *Data* and *Search* tools. These tools usually are invoked at the beginning of any typical workflow for all the ReX tasks.

The *Data* tool is a menu with various options related to loading or saving data:

- **Load last session**: this option restores the interface as it was in the previous session, including the items in the clipboard and those loaded in the views;
- **Load group**: loads in the clipboard a set of objects that has been saved previously through the Group view;
- **Datasets**: through this option, the user can choose from a predefined list the dataset on which he/she desires to work;
- **Browse**: opens a pop-up window where the user is able to browse the selected datasets.

The *Search* tool provides the user with a typical semantic search into the RDF triple-store which collect the documentation of the artefacts of the dataset. Moreover, it includes a geometric query-by-example, which outputs the most similar fragments according to a suitable combination of state-of-the-art descriptors and distances. Currently, we are testing different algorithms and measures to evaluate the similarity of fragments (or of facets), which take into account morphological features and coloured decorations [CRC*02, OFCD02, BCFS15]. At the light of the obtained results, the next step will be conceiving a combination of descriptors tailored for capturing the different types of similarity significant in the presented use case. Such descriptors are computed in batch on the back-end of the platform. Regarding the UI, we have already considered some visualization modalities to support users in content-based retrieval. We intend to let the user personalize the query by weighting some aspects he/she is most interested in and this input will result in a consistent tuning of the combination of descriptors and similarity distances underneath.

Even though the dashboard has been initially designed as a single piece of software, its implementation has been separated in two software components: one is a web-based application, running in a web browser, the other is a desktop application running on the operating system. This choice is naturally driven by the different nature of the functionalities combined in the system: on one side, semantic modelling and similarity of the artefacts; on the other side, the 3D modelling and analysis of the fragments.

Moreover, the current status of 3D web technologies is not mature enough to allow an efficient manipulation of high-resolution 3D models; in fact, in the context of cultural heritage applications, a high-resolution mesh has generally more than 1 million vertices and may even exceed 10 million vertices.

In order to assess the real capabilities of state-of-the-art 3D web technologies, we tested different web-based software packages, such as the THREE.js library and web applications like *meshlab.js* [Cig15]. *Meshlab.js*, currently the highest-performing tool, is able to load correctly meshes up to 4 million vertices. Most of the available tools enables the graphical interaction with large 3D models but cannot manage the mesh manipulation.

Therefore, we had to discard the solution of a fully web-based client in favour of a hybrid solution: a *web client* focused on the search and exploration functionalities, which still offers a basic graphical interaction with downsampled 3D models, and a *desktop client* that is able to load large 3D models and manipulate them according to the requirements described in subsection 2.3.

Communication with the back-end of the platform happens through RESTful [Fie00] APIs. The APIs offer authentication functionality, the access to RDF metadata and the access to the content stored in the back-end repository, which is mainly constituted by the 3D models of the artefacts and related pre-computed properties (see sec. 3.2 for further details).

The back-end of the platform offers a set of geometry processing services that can be run on the 3D models in batch, or upon user request; this design choice allows the platform to integrate algorithms implemented in different technologies and languages, without affecting the development of the user interface. Some tools are currently under development, some other are simply not integrated in the platform yet, and therefore they are not available from the user interface yet. Nonetheless, the desktop client of the dashboard presented in this paper has been fully developed, including the communication of the back-end of the platform.

The Clipboard is present in both interfaces: it is not only a place where the user can put the items that are relevant to his/her ongoing task, but it is also a shared space between the web and the desktop interface. Since access to the Clipboard is provided for both the interfaces through an API, they are kept synchronized during the user's activity: this makes it possible to realise a seamless workflow in the concurrent use of both clients.

3.1. Inspection view

This is the default view proposed to the user, called *Inspection*. The user is able to inspect the 3D fragments included in the clipboard along with their metadata. Two (or more) fragments may be displayed in parallel for a preliminary visual comparison (see Figure 3).

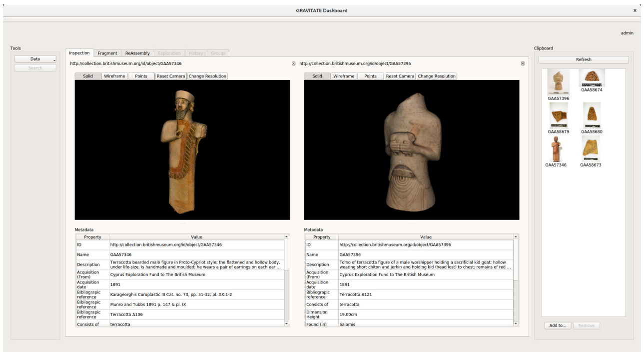


Figure 3: *The Inspection view, with two artefacts visualized side to side.*

Figure 4: *The three available visualization modalities for 3D fragments:* ***solid*** *(left),* ***wireframe*** *(center) and* ***points*** *(right); these modalities are available for all the 3D-related views.*

The 3D visualization panel provides basic graphical interaction functionalities, such as rotating/zooming around the object, and changing mesh visualization modality (solid, wireframe or points, see Figure 4).

The tools in the Inspection view are the default ones. This view is fully operative.

3.2. Fragment view

This view implements some tools devoted to the geometric characterisation and part-based annotation of a single fragment. It differs from the Inspection view in offering a range of 3D model manip-

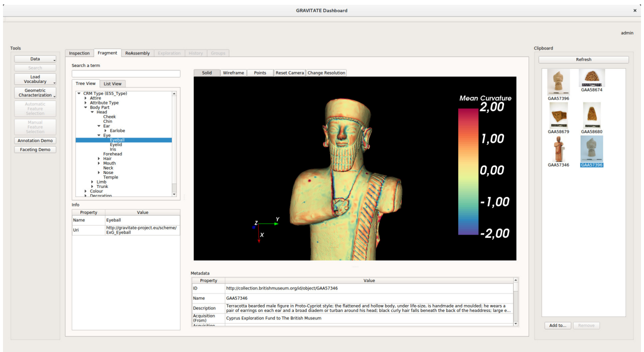


Figure 5: *An overview of the Fragment view interface, with the partonomy tree on the left, and the 3D view on the right*

ulation functionalities, whereas the Inspection view is limited to graphical interaction (see Figure 5).

The specific tools available in the Fragment view are:

- **Load vocabulary**: with this tool the user can load a vocabulary of terms to semantically annotate 3D models (or their parts);
- **Geometric characterization**: tools under this category load and visualize properties pre-computed on the 3D models; the specific properties that can be visualized are described in this section later on;
- **Manual feature selection**: this tool allows for the interactive selection of regions of interest, so that they can be annotated with the vocabulary/partonomy;
- **Automatic feature selection**: this menu activates tools for detecting painted patterns, relief patterns, or specific semantic features (recognisable anatomical parts).

In the project, a partonomy describing the Salamis statues is under development. It is is expressed as a RDF graph in compliance with the CIDOC-CRM [Doe03] and CRMdig [DT11] data model. Morever, it is modelled by means of SKOS, which provides a W3C recommended way to represent knowledge organization systems using the Resource Description Framework (RDF) [MB09, IS09]. Currently, a provisional version of the partonomy is included in the dashboard, which can be browsed by users.

The *Geometric Characterization* family of tools loads and visualizes pre-computed scalar field properties (see Figure 6) calculated on the vertices of the model, such as *Mean Curvature*, *Shape Index*, *Lightness channel* in the *CIELAB* colour space and the *Shape Diameter Function*.

These properties are available in the view and are visualised according to a predefined colour scale and range. It can be noticed in Figure 6 that the ranges are different for each property. The mean curvature is calculated with the Matlab Toolbox Graph package [Pey], which implements the method explained in [CSM03], and it has been bounded in $[-2;2]$; in the case of the Shape Index function, its range is $[-1;1]$ by definition, as explained in [KvD92]; in the case of the lightness property, only the values in the range $[10;98]$ are displayed, since, according to [AKK00], it the most significant range in terms of human perception.

Geometrical properties of relevance for the users include also area and volume; they are stored as RDF metadata, therefore they can be used as search parameters in a SPARQL query and displayed in the 3D canvas.

Another available visualization option is related to the *fragment facets* (Figure 7): they can be visualized with different colours according to their type (internal, external, fracture).

The annotation tool allows to select a region of interest on the 3D surface (either automatically or manually) and annotate it using terms from controlled vocabularies that are made available to the user. The tools for feature selection, both manual and automatic, have been partially implemented in the current state, then they have not been integrated in the dashboard yet.

3.3. ReAssembly view

This view contains a 3D canvas, similarly to the Fragment and Inspection view, and a *workbench*. The workbench is a space where the 2D thumbnails of the candidate items to be reassembled are displayed.

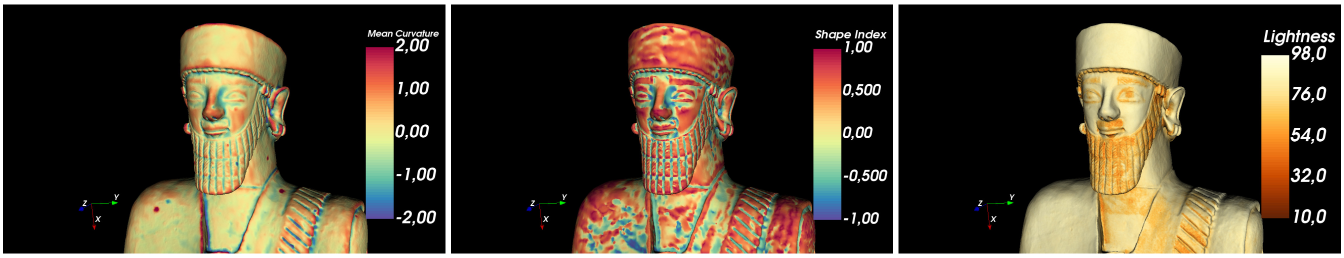
The algorithm that performs ReAssembly of fragments is under development as a back-end service. However, we can outline the design of its user interface.

A ReAssembly workflow typically begins with a search performed by the user in the web interface to identify candidate fragments. The selected ones will be placed in the workbench, where the ReAssembly tool is activated, and the objects are tested one against the other, looking for complementary shapes. At the end of the process, the user decides either to "approve" the pair as a valid *Partial Assembly* or to discard it. After all the possible pairs have been found, the user can run the algorithm on the remaining pieces again, until the object is satisfactorily composed. The user may then store the new object in the repository as a ReAssembly Group (see sub-section 3.6).

A second modality of ReAssembly under investigation make use of a deformable template model. The 3D template is annotated according to the concepts of the statue partonomy and is used as a guidance to find the optimal placement of the fragments in the 3D space, especially in the challenging case where fragments do not match because of missing parts.

The tools that will be integrated in the ReAssembly view are the following:

- **Template**: this tool loads a template from a predefined list; two templates have been considered so far, one for statues and one for vases;
- **ReAssembly**: this tool starts the ReAssembly pipeline described earlier, by considering the objects that have been placed in the Workbench panel;
- **Aggregation by similarity**: this tool aims to cluster the candidate fragments according to specific compatibility proprieties, e.g. thickness, continuity in decoration or colour;
- **Adjust fragment position manually**: a tool for manual adjustment of the ReAssembly result, in case the user does not consider it satisfactory.



(a) Mean Curvature (b) Shape Index (c) Lightness channel (CIELab)

Figure 6: *Visualization of three geometric properties on a sample model*

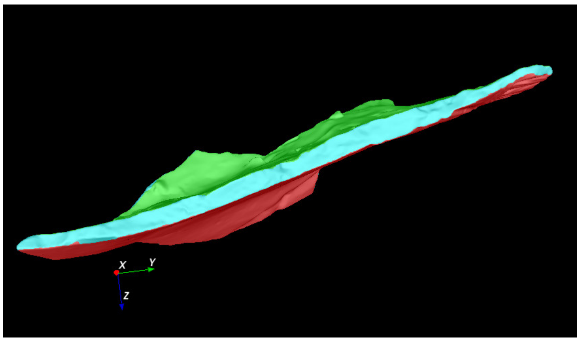


Figure 7: *The faceting visualization of a sample fragment. The* external *facet is coloured red, the* internal *green and the* fracture *facet blue*

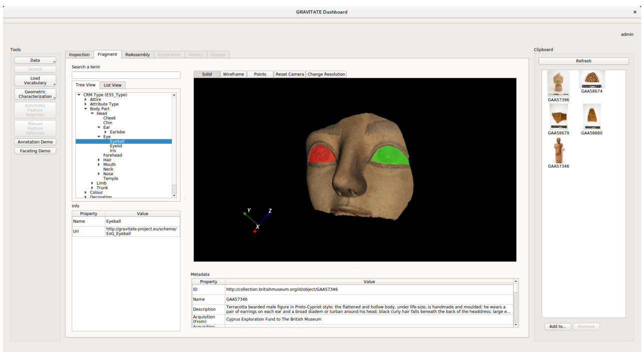


Figure 8: *An example of visualisation of part-based annotation on a sample fragment*

3.4. Exploration view

This view is intended as a modality of exploratory search, in which the user navigates the entire repository by similarity.

The user will combine different similarity measures, by tuning a set of weighted parameters, according to the current ReX task. Such parameters correspond to a combination of semantic and shape descriptors, where the latter are related to the overall geometry, colour and 3D patterns.

This view is currently under development. Being a search-related view, it is going to be implemented in the web-based interface; integration in the desktop GUI has been taken in consideration as a future work.

3.5. History view

The History view has been designed to fulfill the requirement of documenting rigorously the identification of new findings. It pertains the concept of workflow provenance, that is the sequence of steps that brought the user to a certain result. Through this view, relevant parts of history can be extracted out of the user workflow, and reported in a single textual file.

The History view has not been finalized yet.

3.6. Groups view

Once the user has obtained a new finding, he/she has the necessity of saving the work done on the platform.

The name "Groups" derives from the fact that the three ReX activities revolve around the creation of groups of objects; either as part of the same object (ReAssembly, ReUnification) or different objects with shared characteristics (ReAssociation).

Currently, we devised two main types of groups: the generic ones, which are simply sets of objects with common characteristics, and the ReAssembly groups, which are enriched with an additional file describing the spatial positioning of the fragments in a common reference frame.

This view is available and includes tools to **add, modify and delete groups**; groups are by default visible only to the user who created them. Also, it is possible to **add textual notes** to groups, which are meant to enrich the description of a set of objects with additional observations. In order to be shared to other users as a valid research outcome, they should be approved by a user with special rights, named "Publication authority", who is in charge of reviewing the new findings obtained through the dashboard. For this activity, there is a specific tool: **Submit group to the Publication Authority**. Handling the visibility and permissions of groups in order to meet the needs of all institutions involved is not an easy task, and needs to be supported properly by the back-end. For this reason, the design of this specific functionality is not finalised yet.

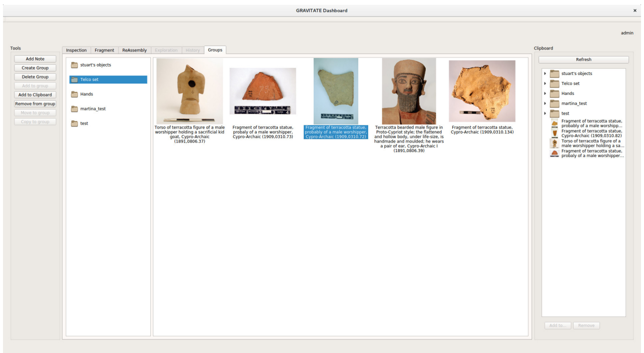


Figure 9: *The Groups view displaying the content of a group.*

3.7. Technical details

From a technical point of view, the GRAVITATE desktop client is implemented in C++, using Qt v5.7 [TQCL] as a GUI library. Qt is one of the most popular libraries for GUI development in C++: it is very complete and feature-rich, and can be integrated with other visualization frameworks, such as VTK. Indeed, we used VTK 7.0 [SLM04] for the 3D visualization, since it is specifically designed for scientific visualization, and it is highly customizable thanks to its modular design.

VTK is able to process large datasets, avoiding unnecessary computations. This is because data processing modules are organized as a set of C++ classes called *filters*, while those responsible to visualize data are called *sinks*. Filters can be concatenated with each other, forming a computational pipeline. The pipeline architecture is highly optimized, since the computation is demand-driven, i.e. data is computed only when some object (filter or sink) actually "asks" for input.

Another advantage of VTK is the great availability of built-in filters, for common processing and visualization tasks. For example, the visualization of coloured properties on the 3D mesh was easy to implement, thanks to the use of the `vtkColorTransferFunction` filter, which is a configurable mapping function between scalar values and RGB colours. The pipeline architecture allows to associate a colour bar to the colour transfer function, as displayed in Figure 6.

The desktop client has has been compiled and tested on GNU/Linux (specifically Ubuntu 16.04) and Windows 10 operating systems.

4. Conclusions

In this paper we presented a software interface, called *Dashboard*, designed to support research in archaeology, with a focus on virtual ReUnification, ReAssociation and ReAssembly of digitized dispersed, eroded, and broken artefacts.

The novel contribution of the paper is the integration of tools for geometry- and semantics-driven analysis of digital artefacts in a unique platform, showcased in the GRAVITATE project. The design of the dashboard was originated by a user requirement elicitation phase, which involved experts with different roles in the CH domain, both internal and external to the consortium.

Currently, the dashboard intended as a UI client is in the final stage of development and a prototype will be available to the public soon. Oppositely, the integration of the functionalities described in this work has been recently started. Nonetheless, user trials of the platform have been already begun in order to test and validate the functionalities, the performance and the integration of the several proposed services and tools according to agile programming principles.

One of the next issues to be tackled will be the separate development of the two web and desktop clients. We expect that the limitations of the web technologies in terms of memory management will be overcome in the following years, and thus some functionalities currently developed in the desktop client will be easily transferred to the web client. There are already few initiatives in this direction, such as WebAssembly [Web17]. It has been proposed by a W3C working group composed of the major web browser vendors, and it is specifically designed to support 64-bit memory address space, and thus hopefully to load and manipulate 3D models of larger sizes, with the same capabilities of a desktop application.

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