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# **Aioli: a reality-based 3D annotation cloud platform for the collaborative documentation of cultural heritage artefacts**

V. Abergel, A. Manuel, A. Pamart, I. Cao, L. De Luca

## **Abstract**

Archaeologists, architects, engineers, materials specialists, teachers, curators and restorers of cultural property, contribute to the daily knowledge and conservation of heritage artefacts. For many years, the development of digital technologies has produced important results in the collection, visualisation and indexing of digital resources. Whilst these advances have made it possible to introduce new tools that are making documentation practices evolve within the cultural heritage community, the management of multi-dimensional and multi-format data introduces new problems and challenges, in particular the development of relevant analysis and interpretation methods, the sharing and correlation of heterogeneous data among several actors and contexts, and the centralised archiving of documentation results for long-term preservation purposes. Despite their different approaches and tools for observation, description and analysis, the actors of cultural heritage documentation all have a common interest and central focus: the heritage object, the physical one, whether it is a site, a building, a sculpture, a painting, a work of art, or an archaeological fragment. This is the starting point for the development of “Aioli”, a reality-based 3D annotation platform, which allows a multidisciplinary community to build semantically-enriched 3D descriptions of heritage artefacts from simple images and spatialised annotations coupled with additional resources. Resulting from more than 10 years of methodological and technological contributions concerning different steps of the workflow starting from reality-based 3D reconstruction to the analysis of cultural heritage data, this platform introduces an innovative framework for the comprehensive, large-scale collaborative documentation of cultural heritage by integrating state-of-the-art technological components within a cloud infrastructure accessible via web interfaces from PCs, tablets and smartphones online and onsite. This paper aims to provide a synthesis of the work done to build it, to describe its main features, and to discuss the limitations and opportunities it raises for cultural heritage studies.

## **Keywords**

Digital documentation, image-based 3D reconstruction, semantic annotation, 3D information system, collaborative platform, cloud computing

## **1. General motivation**

For the last few years, the cross-disciplinary community working on digital technologies applied to cultural heritage has been involved in national and international projects for building next generation tools and information systems for analysing the state of conservation of heritage artefacts, studying their temporal transformations, extracting their morphological features, correlating heterogeneous data coming from several disciplines. Even if the collective enthusiasm for the technological progress is certainly opening new and unexpected opportunities today, with regard to the main role of the documentation activity for cultural heritage (to transfer the current state of knowledge to the next generation), one can easily observe that if the impressive and fast evolution of digital technology in the last decades has produced more and more proficient hardware and software for the automated data acquisition and processing, at the same time, the main actors of everyday production of knowledge on cultural heritage are progressively losing the ability to embed their knowledge in the digital representations of the studied heritage artefacts. Behind this: a diversification of analysis media, a massive data production, the in-situ to ex-situ shift of most part of studies activities, and of course, a well-known data dispersal effect affecting widely heritage sciences. Moving from data-driven to a semantic-driven digital documentation approach is an essential challenge today, especially in Cultural Heritage (CH), where knowledge is always the result of a combination of complementary skills and disciplinary profiles.

This is the main purpose that drives our motivation and the development of the Aioli platform, which is the result of many years of research and the convergence of several contributions concerning different steps of Cultural Heritage documentation processes. This article is intended as a synthesis, and aims to present this work in its entirety, tracing the open issues that motivated it, the key methodological and technological elements on which it is based, and the opportunities, limitations and challenges it raises for the future. In the next few sections, we'll discuss the state of the art and the open issues (section 2), as well as the basic principles of the innovative solution we propose (section 3). Sections 4 to 6 will present the innovative contributions integrated into the design of the platform, while section 7 describes the informatics implementation aspects as well as the ongoing beta testing programme. The last sections present the conclusions and the ongoing and future actions.

## **2. Related works and open issues**

The interest for emerging technologies has inspired many documentation projects in the last few years, these projects demonstrate the potential of digital representation for heritage artefacts at different scales. In particular, the use of 3D digitisation technologies within cultural heritage documentation programmes allows the growing development of a new generation of graphic support, useful for multiple purposes. This state-of-the-art focuses on the relationship between emerging methods of acquisition, observation and multi-dimensional analysis of heritage objects and the renewal of documentation practices for heritage objects. In particular, it seeks to link the evolution of scientific imagery and the management of data for the observation and analysis of CH objects with the recent advances in several scientific areas. This issue crosses two main topics by integrating methodological and technological aspects: reality-based 3D reconstruction and information systems.

### **a. Related works: reality-based 3D reconstruction and 3D information systems**

Reality-based 3D reconstruction is considered a research area based on the use of active range and/or passive image sensors for creating digital replicas of real objects and scenes (Remondino, 2011). Thanks to advances in photogrammetry and computer vision, the last decades have been characterised by an impressive growth of image-based modelling approaches, capable of automatically reconstructing dense 3D point clouds and meshes from sets of non-oriented photographs (Vergauwen and Van Gool, 2006; Hiep et al., 2009; Pierrot-Deseilligny and Clery, 2012; Rothermel et al., 2012). During the last few years, these advances have contributed to the emergence of new competitive open-source solutions (Martinez-Rubi et al., 2017), (Stathopoulou et al., 2019) and to the development of cloud services (Poiesi et al., 2017), (PhotoCatch), paving the way for more flexible and mobile uses. However, beyond the generation of dense and coloured 3D models, the creation of intelligible 3D representations of CH artefacts is a much more complex problem. Research works on this issue are generally applied to architectural heritage, and mainly aim at integrating a semantic description of morphology within its multiple geometric representations, by relying on prior segmentation and classification phases (Grilli et al., 2017; Pierdicca et al., 2020; Croce et al., 2021), or on parametric reconstruction through the joint use of reality-based reconstructions and knowledge models (Gros et al., 2019), (Capone and Lanzara, 2021).

However, beyond the geometric and visual representation of shapes, a large amount of data is usually collected, organised, and analysed for the study of a CH artefact. Some works like (Amat et al., 2013) focus on data management for CH investigations, connecting multi-technique data to a same spatial reference system, even proposing various analysis tools, including annotation ones. But while such approaches are highly relevant, the unstructured nature of semantic descriptions associated with their contents hinders their exploitation. Thus, many methodologies and technologies have been developed to improve the management of linkable digital contents, mostly relying on formal structures describing implicit/explicit conceptual elements and their interrelationships (Doer, 2009). Beyond the pure

theoretical and methodological level, some work focused on methods for linking semantic tags or attributes (vocabulary terms, structured concepts, ...) to orthoimages (Wefers et al., 2016), (Fabiani et al., 2016), or 3D digitisation (Serna et al., 2012; Yu and Hunter, 2014; Poux et al., 2020), as well as for inserting the results of a 3D digitisation within the Building Information Modelling (BIM) paradigm (Bruno et al., 2018).

But reality-based 3D reconstruction and 3D information systems are still generally considered as distinct topics. Few projects consider them as complementary parts of a unique framework even if using very different approaches. On one hand, works on the management of the documentation activities (Blaško et al., 2021; Boochs et al., 2014; Niang et al., 2017) are mainly knowledge centred, with no explicit or direct exploitation of geometric and/or visual properties belonging to 3D representations. On the other hand, recent works on 3D annotation of reality-based models (Soler et al., 2017; Garozzo et al., 2017; Wang et al. 2018; Apollonio et al., 2018; Yang et al., 2020) are mainly object-centred and miss references to the complex relations that shape the documentation and interpretation process, in a highly pluridisciplinary context where differences in observation scales, interests, vocabulary, work habits, ... require a major structuring effort to bring individual knowledge onto a common intelligibility framework and to enable its processing and analysis.

Some works intend to link both paradigms, like (Catalano, 2020) which proposes part-based annotation systems describing morphological and semantic features of artefacts or (Catalano, 2017) which aims to combine semantics and geometry through a CIDOC CRMdig extension. But, aside from a few explorative approaches such as (Scalas et al., 2020), 3D annotation methods are mainly constrained to pre-processed, static, and non-scalable representations of the study objects, which considerably restricts the opportunities in CH study contexts, which require continuous informational input.

#### **b. Open issues on observation and analysis means: between technology and methodology**

As explained in the next sections, our main purpose is to merge all these aspects (geometry, visual appearance, semantics) within an integrated documentation approach built on an informative continuity merging the acquisition, analysis, and interpretation phases within a collaborative framework. This corresponds to three major gaps.

- **The semantic gap.** The growing diffusion of flexible and easy-to-use 3D digitisation tools allows envisioning the opportunity to build, in a collaborative way, a large digital library of reality-based 3D models of heritage artefacts. But, if the development of machines (Santos et al., 2017) or the implementation of crowdsourcing strategies (Vincent et al., 2015) for the massive gathering of digital representations of CH objects is to become a realistic perspective, the growing mass of un-interpreted point clouds and 3D models is today underlining an essential need for innovative methodologies for assisting **data processing, sorting and analysis** towards effective knowledge-enhancement scenarios.
- **The communication gap.** The use of digital tools today is included in more and more consolidated observation and analysis protocols according to various aspects of a CH artefact (history, conservation state, management, dissemination, ...) belonging to several scientific and professional areas. This underlines the need for an effective solution for **collecting, storing, and sharing data and extracted information**, while it's still difficult to bring together (physically or digitally) the multiple actors of this continuous documentation process. Of course, semantic annotation specifically aims to address this problem and ease communication, either among humans or with machines. However, the above mentioned methodological and scientific open issues raised by existing systems (see section 2a) still hinder the democratisation of such

practices among CH communities, and incidentally, of collaborative work leading to an efficient sharing, multi-thematic enrichment, and interrogation of digital data. It is especially the case when the end-users can be experts in one or more domains of CH but without necessarily being familiar with the core principles and technological keys of 3D heterogeneous data manipulation.

- **The interoperability gap.** Structuring heterogeneous data belonging to the same heritage artefact still remains a critical issue today: if on the one hand, file-centred approaches use unstable “anchors” (metadata, terminology, conceptual reference models, ...) for establishing semantic links between digital resources belonging to the same physical object (Ronzino et al., 2011), (Pitzalis et al., 2011), (Lo Turco et al., 2019), (Salse et al., 2022); on the other hand, all the 3D-centred approaches presented above (also including our previous works) are limited to the adoption of static representation, sometimes with a pre-established segmentation that strongly constrains the data structuring strategies. Some works like (Catalano, 2020) or do aim to reconcile these two main approaches. They benefit from 3D and provide very promising functional solutions for CH study, but the management of three-dimensional properties and the descriptive models associated with the observations usually focus on very specific cases study and do not provide the genericity required to accommodate the great diversity of CH communities' interests and backgrounds. This underlines the essential need for a highly flexible solution allowing to **manage several acquisitions, temporal states, levels of detail, geometry segmentations, annotation layers and data properties according to very heterogeneous observation and analysis scenarios.**

### 3. Basis principles and innovative contributions

All this context finally highlights a central issue for which our contribution introduces an innovative solution: the need for a stable denominator (from a conceptual and technical point of view) for structuring data and annotations coming from a continuous process of observation and analysis carried out by multiple actors (with different profiles and description approaches). Our starting point is that archaeologists, architects, engineers, material specialists, curators and restorers, teachers, students and tourists, all produce various valuable observations regarding a heritage object, which is probably the unique denominator able to cross actors, observation means, description models, mapping technologies, ... Thus, our approach puts the heritage object (the physical one) at the heart of the documentation process by considering reality-based 3D and semantic descriptions in a strongly integrated way. By correlating simple images (probably the most stable support for registering field observations since the invention of photography), our platform generates a dynamic 3D morphologic scaffolding for structuring data and annotations. At the same time, this data structure becomes a way of enabling communication between several actors involved in the documentation and the study of the same object. This is made by interlinking all phases that characterise the overall documentation process within an ‘informative continuum’ by combining three essential features (Fig. 1):

- A continuous 3D mapping and annotation process. Our approach creates a sort of bridge between the real object and its digital representation by introducing a solution for memorising spatialised annotations made by different actors.
- A morphology-based documentation framework. Based on a spatial overlapping factor, our multi-layers description model allows the simultaneous structuring of data and geometry as well as the continuous correlation of semantic annotations (with relative attributes).

- A flexible and scalable technology. Our platform is built on a cloud computing service allowing the gathering, processing and sharing of semantically-enriched 3D data within online and onsite documentation scenarios.

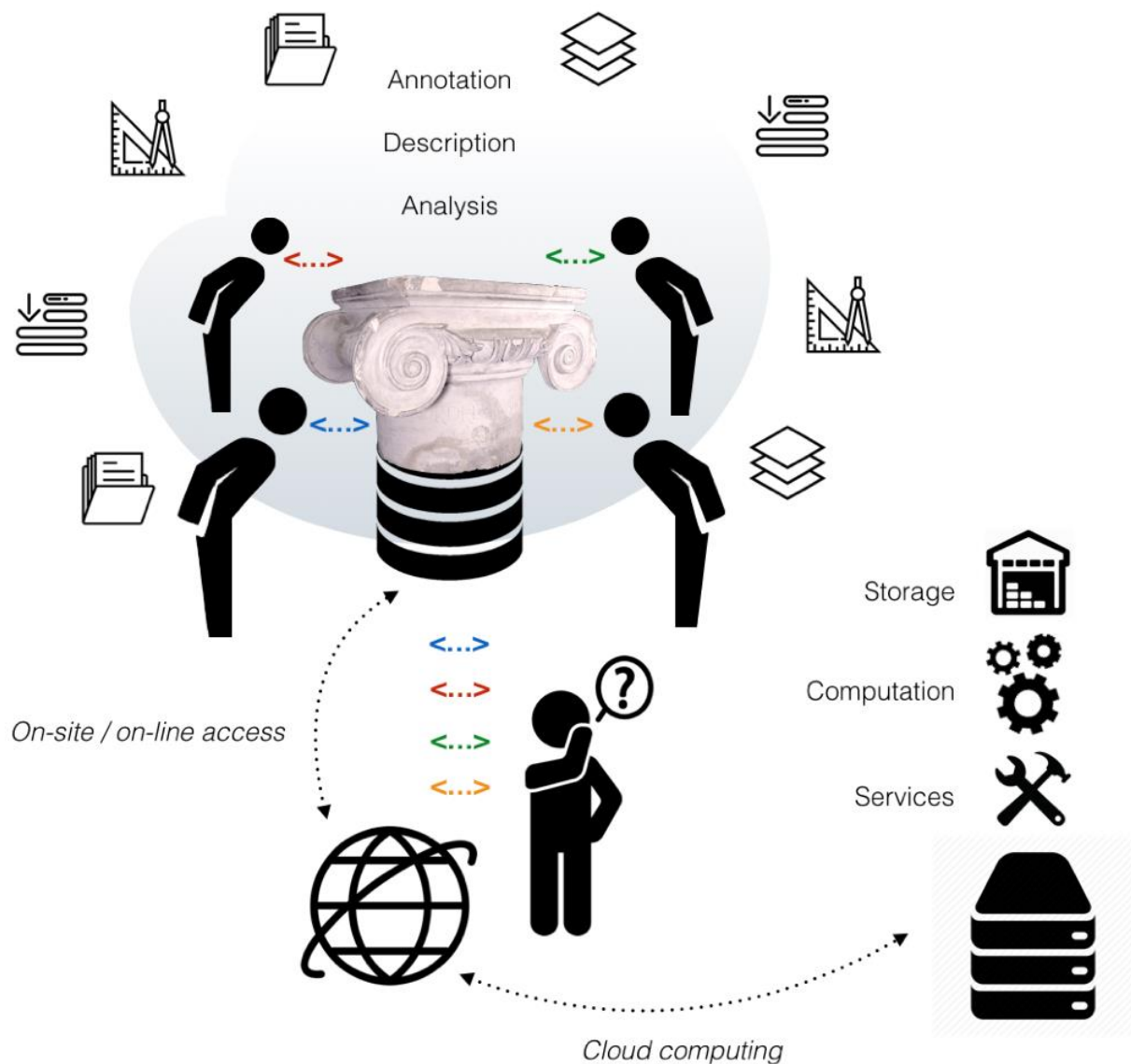


Figure 1: Schematic representation of the framework introduced by the Aioli platform.

Although we had already discussed some aspects of this ongoing research in the past (incremental spatialization, annotation propagation, or automatic annotation approaches (Pamart et al., 2020; Manuel, 2016; Manuel et al., 2018)), the joint integration of all the parts of the complete pipeline within the very same platform had never been addressed and remains quite challenging. Hence, the aim of this paper is to present a synthesis of the work that led to the construction of the Aioli collaborative platform and the state of our progress to date. In addition, new contributions concern the design of the system architecture, the definition of its main functionalities and their ergonomic and technical articulation in relation to potential use scenarios. Compared to state of the art presented in the previous section, our system introduces an original informative linkage between the physical object space and its digital representation by covering two interconnected technical issues: firstly, the onsite retrieval of structured information according to the physical object's annotation; and secondly, the onsite collection and processing of new data to be spatially referenced and semantically correlated with previous data. This is achieved by integrating the following features:

- An incremental image-based 3D spatialisation process to manage the geometric merging of several images coming from different actors at different temporal states.
- A 2D/3D annotation framework enabling users to draw, visualise and register relevant surface regions by handling simple 2D images spatially oriented around a dynamic 3D representation.
- A multi-layered morphology-based data structuring model to accurately describe real objects in all their geometric complexity and according to multidisciplinary observations.

In the next sections we provide concrete details on how we tackled these central and interrelated issues in order to develop the Aioli platform, then we present its technical implementation (section 7).

#### **4. A robust and versatile image-based 3D spatialisation process**

Since its earliest development, Aioli has relied on photogrammetric based methods for the 3D reconstruction of the object along with the computation of camera positions. The goal of a web-based platform and collaborative expectations imply many issues to reach satisfactory results in terms of versatility, robustness, scalability, and accuracy in order to compromise between all of these constraints within a fully automated pipeline. Despite the progress made in automation for Image-Based Modelling (IBM) method, it is not an easy and trivial task to ensure a generic yet reliable reconstruction while the input is mostly unknown and user-dependent. This is especially true for Cultural Heritage applications with a very high variability in terms of scale, complexity, material to be addressed for efficient IBM. In this context, a dedicated library has been developed to benefit from a Totally Automated Co-registration and Orientation (TACO) process extensively described in a past publication (Pamart et al., 2020). This photogrammetric engine of Aioli is currently based on MicMac while inter-operatives are under development to bridge TACO with other Structure-from-Motion (SfM) FLOSS solutions (Open-MVG, AliceVision, COLMAP). From a computational point of view, TACO is an algorithm aiming to solve a 2D to 3D image registration by modulating key parameters into an iterative-recursive script for each photogrammetric steps or sub steps (feature extraction, image matching, internal and external calibration) to maximise the chance to end with a successful solution.

TACO consists of different modules to generate an initial scene or to orient new images on existing data sets (respectively detailed in the next subsections). This *initial* reconstruction pipeline is fully implemented and operative in the current version of Aioli while the *incremental* integration is planned but raises many technical and methodological issues to Aioli's. So far, TACO has performed with promising efficiency (balance between, accuracy, robustness and computation time) from two to almost a thousand pictures on various type of CH oriented case-studies thank to its ability to handle multimodal dataset (multi-sensors, multi-temporal, multi-scale, multi-band, ...).

##### **a. A fully automatic 3D reconstruction pipeline**

Photogrammetric computation is widely described in the literature but its implementation in remote-computing web platforms can cause problems considering the size and quality of input data remains variable and unknown. TACO is initialised with optimum parameters which are sufficient for most common and photogrammetric-friendly data sets. However, in automated photogrammetric processing, sources of issues are numerous (image quality, lack of overlapping, lack of texture, suboptimal camera network, ...). Beforehand, TACO analyses images and their metadata to adapt the processing strategy (numbers of pictures, missing exif, use of fisheye lens, use coded-targets). Firstly, image matching is performed in optimal resolution that will be increased in next iterations if camera orientation fails. Secondly, it tries to resolve camera calibration by solving separately or simultaneously extrinsic and intrinsic parameters with demanding camera model (10 parameters) decreased iteratively. If camera orientation remains unresolved, TACO starts a new iteration until a given number of

combinations have been tested. In case of image set containing coded-target or if the upload Ground Control Point data, a global orientation is performed to orient consistently the scene according to the coordinates reference points given. Then, a sparse point cloud and camera positions are exported separately for the Aioli viewer. Finally, a point cloud is generated using MicMac's automated dense matching method (Fig. 2).

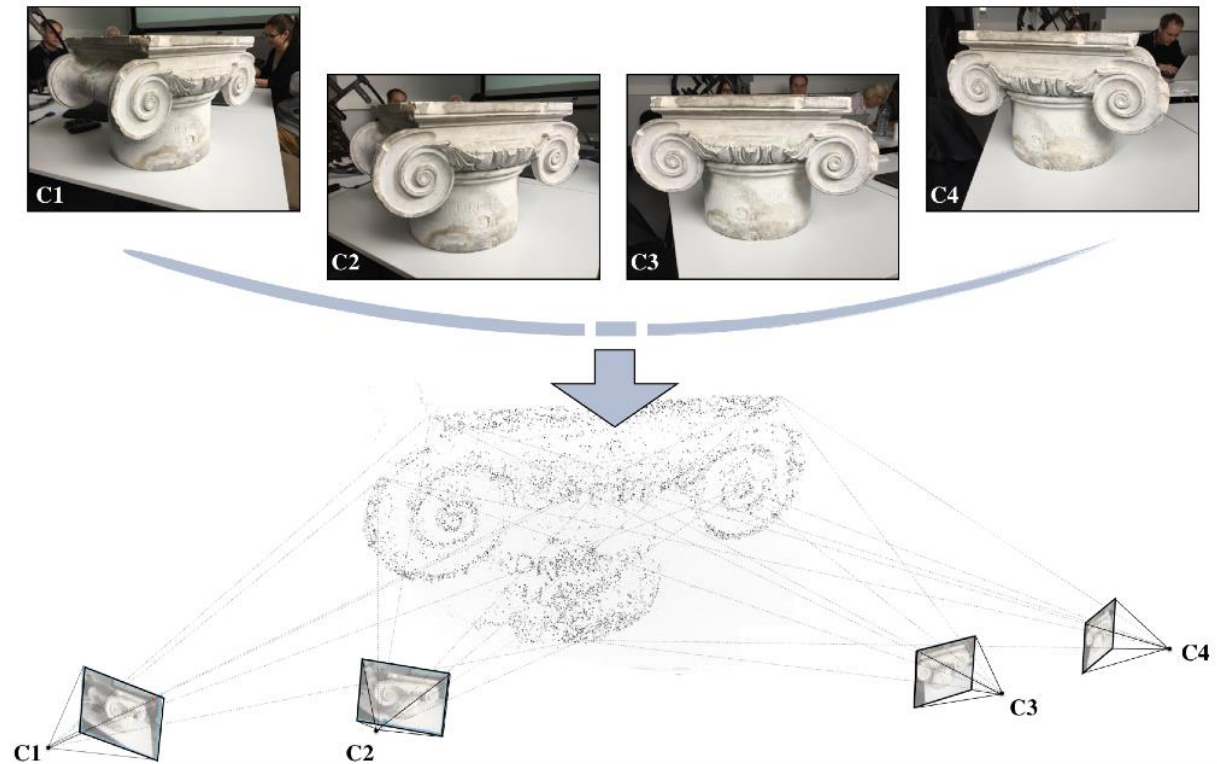


Figure 2: Results of the first image 3D orientation process.

#### b. Incremental orientation of further images to an existing image set

As a matter of fact, Cultural Heritage scenarii exploiting real-based modelling are no longer straightforward and one-shot applications performed by a single actor or institution. They usually imply different experts documenting using different modalities or techniques the same heritage asset over the time to enrich its documentation. Once a 3D scene is created, for the collaborative expectations of Aioli one user might want to enrich this initial capture with new resources from a new acquisition campaign or an old photograph revealed from archives. In this context, the incremental module of TACO will support the spatial registration of new images to an existing oriented dataset (Fig. 3). This module shares and exploits the iterative-recursive strategy because the possible deviations in terms of quality, resolution, overlapping region, temporal changes between the two datasets stand as many potential sources of issues. The TACO-based co-registration to be implemented within Aioli will combine two sub-modules.

The *incremental* one tries to solve several camera positions on a conventional bundle adjustment-based method and is dedicated to photogrammetric sequence with reasonable deviation (as long as a minimum threshold of tie-points enable to orient the new pictures among the oriented ones). A surrogate *resection* sub-module is dedicated to high deviation and isolated pictures. The spatial resection mode is less accurate than the bundle adjustment but can theoretically compute a camera position from a minimum of 6 points with known object coordinates (derived from a Direct Linear Transformation method available in MicMac). To the condition that the dataset from a new iteration has enough overlap with the previous ones TACO has demonstrated interesting spatial registration performance for a wide range of scenarios (Pamart et al., 2019, 2020; Abergel et al., 2021). The main



condition for the spatial registration efficiency is thus related to the global correspondence and the photogrammetric consistency (i.e., spatial and resolution gaps, spectral or radiometric deviations, temporal or contextual variations) between the calibrated pictures with the further new ones. At the current stage of development and for Aioli computational requirements (because it will affect indexation and propagation) new poses are calculated without refining with previous ones that remain frozen. Indeed, from a technical point of view those incremental features combined with automated remote computing processing needs raise several accuracy and qualitative control issues. Moreover, data fusion issues must be addressed because the geometry resulting from multi-source processing also require a special care while variable uncertainties through iterations (possible gain or loss of accuracy, density or completion) could affect the quality of the updated dense point cloud which is a primal source for Aioli's semantic annotation framework.

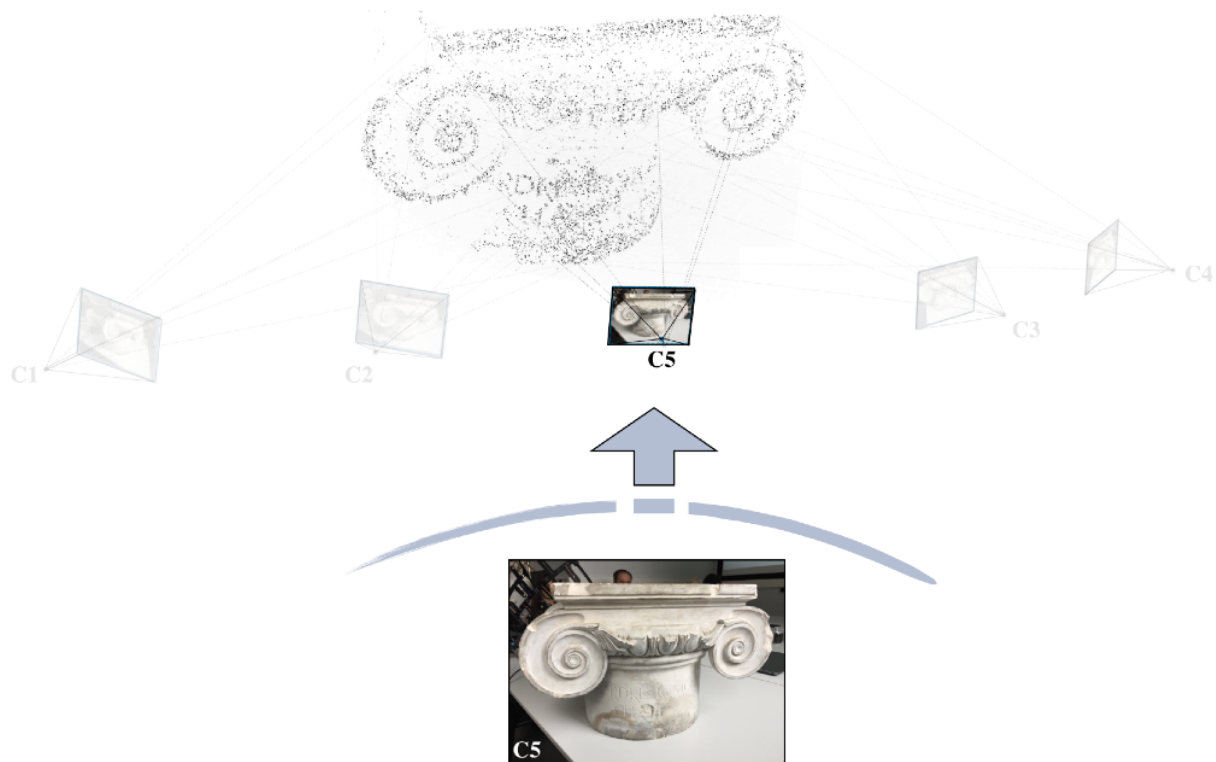


Figure 3: Example of spatial registration of an additional image on an existing image set.

### c. Interoperative features

In order to anticipate the above-mentioned issues, export and import functionalities have been recently integrated into Aioli's workflow. Those features allow users to save an Aioli project to prevent potential regression from a mismatched or erratic iteration that could corrupt an initial scene integrity and accuracy. Beyond the import of a complete Aioli project, this function also provides interesting perspectives as it allows importing a pre-computed or recomputed dataset (images, oriented images and corresponding point cloud) in MicMac compliant format. It enables to cope some TACO limitations to let MicMac users import any kind of complex or large dataset, overpassing the need to process it using TACO photogrammetric engine. More recently, to extend those benefit to a wider community, a Python script has been developed to convert through Agisoft MetaShape API a project from this user-friendly commercial solution to make it importable directly into Aioli. Thanks to those features, Aioli gains in flexibility and intends to make semantic enrichment open to a broader audience and scenario.

## 5. The 2D/3D reality-based annotation framework

### a. Definition of a 2D/3D projective relationship based on image indexation

By establishing a stable relationship between a real object and its reality-based 3D digitisation, our platform allows users to create 3D annotations by simply annotating 2D images. This stable relationship is produced by a “2D to 3D to 2D continuous propagation mechanism” based on the linking of image’s coordinates with the corresponding 3D reference space, by means of a hybrid (2D/3D) indexation process. At the end of the initial image spatialisation process (see section 4.a), the dense 3D point cloud is first indexed, then reprojected on the initial 2D images (as well as on further images added to the scene), by exploiting the computed camera’s calibration and orientation parameters. Thus, for each image, an array is created for storing indexes of the 3D points corresponding to the projected pixel. During this process, some geometric descriptors (normals, curvature, ambient occlusions, ...) of the 3D point-cloud are also computed, coded in colormaps, then reprojected on the original images (Fig. 4). These image layers then become alternative supports for the object observation and interpretation, as well as for the annotation process.

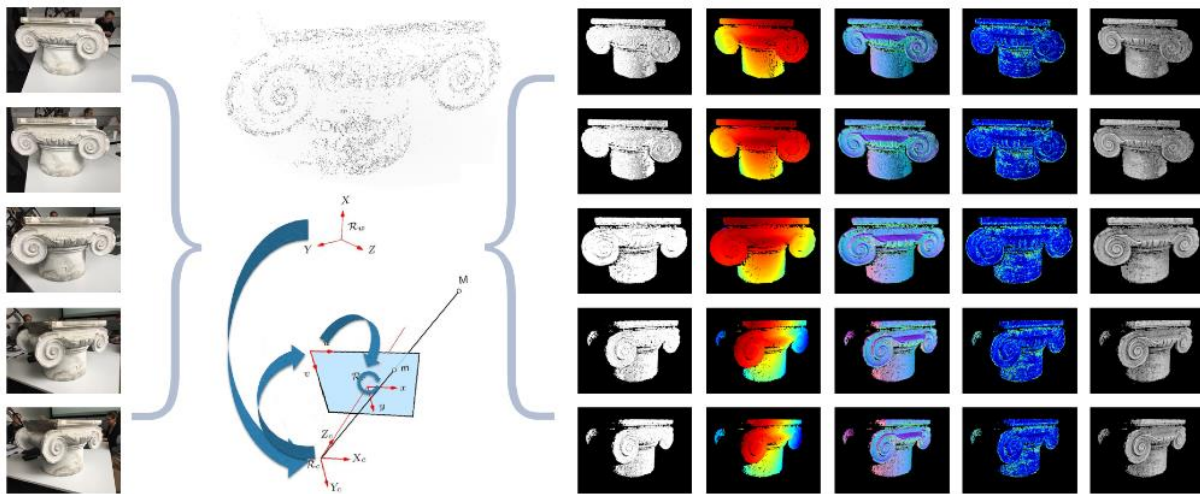


Figure 4: Geometric properties computed during the 3D point cloud indexing process reprojected on the original 2D images. From left to right: original image, 3D indexes mask, depth map, normal map, curvature map and ambient occlusion.

The above mentioned 2D/3D indexing process generates a data structure allowing us to easily switch from 2D to 3D coordinates and inversely. Then, any selection of pixels on an image (points, lines, regions) related to interest areas can be automatically translated into its corresponding 3D or 2D projection, and thus propagated to all other 2D and 3D resources on which it is visible. To do that, after the selection of 2D region, a list of 3D indexes is extracted from the used image, then mapped with the main 3D point cloud array and finally compared with those belonging to all the images on which the selected region is visible. The selected spatial region is then accurately located in the 3D space as segmented point-based representation, as well as on all 2D images as vector-based representation (Fig. 5). This method has been introduced on (Manuel et al., 2016).

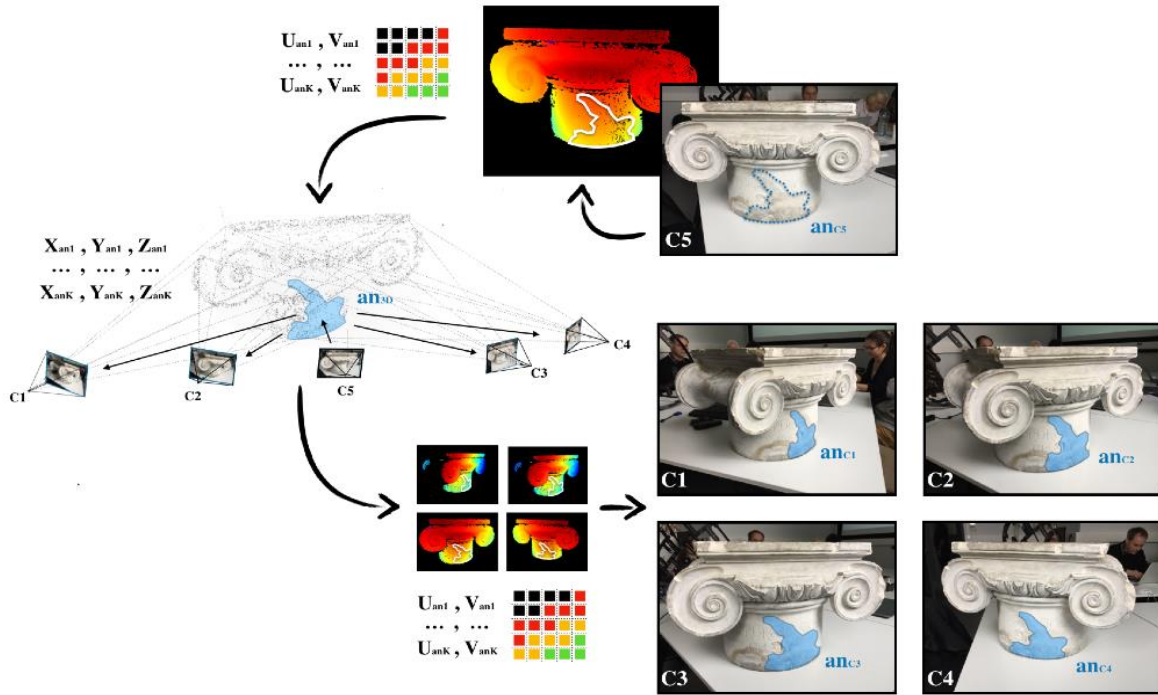


Figure 5: The 2D/3D hybrid annotation process. Above, the annotation drawn on an image and projected in the 3D point cloud. Below, the results of the automatic propagation method.

### b. 2D/3D hybrid annotation process, method and tools

The main advantage of this propagation method is its independence from the modalities employed for a region's selection. Thus, the selection of an image interest area could be determined by several methods, be it manual, automatic, or semi-automatic.

In the first case, we simply must recover contours directly drawn by the user on the images in order to isolate regions. In the automatic case, we considered the use of automatic segmentation of images or 3D point cloud to define regions on images or on the point cloud that could be directly propagated. On point cloud, this approach has been validated during some experimentations on a plane segmentation detailed in (Manuel et al. 2018). We also experimented a simple KMeans segmentation on point cloud by using either RGB values or normal values as input (Fig. 6).

		POINT CLOUD	IMAGES			
			ITERO_1.JPG	ITERO_3.JPG	ITERO_5.JPG	ITERO_7.JPG
KMEANS SEGMENTATION	RGB					
	NORMALS					
ORIGINAL DATA						

Figure 6: KMeans segmentation projections with 3 clusters.

In the last case, different scenarios can be considered. One is to simply define a ‘magic wand’ selection on images by exploiting the computed geometric properties reprojected onto images, i.e., to automatically select regions starting from a reference pixel and a tolerance value selected by the user (Fig. 7). This method could be used either on RGB images or any images of projected geometrical descriptors (normal, curvature, ambient occlusion, ...).

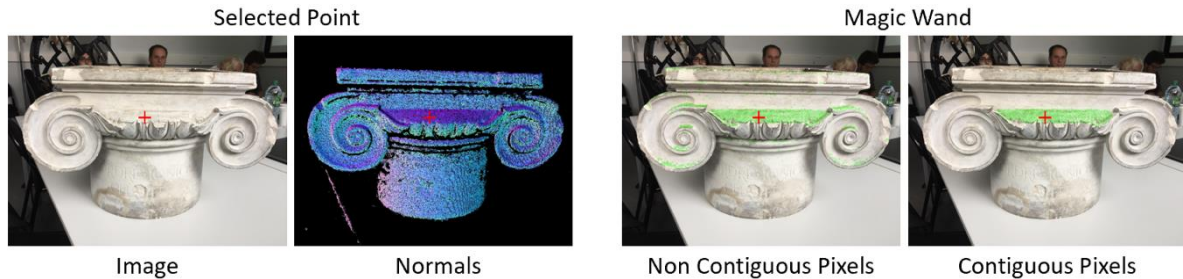


Figure 7: MagicWand on Normals values with threshold = 50.

Another semi-automatic scenario would rely on the use of supervised machine learning segmentation. The aim would be to define some manual regions with Aioli that could serve as training sets for the segmentation process. We are currently experimenting this approach with the random forest algorithm. In addition, as our annotation framework allows to easily translate the result of a selection from 2D to 3D and vice-versa, we are currently testing some mixed 2D/3D approaches to provide users with pre-segmentation layers (in 3D and in 2D) aimed at enhancing the annotation process. In this case, our goal is to provide the user a large panel of segmentation algorithms aimed for different use cases that would be implemented as plugins on the platform.

### c. Re-projection of existing annotations on new images

As explained in section 4.b, new images can be oriented towards an existing dataset. At the end of this process, the orientation and the calibration parameters are estimated for these new images. Thus as described in section 5.a, new oriented images could be indexed relative to the already-generated 3D point cloud, then included in the 2D/3D annotation framework. In this way, when new images are added to a scene, the existing registered annotations are automatically re-projected onto them. Moreover, new annotations can be drawn on the recently added images and propagated onto the entire image set.

## 6. A multi-layered morphology-based data structuring approach

### a. A flexible data model for managing a wide range of application scenarios

In order to cover the potential range of applications (surveying, archaeological analysis, diagnosis, documentary studies, dissemination, ...), we first defined a generic data model whose main elements are listed below:

- A *Heritage Asset* corresponds to a physical cultural heritage artefact (archaeological site, historic building, furniture, archaeological fragment, ...). It is associated to *actors* and *projects*.
- A *project* is a subset of a *heritage asset*, which covers an area of interest of the considered artefact regarding a specific application. A *project* includes an *acquisition dataset*, *layers* and *regions* documented by *description sheets*, and is associated with one or more *actors*.
- An *acquisition dataset* is a set of pictures exploited by the spatialisation processes to provide a basis for the hybrid 2D/3D annotation of the considered heritage artefact.

- An *actor* is a person involved in the analysis of a heritage artefact, likely to produce semantic annotations through the prism of his field of expertise.
- A *region* corresponds to the spatial delimitation of an observation made on the object of study. *Regions* belong to thematic *layers* defined by the user to structure the information contained in a *project*.
- A *description sheet* is a set of fields allowing to link information to the project data through *regions*. Freely structured, the nature and content of the descriptors that compose them are defined by the *actors* according to the needs raised by their various knowledge areas (see section 6.c).
- A *semantic annotation* is the association of a *region* and a *description sheet*.

### **b. Data structuring approach**

The central question at the basis of the definition of our data structuring approach is: how to effectively record multiple scientific observations made on a heritage artefact overtime? This corresponds to building a formal representation of the interactions between the produced data, the extracted information and the mobilised knowledge coming from several actors on the basis of the generic model described above. Taking into account both quantitative and qualitative aspects, our structuring approach consists of an interconnection of three layers around the reality-based 3D annotation framework (Fig. 8):

- The *semantic layer* integrates and organises the set of freely structured user descriptors to designate specific aspects of a heritage artefact according to specific application contexts (archaeology, conservation, restoration, maintenance, historical analysis, management, ...);
- The *morphological layer* brings together computed geo-visual descriptors resulting from the extracted 3D spatial regions to enrich user descriptors by complementary aspects needed for geometrical and statistical analysis purposes.
- The *spatio-temporal layer* explicits the relationships between the acquisition / spatialisation of 2D images and the annotation / segmentation of 3D data overtime. It constitutes the framework for the analysis of the spatial and temporal distribution of annotated qualitative (*user descriptors*) and quantitative (*computed descriptors*) aspects.

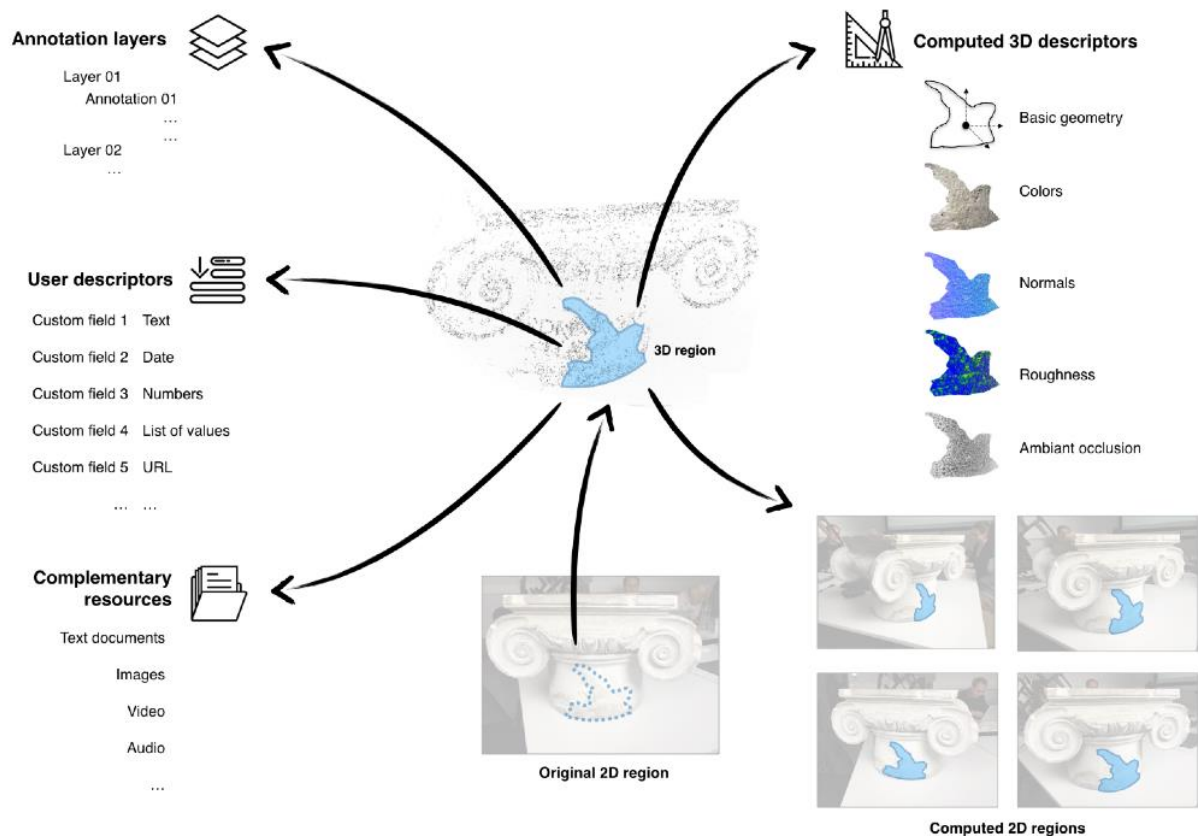


Figure 8: The multi-layered data structuring approach. On the left: the semantic layer. On the right: the morphological layer. At the bottom-right: the spatio-temporal layer.

On the computer side, the nature of the entities represented in the above-mentioned descriptive layers is quite diverse: i) free text, vocabulary terms, numbers, dates inserted by the users during the annotation process for the *semantic layer*; ii) compact representations of geometric and visual features (mean values, colour palettes, ...) computed on property maps for the *morphological layer*; iii) Parameters for the spatial and temporal referencing of annotation supports (collection of images) and their relative annotated regions for the *spatiotemporal layer*.

Aioli's data model allows to store, for each annotation ID, the raw data of the drawing (path, image(s) used as support, image and 3D scene parameters if applicable), in an attempt to keep track of the user's intentions. In addition to this, we store the contours of the reprojected region on each image of the acquisition dataset, the list of the region's 3D points indexes, all the user entries and complementary files describing it, and the computed geometric and visual attributes. Of course, alone, the joint storage of calculated descriptors and vocabulary terms associated with a given region by no means would suggest a direct link between semantics and appearance (e.g. the fact that a region described as a 'moisture' alteration is associated with a predominantly green colour palette would be absolutely insufficient to rule on a possible link between these phenomena), but on a large collection of annotations made by a same community, it becomes possible to carry out a more in-depth analysis and to investigate possible correlations.

Concerning interoperability aspects, it seems essential to comply with standards. The W3C annotation model could be flexible and generic enough to be suitable for the particular case of Aioli's instantiated 2D/3D annotations. However, this model doesn't allow to document the spatial reference system and geometric projections used to link Aioli annotations to their supports. The first IIF 3D Technical Specification Group recommendations, expected in 2025 and better suited to the specificities of 3D data, should provide some answers. In the meantime, we focused our efforts on the mapping of Aioli classes and attributes with the CIDOC CRM and its extensions, in particular CRM Dig (see section 7.b).

All the annotations can still be freely exported in JSON (semantic descriptions, 2D paths) and PLY (annotations point clouds) formats.

This structuring model is designed to meet the needs of a multi-layered description (multiple actors and applications) that unfolds over time and includes three broad categories of processes, described in Table 1 by distinguishing the user and the platform sides.

Process	User side	Platform side
The 3D spatialisation of annotation supports (2D images)	The user takes simple 2D images to record aspects of his observation of the CH object	The platform recovers 2D images, then spatialise them within the reality-based 3D representation of the CH object
The recording of annotations linked to qualitative and quantitative descriptors	The user draws simple 2D entities (points, lines, regions, ...) on the captured images, then he adds textual content (vocabulary terms, numerical values, comments, ...) belonging to the designated entity and according to a given annotation layer.	The platform ensures the propagation of the 2D drawn annotation on the reality-based 3D representation and on all the related 2D images, it computes geovisual descriptors, then it links the computed spatial region to the user descriptors.
The addition of complementary resources to enrich the description and / or to justify the choice of designation	The user associates complementary files (text documents, images, videos, sound) to the created 2D annotation.	The platform recovers and stores the added files, then it links them to the barycenter of the computed 3D region and relative 2D projections.

Table 1: Three main processes managed by our system described by distinguishing user and platform sides.

### c. Correlating user and computed descriptors on multi-layers annotation structures

Thanks to the features concerning the 3D spatialisation process and the 2D/3D annotation framework, a simple annotation drawn on an image (taken by digital camera, smartphone or tablet) by the user generates a complex data set describing the annotation within its spatio-temporal and morphological layers, plus a flexible data container to be enriched by customisable user attributes.

On the *spatio-temporal layer*, a set of *data* describes the inserted image, its spatial (results of pose estimation) and temporal (acquisition time) location. The annotated region inherits spatio-temporal attributes from the oriented image (in order to store the precise conditions of the annotation context), then it is described by basic attributes extracted from point-based 3D representation: translation, main orientation, scale. These attributes are provided as absolutes (with regards to a metric reference unit defined within the programmatic process) or relative (compared to the overall 3D point-cloud) values for classification purposes.

On the *morphological layer*, the drawn annotation is described by a set of attributes synthesising the results of the computation of geo-visual descriptors on the segmented 3D region. Beyond the basic geometry attributes (stored in the spatial layer) the 3D region extracted by the 2D annotation is characterised by colour, normal, curvature and ambient occlusion attributes, represented as mean values, palettes (10 representative values + relative rates) and complete maps.

On the *semantic layer*, the annotated region is linked to a flexible data container that the users can customise according to their description needs (by avoiding rigid descriptive sheets). User descriptor fields can be defined as text, numbers, currency, dates, hyperlinks, memo. Users can also add file attachments (documents, images, videos, audio) to any annotation. Values can be freely entered by the user on automatically generated forms. The free-text description fields can be analysed by text mining approaches for an entity-based recognition and associated at a data level with the type of annotation. However, collaborative projects mean multiple actors that each have their own semantic specificities rather it is related to their domain or natural language. Controlled vocabularies are one solution to this terminology variation that can cause misunderstanding between collaborators and data indexation confusion. The use of controlled vocabularies in Aioli allows to assign types to annotations and help users describe them, thus overcoming problems related to lexical disambiguation by promoting the consistency of terms.

The integration of controlled vocabularies is done through a connection to OpenTheso, a web-based multilingual thesaurus management tool (Rousset and Nouvel, 2014). Conforming to ISO 25964-1 2011 (ISO 25964-1 2011) and ISO 25964-2:2013 (ISO 25964-2:2013) standards, it offers tools to create, insert, and manage thesauri in SKOS and also a complete REST Webservice. In Aioli, a portable and lightweight component dedicated to the visualisation, search, and term selection allows to browse an entire thesaurus hierarchy directly when annotating the scene, and display information about a selected term (e.g., its notes and relations). A word autocomplete function helps the user to enter thesaurus terms. Thus, each annotation can be linked to one or several concepts stored in OpenTheso, through a URI in a thesaurus field type.

Moreover, several controlled vocabularies have been collected and integrated into OpenTheso, especially identified vocabularies from Cultural Heritage that are known and used by the different actors in the domain, in order to reuse it in the Aioli platform and for the description of data using thesauri. Some of these were already in the form of thesauri, such as the vocabularies of the French Ministry of Culture (MC) and the Analysis and examination techniques from the PARCOURS project (Niang et al., 2017). For other glossaries it was necessary to transform and adapt them to the SKOS model (W3C) as for the 3D Vocabulary - Lexicon for the Humanities and Social Sciences, from the French Consortium 3D SHS (Granier et al., 2019), the ICOMOS-ISCS Illustrated glossary on stone deterioration patterns (Vergès-Belmin, 2008) and the EwaGlos - European Illustrated Glossary of Conservation Terms for Wall Paintings and Architectural Surfaces (Weyer et al., 2016). Thus, attention is paid to the restitution in the SKOS encoding of all the information concerning the terms of the glossary while respecting the integrity of the sources. Using the OpenTheso alignment module allows concepts to be semi-automatically aligned with thesauri collected in the same instance but also with external controlled vocabulary such as the Getty vocabulary Art & Architecture Thesaurus (AAT) or large semantic network e.g., Wikidata. In this way, the different vocabularies used by one or more Aioli projects are linked to each other through SKOS alignment properties (*skos:exact/related/close match*) in order to make them interoperable and facilitate data integration.

Data structured around the same annotation are linked to an *Actor* belonging to an analysis driven on a *Heritage asset*, and can be always used for correlation purposes. In fact, 3D regions belonging to different annotation layers (and potentially to different *Actors*) can partially share the same spatial region on the real object (e.g., an annotated region concerning a figure on a bas relief could overlap another annotation region concerning a degradation phenomenon, and so on ...). The spatial



overlapping between annotated regions belonging to different annotation layers is then used as primer for the correlation process. This action is embedded into the 2D/3D propagation and allow identifying overlapped annotations (by computing an overlapping rate - expressed in surface area) by referring to the general indexing of the 3D point cloud. The consequent correlation process is then used to create relationships between the annotations, as well as the related descriptors. For example (see Fig. 9), an annotation concerning a 'degradation phenomenon' can overlap an annotation concerning an 'engraving'. This correlation mechanism is very flexible and allows the generation of hundreds of relationships in a spontaneous way (by avoiding rigid descriptive approaches) between annotations (also belonging to multiple actors) by augmenting in an exponential way the querying possibilities.

In fact, the correlation of qualitative (user descriptors) and quantitative (computed geo-visual descriptors) attributes belonging to the overlapped annotations generates a rich environment for analysing the co-occurrence of factors (e.g., a given material is generally used for a given building technique, a category of figures is mainly represented on a given type of ornament, a degradation phenomenon is mainly observed on elements with a given orientation, ...). We intend to explore the potential of this correlation framework in further works by assessing its applicability at several scales: by correlating annotation layers belonging to a unique object or to collections of objects, as well as by analysing the variability of attributes belonging to the same concept (e.g., a vocabulary term). In a paper we explored the potential of our annotation framework (linked to a domain ontology) for analysing the relationships between degradation phenomena, materials, building techniques and architectural elements within the study of the conservation state of a heritage building (Messaoudi et al., 2018).

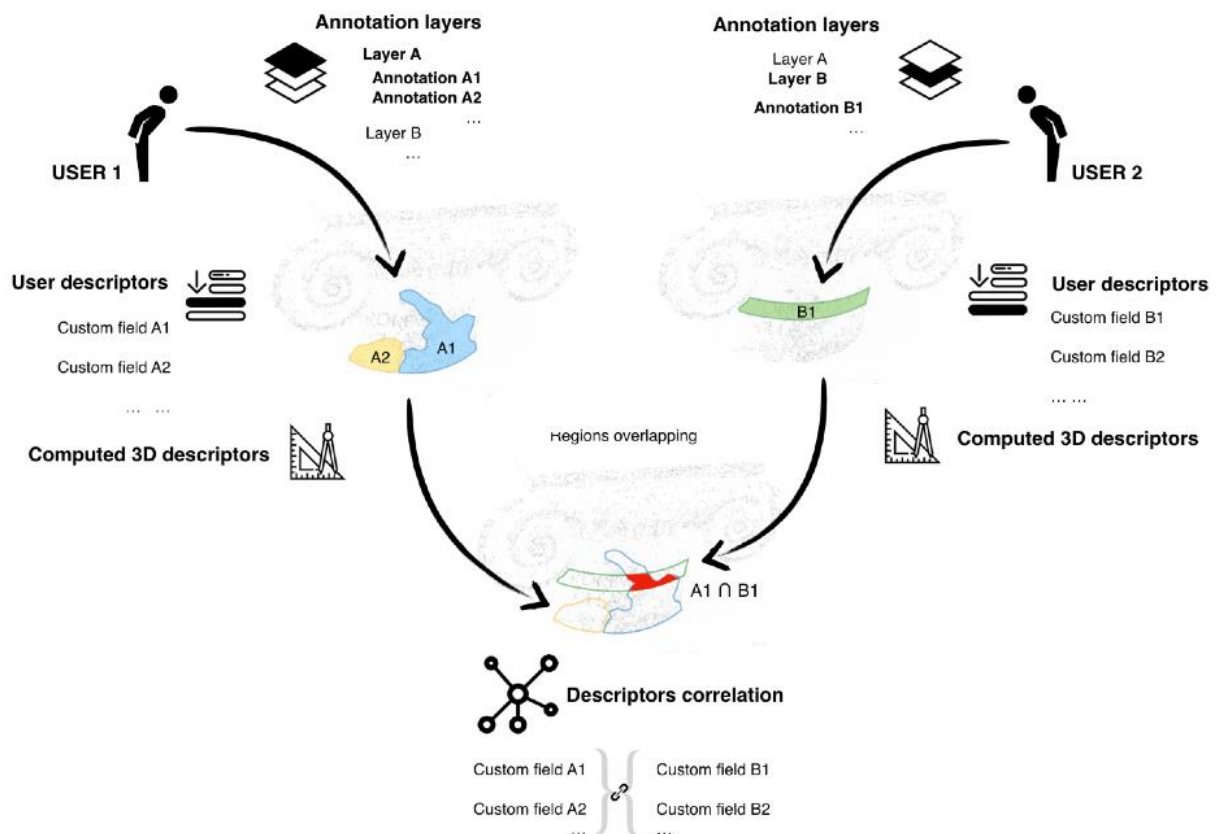


Figure 9: The correlation of two annotated regions defined by their spatial overlapping.

#### d. A collaborative framework

Given the emphasis put on the multi-user aspect, the interface for Aioli must ease the collaborative work on shared projects. This has been enabled by adopting a social network-like approach for the end-user. In the settings, users can set their discoverability (called visibility, which can either be public or

private), to enable other users to see them within the community. This setting allows the users who would like to remain invisible to do so, while giving the opportunity for others to share their work to some/all of the other users. When a user visibility is set to public, all other users can *invite* them as a *collaborator*, which then allows them to interact and to work on *shared projects*. Projects can be set using *sharing options* and *visibility options*. These two settings allow the users to share some projects to specific people (as long as they are *collaborators*), or to *publish* their projects on the community space. Collaborative projects can be defined by two categories of settings:

- *Sharing options* allows specified *collaborators* to open the project as if it were their own, with limited access through a *Read/Write/Execute* rights policy. Once a project is *shared* with a *collaborator*, the latter can open the workspace and use the application to annotate regions, describe layers and regions and consult the project, based on the permissions given by the project owner. Of course, for a project, only the owner can access and modify the global settings, such as the title, thumbnail picture or visibility status (Fig. 10). In these settings, the owner can easily modify the list of allowed users, in order to give collaborators an access to all (or some) of the project content. The read/write/execute rights policy then determines the ability for a non-owner user to add layers, upload new images, describe already annotated regions, or link new data.
- *Visibility options* concern the project discoverability within the public area. As any other collaborative platform, Aioli gives the possibility for willing users to give a *read-only* access to their work, through what we call the *community space*. This interface gathers all the projects published by their respective owners, and allows anyone (with an Aioli account) to access any project set to *visible*.

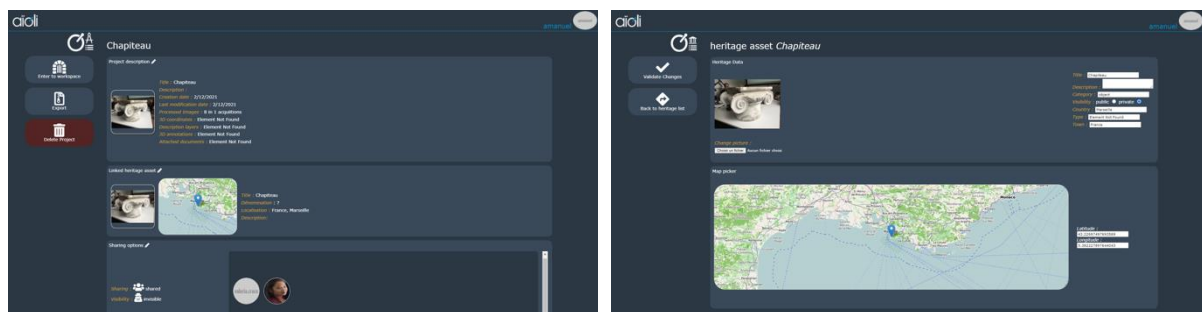


Figure 10: Screenshots of the project settings interface showing a project's sharing options (left) and the geo-referencing (right).

For frameworks subject to confidentiality constraints, users can set their project to be *undiscoverable* by other users, but accessible to some of their *collaborators*. On the contrary, users that want to disseminate results to the public can set their projects to *visible* and use the *community space* as a showcase as well as for exploring new cooperation opportunities.

## 7. Technical implementation

In practical terms, the expectations about the platform were as follows:

- To allow working on different 2D or 3D supports, and indifferently in situ or ex situ, which led to the choice to favour web technologies;
- To allow the dataset of the current project to be completed in an incremental approach, according to the needs that gradually emerge from its study, which led to the development and integration of TACO (see section 4)
- to allow the annotation of photographs of different nature, whether in the visible or non-visible domain (this modality being considered more intuitive by the users than direct point cloud annotation), and to quickly project these annotations on all the other resources of a corpus, which led to the 2D/3D hybrid viewer;

- To provide basic customisation tools regarding the appearance of the scene (annotation colours, point cloud texture, ...);
- To handle the layers resulting from multidisciplinary observations, which led to the management side panel;
- To allow to freely design the description model according to the needs of the study while keeping the benefit of each data types, which led to the semantic side panel;
- To provide a seamless access to quantitative information regarding the manipulated data, which led to the right panel quantitative data sub-section.

The main ambition at the basis of Aioli's interface design and implementation is to fit the level of ergonomics required by a large range of potential users, whatever the user's profile might be. The diversity of the disciplines and professional profiles involved in the documentation of the cultural heritage leads to important needs in terms of flexibility. At the user-interface level, the adaptation to the multiplicity of devices and media available today seems fundamental, while maintaining an ergonomic unity and simplicity. In this respect, responsiveness was an essential feature. It is not only a matter of allowing users, through a desktop interface, to work efficiently with the digital instance of the study object, but also to make these tools deployable at any time, as close as possible to the real object, using the specificities of handheld devices. From a technical point of view, Aioli is made of four main elements:

- The *thin client*, which ensures the cross compatibility of devices, allowing users to create, manage, and share content with all devices, PC, smartphones, and tablets using the same account.
- The *web server*, which constitutes the central node of Aioli. It dispatches requests to the application server, triggering the appropriate processing pipelines according to the different usage scenarios. Main project files are also hosted on this server (i.e., project's point clouds, acquisition dataset, texture maps created by indexation processes, ...).
- The *application server*, which contains all the calculation processes. It relies on DOCKER technology (Docker) to provide separate containers specifically dedicated to each step of the processing pipelines (spatialisation process by photogrammetry, data conversion, indexing, annotation propagation, ...).
- A document-oriented *database*, designed to store and query data as JSON documents. It includes all the application data (users, heritage assets, projects, layers, regions, ...).

Some of Aioli's processes require high computational power. Keeping all processing tasks independent from each other allows not only to minimise the used resources, but also to avoid heavy maintenance procedures, and more of all, to ensure scalability scenarios. For example, when creating a project from scratch, the uploaded images are transferred by the thin client to the web server, which will trigger the processing pipeline including the photogrammetric computation, the 2D/3D indexation, and finally the conversion of the 3D point clouds for web visualisation. During a 2D/3D annotation process, several containers are likely to be mobilised depending on the method used. In the case of a manual annotation, all the geometric entities (points, lines, polygonal regions) drawn by the user on a 2D image are collected by the thin client and transmitted by the web server to the application server as a list of UV coordinates belonging to an image with a given spatial orientation (provided by the spatialisation process). These coordinates are then exploited by the propagation and correlation functions (see section 5). Once the 2D/3D propagation and the extraction of geometrico-visual descriptors have been computed, the resulting 3D region and the boundaries resulting from its geometric projection on each oriented image of the acquisition dataset are sent back to the web server and then to the client to be finally rendered in the viewer. However, as we have seen previously, this process can be partially automated to assist the user in the region generation, for example by relying on a prior geometric segmentation of project data. In this case, the first drawing step is substituted by the activation of a container dedicated to the

segmentation, whose output will correspond to the regions' paths required for the propagation calculation.

#### a. 2D/3D visualisation and interaction

The aim of the viewer, at the heart of Aioli's interface, is to unify projects' 2D and 3D contents within the same representation space dedicated to their visualisation and interactions. Based on the WebGL API and specifically on Three.JS (Three.js) and Potree.JS (Schütz, 2021) JavaScript libraries, the viewer builds a 3D scene by positioning and orienting the various iconographic resources of the project and semantic annotations around the dense point cloud. For this purpose, we distinguish the images of the acquisition dataset, called Master, from the auxiliary images, which share the same poses but are obtained from complementary processings or sensors (e.g., normal or curvature maps, decorrelated images, multispectral images, RTI, ...). Master images are used to simulate virtual cameras from the calibration parameters given by the spatialisation process. All the other ones are displayed by texture projection on the near plane of the corresponding Master image's frustum (Fig. 11). In this way, the user can benefit from a free 3D navigation, or from the possibility to move directly on 2D views and visualise in transparency the underlying 3D data. More of all, the 2D/3D projective relation exploited in particular for the annotations propagation is preserved at any time. Thus, when the user wishes to draw an annotation, he can switch from one representation to another of the same point of view, for example from a visible light picture to a normal map without interrupting his drawing, in order to delimit more precisely his observation by taking into account both visual and morphological characteristics of the studied heritage object (Pamart et al., 2019). By taking advantage of the projective relationship in use, we can also propose a 3D preview of the drawn region by the real-time projection of its control points on the point cloud<sup>1</sup>. Other interaction modalities are currently being implemented, in order to allow annotation from boolean operations of several regions made from different viewpoints, or to annotate directly the point cloud in 3D.

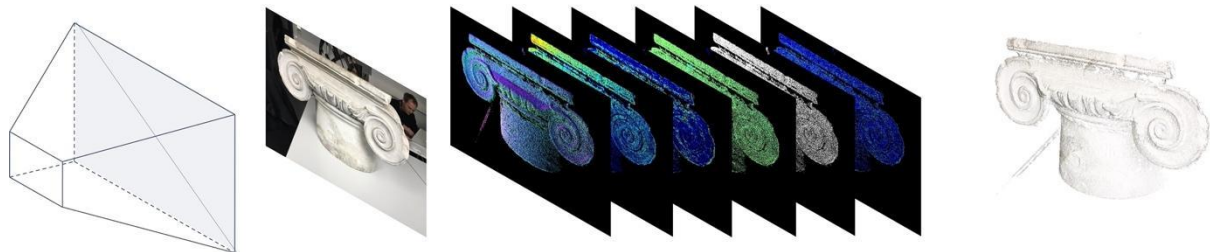


Figure 11: Structure of Aioli's multi-layered cameras. From left to right: camera's frustum, master image, auxiliary images, project's 3D point cloud.

#### b. The CIDOC CRM compatibility

The definition of a data scheme able to provide a complete set of descriptors adapted to each specific domain involved in the study of a *heritage asset* is essential for indexation, research, and retrieval of all the aggregated data. For this reason, we are working on a mapping mechanism to ensure full traceability of the Aioli 2D/3D collaborative annotation framework and heritage information (Cao, 2020) using the CIDOC-CRM, a high-level ontology for the description of Cultural Heritage whose documentation provides definitions for each class and property and their relationships in the model (Doerr et al., 2020). We are currently focusing on mapping of Aioli classes and attributes with CIDOC CRM high level classes, but some compatible specialised thematic models, adding classes and properties to the main one are particularly interesting for our needs, like CRM Digital (Doerr et al., 2016), a model to describe the

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<sup>1</sup> This functionality has been implemented on a development version of the Aioli platform, and is not yet released on the beta-testing one.

provenance metadata. In particular, we proposed a conceptual modelling taking into account three main aspects of Aïoli:

- the description of the *projects* (heritage asset, main author, collaborators, project context),
- the description of the *annotation* processes (2D/3D canvas, annotation layer and shape, description fields and values, computed geometric and visual descriptors),
- the semantic representation of the photogrammetric processes as well as indexing and propagation processing using the CRM Digital.

In a *project*, we document elements related to the *heritage asset* such as the type of object, its label, or its location. Information about the users/collaborators can be specified through function, affiliation, or contacts. The 3D coordinates that have been provided, the number of annotations, the attached documents and the sharing options are also indicated. All this information is described and stored in the Aïoli database and can be expressed semantically through CRM classes and properties.

The description of the *annotation* process includes elements about the annotation subject, its content and the event that created it. For example, an annotation was made by a person, on a certain date, on the basis of a document, and contains one or more descriptions of a certain type or refers to a controlled vocabulary. This semantic representation takes into account the description form in three levels according to the group, layer, and region which are nested in each other, but also the visual and geometric descriptors. The connection to the region path, thus the connection with the 2D images and the 3D model, is also represented (Carboni, 2020). Thus, the user's annotation process is expressed semantically from the creation of annotation groups with several layers to the tracing of a region and the annotation (Annex 1).

The semantic representation of the *digitisation* process includes information on the methodological approach, the image set used, the processing parameters (the commands used and the log files are preserved at each stage of the processing), and the final 3D model. CRM Digital classes and properties are used to complete this mapping, which covers the creation of the 3D model, its georeferencing, the point cloud indexation, and finally, the propagation of regions from 2D paths (Annexes 2, 3, 4).

The definition of the interconnection between the main aspects and processes of Aïoli and the CIDOC-CRM ontology provides a comprehensive description framework capable of integrating two- and three-dimensional data and information from internal/external sources. Mapping to the CIDOC CRM ontology adds a semantic layer to the data so that it can be formally interpreted for data sharing and interoperability with other existing or future systems aligned to it.

### **c. Ongoing beta testing and case studies**

In order to try out the experimental features of Aïoli, a beta-testing program is currently ongoing and involves selected actors from cultural heritage scientific and professional community. The aim is not only to pinpoint technical difficulties, but also to collect feedback on the features and discuss the issues and challenges of data sharing (images, 3D models, annotations, descriptions, ...). During this programme, a wide range of heritage artefacts, belonging to different scales and photographed by different sensors, have been used for experimenting the implemented features: archaeological sites, buildings, archaeological artefacts, archaeological fragments and parietal art, ... Different devices were successfully tested for the photogrammetric acquisition: unmanned aerial vehicle (UAV), digital reflex, tablets, and smartphones.

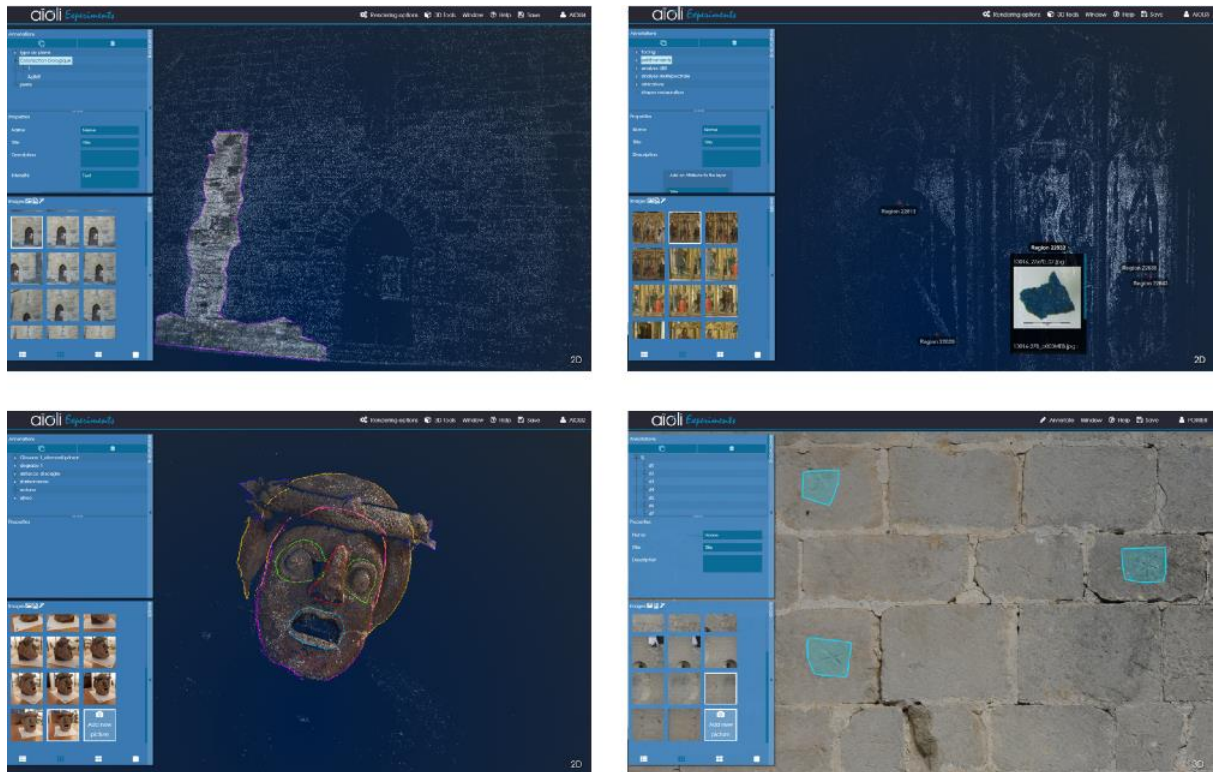


Figure 12: Screenshots of some case studies carried out within the beta-testing program: Usage 1 (top-left) – Mapping of biological colonisation on the East wall of the Caromb’s church, France. Usage 2 (top-right) – Spatialisation of a pictorial sample from the painting *Triptyque de Venasque*, Musée du Petit Palais, Avignon, France. Usage 3 (bottom-left) – Morphological analysis of a theatrical mask of the archaeological Museum of Lipari, Italy. Usage 4 (bottom-right) – Annotation of lapidary signs on the meridional wall of the castle at Les Baux-de-Provence, France.

This beta-testing programme was also an opportunity to explore the potential uses of the platform within the CH community (see Fig. 12). In the case of curation and restoration of cultural property, building specialists could analyse, for instance, the type of stone, alteration morphology, lost material and biological colonisation, in order to help preventive conservation (see Fig. 12 cf usage 1). In the frame of study and restoration of paintings, experts could use the annotation tool to map materials such as pigments identified thanks to techniques such as Scanning Electron Microscopy (SEM) or Laser-Induced Breakdown Spectroscopy (LIBS) and also examine the underdrawings using technical imaging (see Fig. 12 cf usage 2). The 2D/3D annotation framework can be very useful for isolating and analysing the morphological features of archaeological fragments (see Fig. 12 cf usage 3). Finally, Aioli may be used to help stratigraphic studies by spatialising and retrieving 3D information (dimensional layouts, orientation attributes, ...) such as lapidary signs (see Fig. 12 cf usage 4).

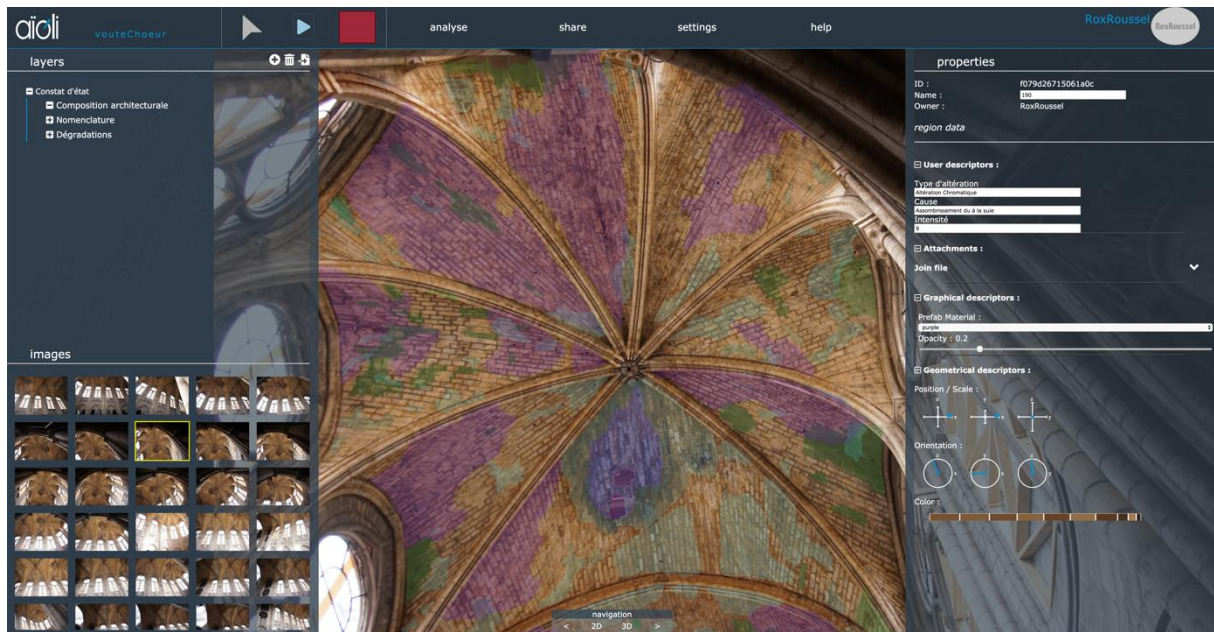


Figure 14: 2D/3D annotation of the alterations on the vaults of the choir of the Notre-Dame de Paris, after the fire of April 15, 2019, (from the photographs taken in October 2019 by Bestrema), for the architectural diagnosis before the restoration.

After the fire that hit Notre-Dame Cathedral in Paris on 15 April 2019, Aioli was used for diagnostic operations carried out by the architectural team in charge of the restoration. Thus, for this work, 242 projects were carried out, totalling around 9500 annotations semantically enriched with descriptions concerning for instance the nature of observed damages, their pre-fire state, or illustrations as additional multimedia contents. A third-party 3D viewer dedicated to the restoration of the cathedral is then used to load all the information contained in these projects into a single 3D scene, and to superimpose them on other three-dimensional resources representing different temporal states of the building (Fig. 14 - 15).

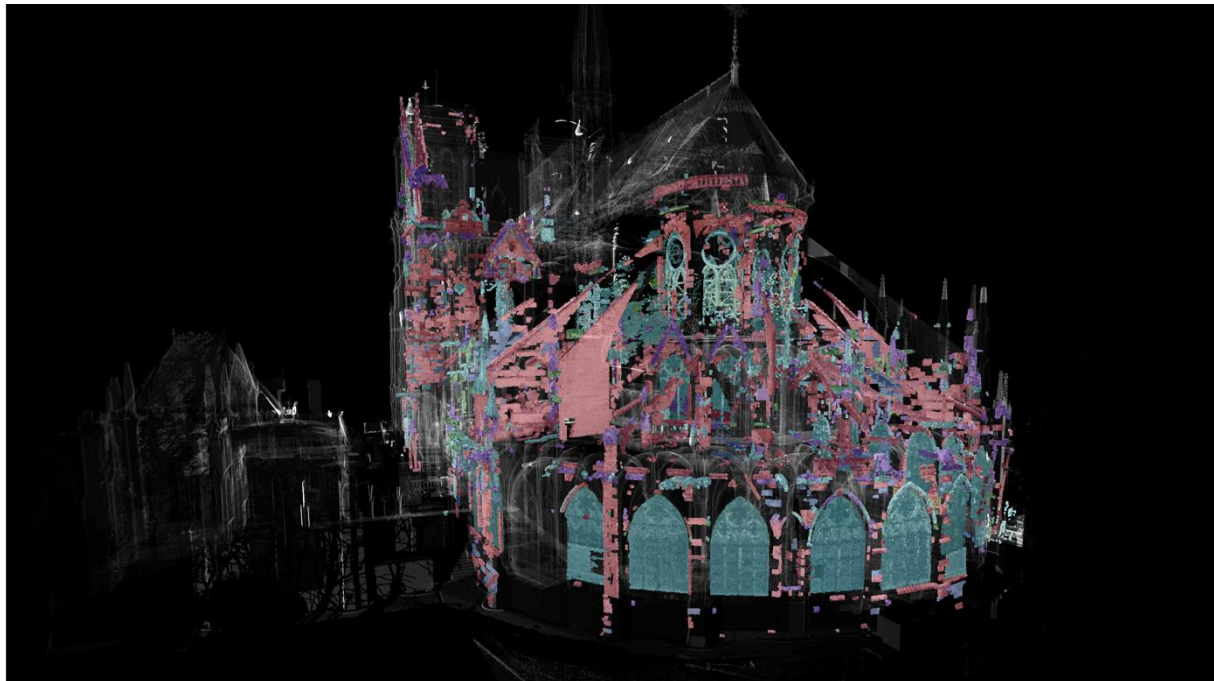


Figure 15: Import of the 113 Aioli projects of the architectural diagnosis of Notre-Dame in a third-party viewer, superimposed with other 3D resources including a 3D point cloud of the cathedral (before fire) from a lasergrammetric survey conducted by Andrew Tallon (Vassar College) between 2006 and 2012.

The scope of this project and of the diagnostic work then clearly showed the relevance of performing a spatial and/or thematic division for the creation of projects, which always remain linked to each other

by their belonging to the same heritage asset. This highlights the importance of processes ensuring the spatial registration of each project in a common reference system, as well as the need to propose restitution methods guided by spatial or thematic constraints, to render the most relevant information regarding a specific field of view in deeply multidisciplinary contexts.

## **8. Limits and perspectives**

In this paper we presented the Aioli platform, the principles at the basis of its design, its main functionalities and current informatic implementation. Today our platform is running on a server appliance composed by 72 cores (developing 144 high frequency threads equivalent to 216 gigaflops) of computing power, completed by 512GB of RAM and supported by 8TB of storage. This first installation demonstrates suitable performances and robustness for supporting more than 20 simultaneous connections. As photogrammetric reconstruction can require the processing of large amounts of data, we have decided not to set any limits regarding image count or dimensions. In this respect, any limits are due rather to the constraints of a web upload and the related security issues. Beyond 10Go, users must contact the administrators to create their project. In the case of complex and very large projects, the calculations can be launched after a direct deposit on an SFTP server.

Given its technical implementation, the platform can easily be installed in larger server appliances. In this sense, we are today exploring several scenarios in order to start its diffusion within the CH community at a national and international level. The technical implementation of the platform presents several limitations today (optimisation, calculation time, ergonomics, ...), the main one being that it currently only works online and needs at least a 4G connection, which excludes many CH context. Beyond the resolution of these technical limitations, this work now opens up many perspectives.

First, concerning the spatialisation of images: the diversity of CH artefacts analysis contexts clearly reveals the need to support a wide variety of imaging techniques in the 3D reconstruction pipeline. While the experiments conducted with TACO underline that it could provide an effective support for data fusion, there are still issues to be addressed, particularly in terms of qualitative evaluation. It would not be relevant to systematically co-register all the cameras without taking into account their potential impact on the calculation results. Then, beyond geometric accuracy concerns, it actually implies a broad reflection on the contribution of each kind of resource to the understanding of a study object: does the value of a given image inserted in an Aioli project reside solely in its capacity to produce geometric information, or on other levels, namely semantic? How can we integrate these parameters into our processing workflows? Besides, in terms of uses, many perspectives concern the implementation of new semi-automatic and automatic annotation methods, capable of handling this diversity of analysis media. To this end, we are currently working on the automatic creation of annotation layers from a semantic segmentation of point clouds by machine learning.

Another perspective concerns the dissemination of the information produced within the platform. We can see that today, the majority of analyses carried out from 3D media are only restituted through synthesis work, e.g., as reports, publications, captures, or diagrams. It is therefore important to discuss the relevance of these restitution methods when it comes to communicating increasingly complex and multi-dimensional information to the greatest number. We are currently working on the interactive publication of thematic analysis scenes from Aioli (using a 3D viewer to be embedded in a web page), and above all on data interoperability to build bridges with external tools. However, it seems that no semantic web standard is yet suitable for sharing 2D/3D annotations as produced by the platform. The work carried out within the framework of Notre-Dame de Paris' scientific project has shown the value of exploring this matter, and although the digital ecosystem produced on this occasion offers promising results, many challenges remain to be overcome, and avenues to be explored.



Furthermore, the collaborative aspect of the Aioli platform and the use scenarios it addresses require particular attention to traceability, both in terms of data and observations. It refers to underlying issues such as the reproducibility of results, legal aspects concerning the ownership of content, the production of metadata in view of dissemination, or simply the ability to preserve the history of an element - for example, an annotation - in order to follow its evolution (creation, editing, description, ...). We can save in the database as much information as necessary concerning the calculation processes carried out or the users' actions on the data (author of an annotation, authors of the elements of its description, original path, support and tool used, ...). Thus, it is no longer just a matter of guaranteeing the description of the contents and user actions, but rather of considering traceability as a key to understanding the relationship between an observer and his object of study. For example, by memorising and analysing the supports that are used in priority for annotations supporting a given semantic, we can hope to understand which geometric or visual attributes best represent a concept. Even more, could we establish a link between the disciplines involved in an interdisciplinary survey and the preferred media for annotation? In other words, what similarities or differences can be noted in the way actors from different disciplines look at the same object of study?

Finally, one perspective concerns the real-virtual continuum. Changed by several decades of technological breakthroughs, CH analysis practices are now at the crossroads between new digital analysis and processing methods, and the much-needed cognitive engagement of multidisciplinary observers facing the same study object. A major challenge is therefore to find a methodological renewal to provide strong ties between real and virtual work environments (Abergel, 2020). By joining the mixed reality and information systems fields, we are working on a paradigm shift that reconciles field practices and state-of-the-art digital processing techniques.

## **9. Conclusion**

Beyond the conceptual, methodological and technical aspects, we consider the work we present in this paper a first contribution for creating a sustainable framework for embedding human knowledge into large amounts of digital 3D representations of heritage artefacts. This ambition, to be pursued within a cross-disciplinary framework (between human and computer science) aims at embedding the development of ad-hoc technologies within the methodological renewal of the documentation practice, drives our roadmap for future works at the crossroads of a few trends that shape the contemporary landscape of digital humanities:

- Democratising digitisation tools by merging data acquisition and visualisation technologies with data analysis and interpretation methodologies, in order to produce masses of semantic-aware digital content instead of masses of raw and uninterpreted data.
- Introducing solutions for large-scale cross-analysis of heritage objects by using computational support in human-driven analysis and classification, in order to open new scenarios for comparing objects distant in space/time, but close in features.
- Building digital ecosystems for assisting multidisciplinary studies by exploring the potential of the semantic overlapping of multiple points-of-view, in order to consider the description of a CH object beyond disciplinary borders (archaeology, conservation science, history of art, ...) and communities (scientists, professionals, teachers, ...).

## **Acknowledgments**

Further information about the Aïoli project (including demonstration videos, case studies, beta testing programme) are available on the platform website: [www.aioli.cloud](http://www.aioli.cloud). This website will be the main support for communicating the current and next steps of our initiative.

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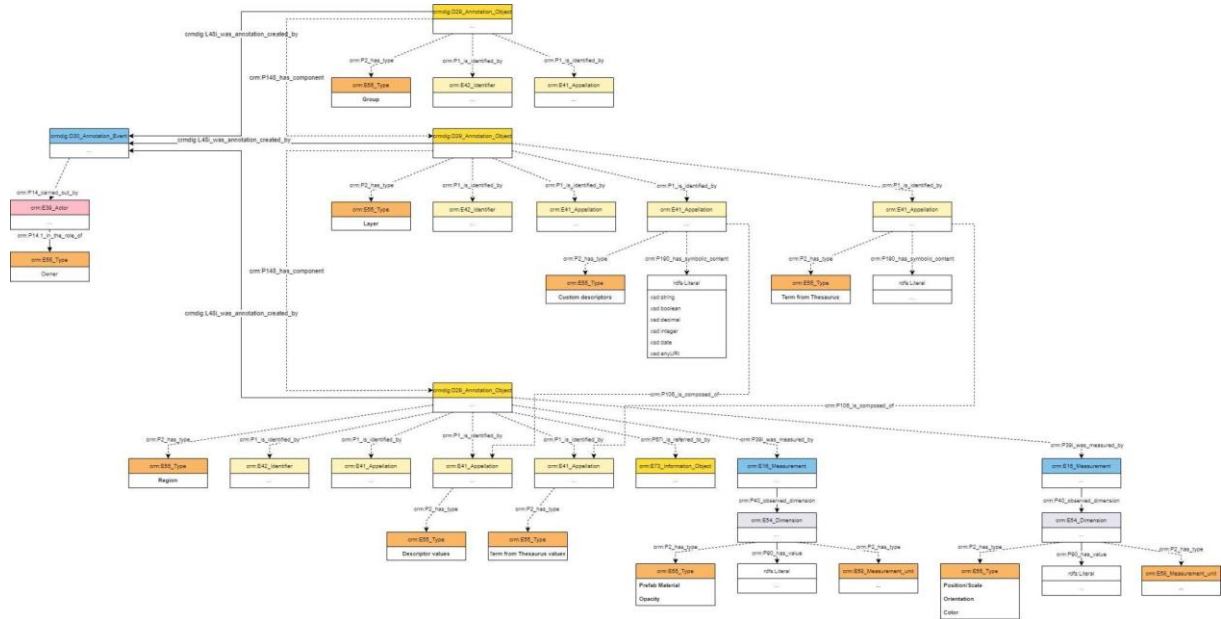
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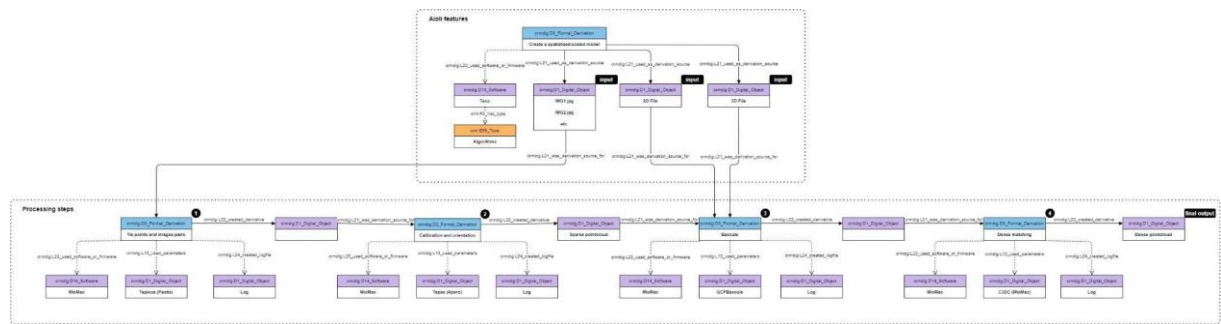
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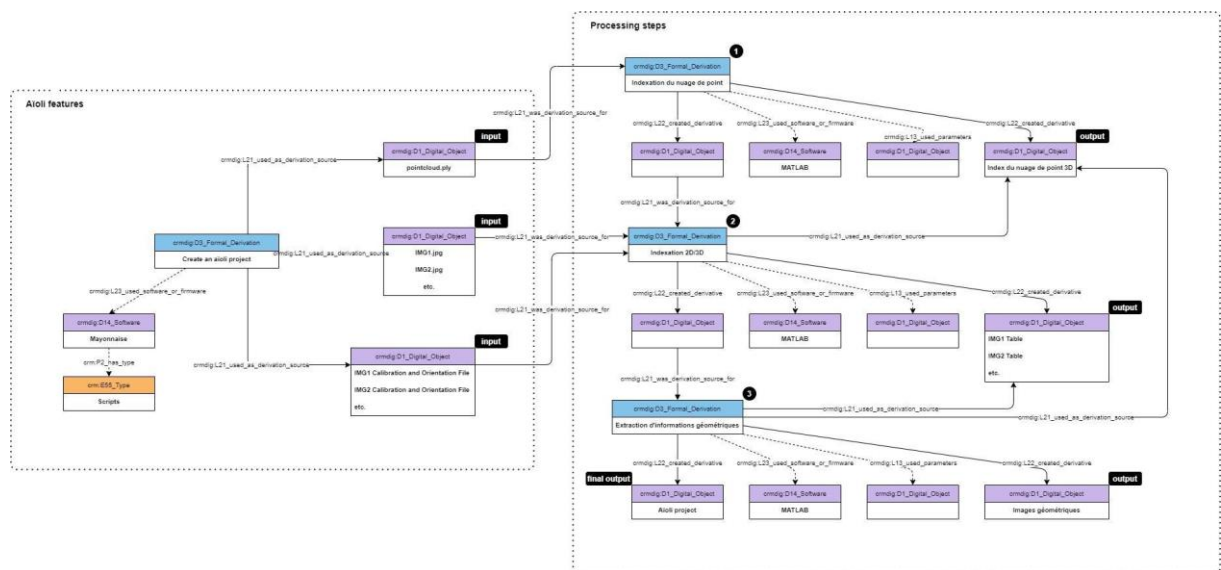
## Supplementary materials



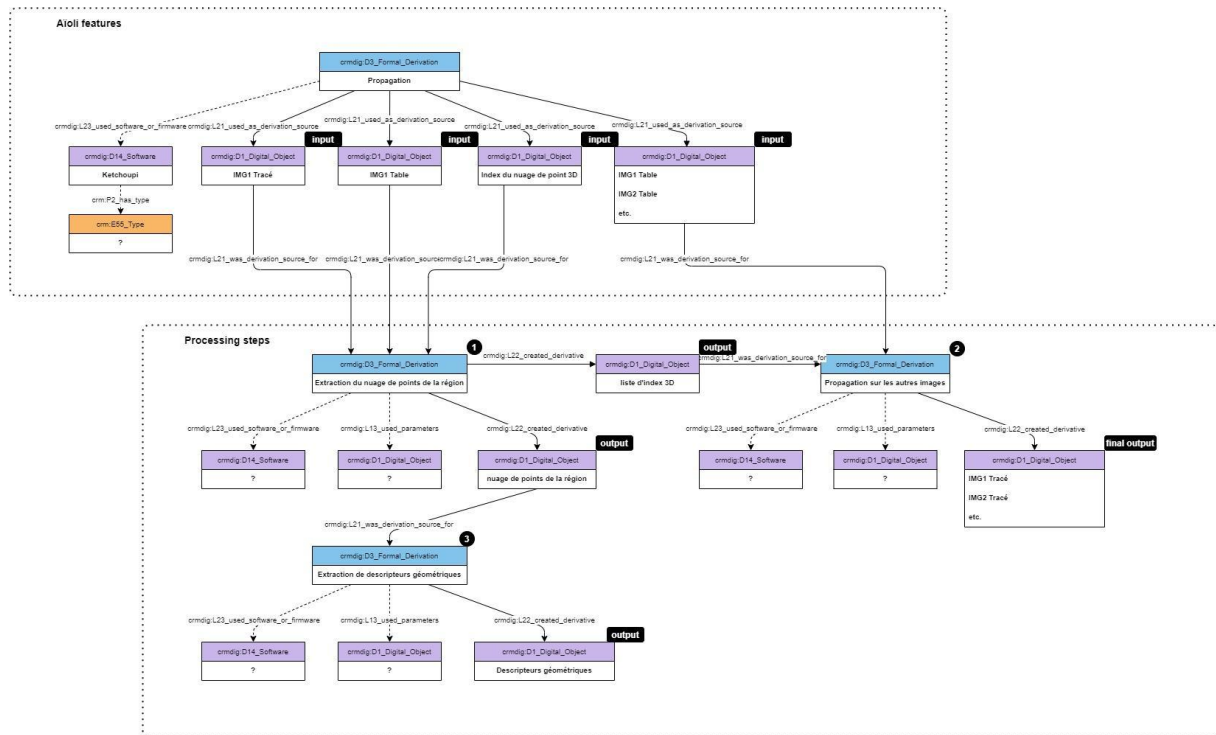
Annex 1: Conceptual modelling of Aioli's annotation process using the CIDOC-CRM ontology.



Annex 2: Conceptual modelling of Aioli's 3D spatialisation process (TACO) using the CIDOC-CRM ontology.



Annex 3: Conceptual modelling of Aioli's indexation process, using the CIDOC-CRM ontology.



Annex 4: Conceptual modelling of Aioli's propagation process, using the CIDOC-CRM ontology.