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3D Modelling and Semantic Enrichment in Cultural Heritage

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ABSTRACT

Three-dimensional representation is becoming an effective support for the documentation of the state of conservation of heritage artefacts, for the study of transformations of the built environment and for cultural dissemination. New 3D digitisation technologies now offer effective means to observe and analyse historic buildings with more accuracy, completeness and timeliness. Nevertheless, the application of these new technologies produces a real problem of information overload. The growing mass of point clouds, 3D models, un-interpreted data make indeed emerge a great need for innovative methodologies assisting data processing, sorting and analysis by researchers who want to use it for advancing the knowledge on cultural heritage. This article presents a synthesis of several research works carried out at the MAP Laboratory (CNRS/MCC) in the last years concerning the geometric modelling and the semantic enrichment of spatial data related to historic buildings through the design and the development of methods, formalisms and tools. These research works aim to identify the potential of structuring heterogeneous data within semantically enriched 3D models of heritage buildings according to multiple contexts: shape analysis, documentation of the state of conservation, indexation and retrieval of iconographic sources, representation of spatiotemporal transformations.

1. INTRODUCTION

The creation of three-dimensional representations of heritage artefacts requires methodologies to digitally acquire, interpret and describe the morphological features and the visual appearance. In particular, the documentation of the built heritage has benefited in recent years significant advances in 3D laser scanning and digital imaging (Cowley, 2011). Today, 3D data becomes a key component to store information of heritage sites. This technological enthusiasm has generated, in the last decade, a large number of projects, led by research groups, which have demonstrated the potential of 3D digitisation on different scales (Levoy et al., 2000; Gruen et al., 2004; El-Hakim et al., 2008; Guidi et al., 2009) and for multiple purposes: historical, digital preservation, monitoring, analysis of deterioration, cultural dissemination and so on. Nevertheless, it is obvious that the application of these new technologies is currently producing an important problem of information overload. The growing mass of point clouds, 3D models, un-interpreted data make indeed emerge a great need for innovative methodologies assisting data processing, sorting and analysis by researchers who want to use it for advancing the knowledge of cultural heritage.

In fact, the 3D representation by itself does not allow capitalizing and managing the entire knowledge fostering the understanding and the analysis of heritage artefacts. As a consequence, some research begins, firstly, to structure information about the building morphology from a spatial and temporal point of view, and secondly, to link the documentation produced during the analysis stage, by creating interfaces for handling this data set and linking it to a morphological representation of the building. If some studies suggest a semantic annotation process based on ontology (Attene et al., 2007), other ones extend this concept to the archaeological field (Manfredini et al., 2008) and to the urban one (Grussenmeyer et al., 1999).

2. GENERAL APPROACH

The analysis of architectural elements may be led by the identification of the process allowing its geometrical construction. Within this context, the codes of the architectural representation can always help in this stage, which remains the most difficult phase of building 3D reconstruction. To give an

example, one can take the example of the geometrical representation of a simple column: this element, far from being a simple cylinder, is characterized by a particular profile (truncated, bent bottom, bent third, or reinflated) and transitions as the *cimbia* (moulding softening the transition from the shaft to the basis) or the *astragale* (sequence of mouldings separating the capital from the shaft). Some proportions can usually regulate its dimensions (Forssman, 1978). The study of shape has a double finality: the first one is that of representation, the second one is the surveying of the object. If one analyses these two moments of the study, one easily understand that they are in a strictly interdependent relation, which is neither hierarchical, nor sequential. To represent an architectural element, its shape should be known; to know its shape, it should be measured; but to measure it, it is necessary to decipher its geometrical nature. In this sense, one of the most effective ways to define the architectural surveying is to consider it as a *reverse engineering* process. The surveying is indeed a reverse process in which, starting from an existing object, one rebuilds the process of its realization, by interpreting the idea of design, which comes before its realization (Migliari et al., 2000).
Within the logical continuity with the history of the architectural representation, our general purpose consists of considering the digital surveying of an historic building as a cognitive act: the moment in which one can analyse relevant relations between shape, geometry and architectural sense. Our works start from the idea that even if today one can use new (and sophisticated) tools, specific requirements coming from the architectural documentation and conservation domains remain and need the development of *intelligible* representations. In this sense, the alignment of emerging techniques to conventional codes of architectural representation is a main issue (see section 3).
A second problem relates to the architectural documentation (see section 4). Organizing the graphical documentation according to the building morphology requires integrating a purely geometric level to a semantic representation one. The concept of *shape* encompasses all instances of the object. Instances can be represented in a digital environment, independently from their format, use or size, considering that their geometrical nature is characterized by their spatial extension (Falcidieno et al., 1998). Architectural objects have a shape (spatial extension), they can be described by structures (entity collections and part-whole relationships), they have quality attributes (colours, textures, vocabulary terms, etc.) and they always have an interaction with time. According with this analysis, our approach is based on the idea that digital models can be considered as the *interface* to various kinds of cultural heritage data: firstly, the ones related to the building current state, secondly, the ones related to its morphology interpretation and finally, the ones concerning the representation of its transformations overtime.

3. DESCRIBING THE GEOMETRICAL NATURE OF ARCHITECTURAL ELEMENTS

The application of geometry to the description and analysis of the architectural shape needs the reduction of *multiplicity* into *intelligibility*. Starting from a geometrical analysis of the various parts of a building, and by having as an objective its geometric and semantic description, we proposed a method for the 3D reconstruction of architectural elements starting from relevant profiles (De Luca et al., 2006). This method is founded on the analysis of invariant and morphological specificities, which one can extract from a semantic segmentation of the building morphology. Throughout the history of architecture, the morphological complexity of

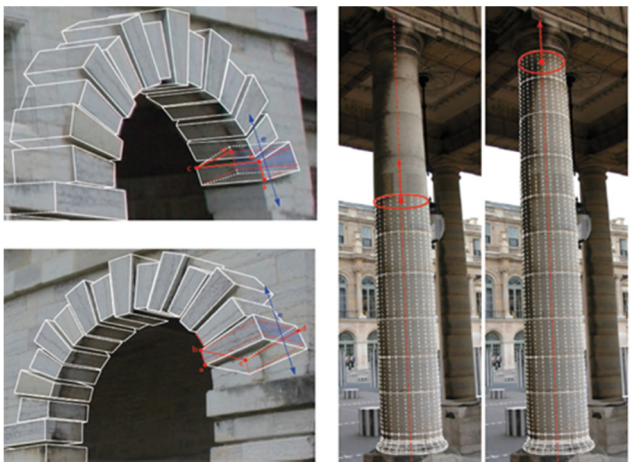

Figure 1: 3D modelling based on the interpretation of the geometrical nature of architectural elements.

shapes was always influenced by the methods of geometrical control that made possible their design. Based on a study of the principles subjacent to these control methods, one can then identify, on one side, relevant information to be extracted from the surveying (e.g. profiles extracted from a point cloud) and, on the other side, the better strategy for ensuring the geometrical modelling of elements (see fig. 1).

3.1. A generic formalism for the semantic modelling and representation of classical elements

Starting from this first work, we defined a generic formalism for the semantic modelling and representation of classical elements (De Luca et al., 2007). The approach we developped in order to describe architectural elements (those mainly related to the classic language) takes into account three distinct aspects: the interpretation of knowledge relating to shapes; the definition of techniques allowing their correct geometric modelling; the identification of the hierarchical relationships that one can establish between their parts and sub-parts.
The formalisation of the element is organised according to two parallel levels of description: geometry and semantics. The first one allows to geometrically rebuild shapes in three dimensions; the second one permits to structure parts and sub-parts according to the vocabulary of the architect. The geometric description is based on the relations among generic nodes (conceptual elements of the formalism) describing the construction of the element from the definition of its geometrical atoms (lowest-level geometrical entities) to the complete generation of its surfaces (see fig. 2).

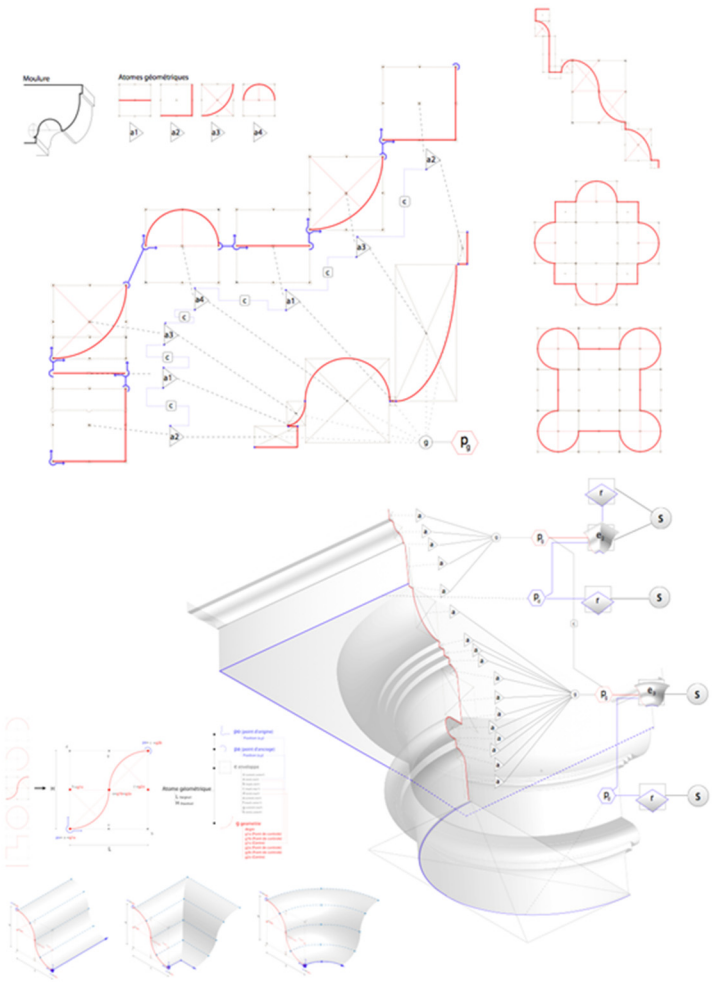

Figure 2: Atoms, profiles and surfaces of the generic formalism for the geometric description of classical elements.

These atoms are the only entities of the formalisation for which we provide geometrical information (control points of a line or of a curve): indeed, the generation of the whole element surfaces is based exclusively on constraint relationships, grouping operators and generic modelling functions. The semantic description level is defined by a structure of concepts organized around the geometrical description. Nodes of the semantic description, on one side, are connected to vocabulary terms, and on the other, gather the geometrical description elements in a hierarchical structure: atoms/mouldings/parts of the profile/profiles/surfaces.

3.2. Reasoning from semantics to geometry and vice-versa

The potentialities of the recent dense image matching approaches (Hirschmueller, 2008; Furukawa and Ponce, 2010) and the availability of web-based and open-source processing tools (e.g. Photosynth, 123DCatch, Apero, MicMac, etc.), have shown very promising results and renewed attention for

image-based modelling as an inexpensive, robust and practical solution for the 3D documentation of heritage artefacts. The introduction of new protocols for acquisition and processing of spatial data (Pierrot-Deseilligny et al., 2011) has given rise to new research perspectives. The opportunity to combine records, geometric analysis and characterisations about several artefacts could also be used for developing new approaches for shape classification and interpretation. The availability of flexible solutions for collecting morphological data on masses of artefacts allow considering the shape analysis as a fundamental moment for reasoning about the relationships between geometry and semantics and in a bidirectional analysis approach.

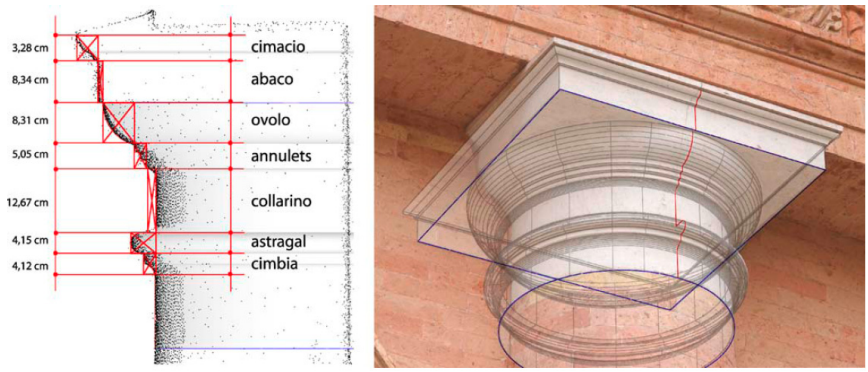

Figure 3: Primitive adjusted on the point cloud. On the left, the vertical profile with dimensional information; on the right, the primitive projected on an image spatially oriented on the point cloud.

In the first case (from semantics to geometry), the idea is to explore ways to insert architectural semantics within the surveying procedures (by associating them with dimensional information). This would allow an immediate reading of dimensional parameters corresponding to architectural concepts that characterize the artefact (see fig. 3). This kind of approach can provide great advantages in the 3D reconstruction process. A correct (and knowledge-based) interpretation of data prevents the production of unrealistic architectural shapes and would provide models linked to specific vocabularies and grammars. In this context, significant efforts on formalizing typical architectural elements can be conducted, including the study and re-interpretation (in the context of the digital modelling domain) of architectural treatises (description of typical shapes, compositional rules, constraints of positioning and orientation, principles of scaling, etc.).

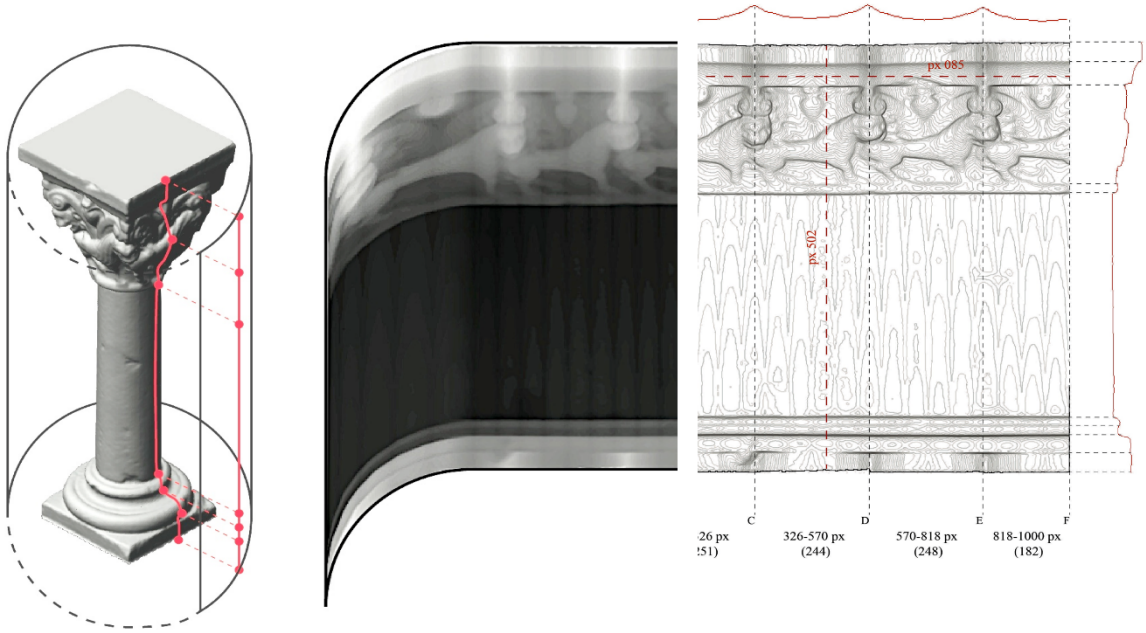

Figure 4: Projection of a cylindrical depth map (starting from the original mesh) used as an analysis support for extracting geometric discontinuities and relevant profiles.

In the second case (from geometry to semantics) it's necessary to investigate solutions for the shape segmentation but also the issues related to semantic annotation. We recently started working on a shape analysis method combining a bottom-up approach, in which the meaning of the elements comes from the combination of a low-level, and a top-down morphological analysis, which takes advantage of pre-structured knowledge (see fig. 4).
This kind of approach is therefore based on the identification of generic models that can integrate multiple instances (e.g. objects belonging to the same stylistic trend) by bringing out common morphological features by means of the identification of semantic /geometric classes.

4. SEMANTIC-DRIVEN STRUCTURING OF 2D/3D/4D REPRESENTATIONS

With the aim of designing a methodological framework for the representation of buildings based on their morphological description, we introduced the principle of *point of view* as a concept determining the structuring of semantically-enriched 3D models (De Luca et al., 2011). A point of view includes three aspects:

- The use of a vocabulary to isolate elements from the building.
- The identification of a relevant logic for the regrouping of these elements in a coherent unit.
- The choice of a type of representation able to extract from the gathered data the information necessary to the analysis.

In line with these principles, we build around the morphology of the building a *description model* defined by three distinct levels: semantics, structure and representation.

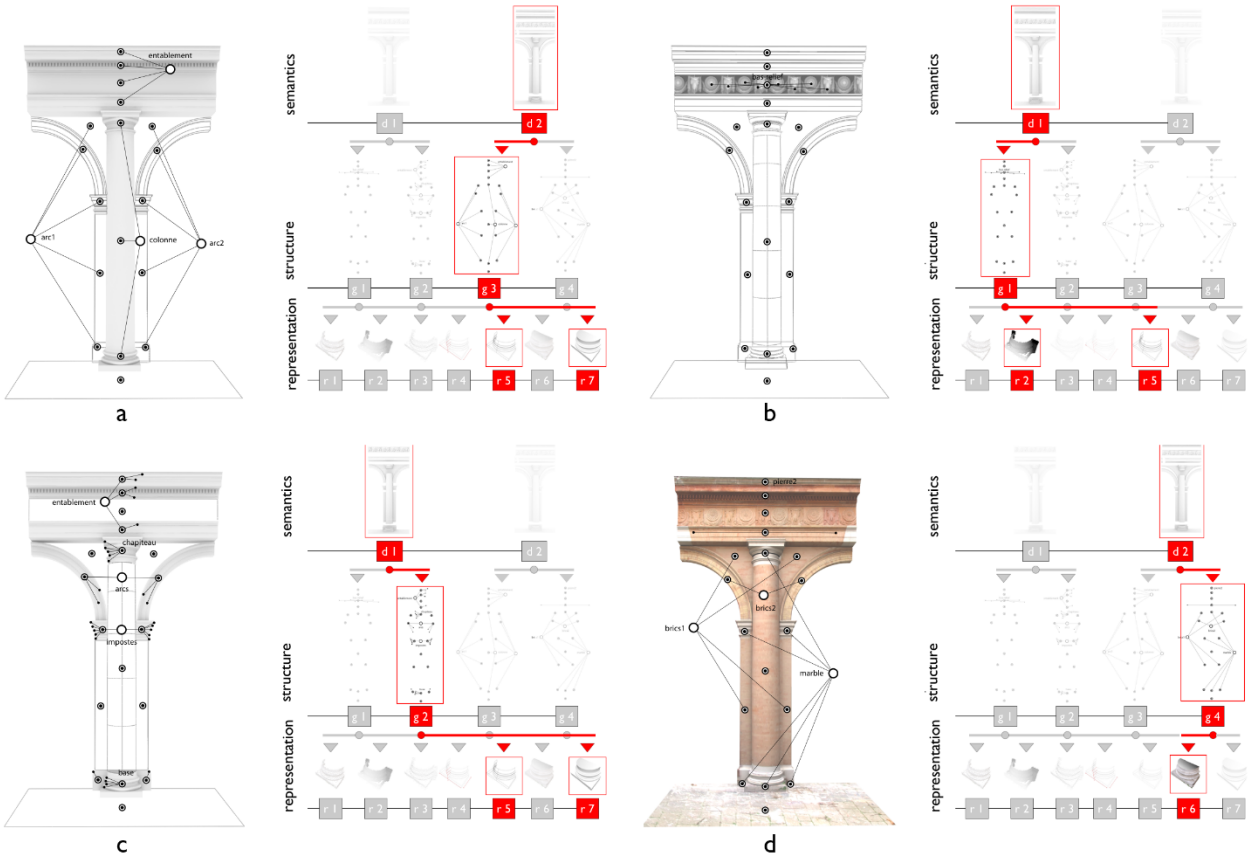

Figure 5: Four *points of view* on the studied object elaborated starting from the same morphological segmentation. Analysis of the order (a), analysis of sculptures (b), analysis of mouldings (c), analysis of materials (d).

Consequently, we distinguish three main processing phases from the analysis of the morphology to its possible representations: a first phase consists of isolating concepts (terms of description) and associating to them parts of the shape; the second one allows establishing a graph of relations between these concepts according to an analysis purpose; the last one allows associating various geometric representations to the same morphological entity according to various objectives of description. This three-levels description confers an important degree of freedom in the exploitation of the data resulting from the surveying phase: starting from the same geometrical model, one can work out various semantic descriptions by exploiting a multi-representations system (see fig. 5).
Moreover, our model of description is not only used for the structuring of the three-dimensional model and its possible representations, but may become the *common denominator* for the establishment of bilateral relationships between the morphology of the object and heterogeneous documentary sources.
By basing on the definition of this model of description, we started the (NUBES Project) that focuses on the development of an information system at the scale of architecture, taking into account the relations that can be established between the 3D representation of historic buildings (shape, dimension, state of conservation, hypothetical restitution) and heterogeneous data concerning various domains (such as the technical, the documentary or still the historical one). The main purpose of this project is to allow users to organise multiple representations (and associated heterogeneous data) around a semantic description model with the goal of defining a web information system for the multi-disciplinary analysis of heritage buildings (see fig. 6).

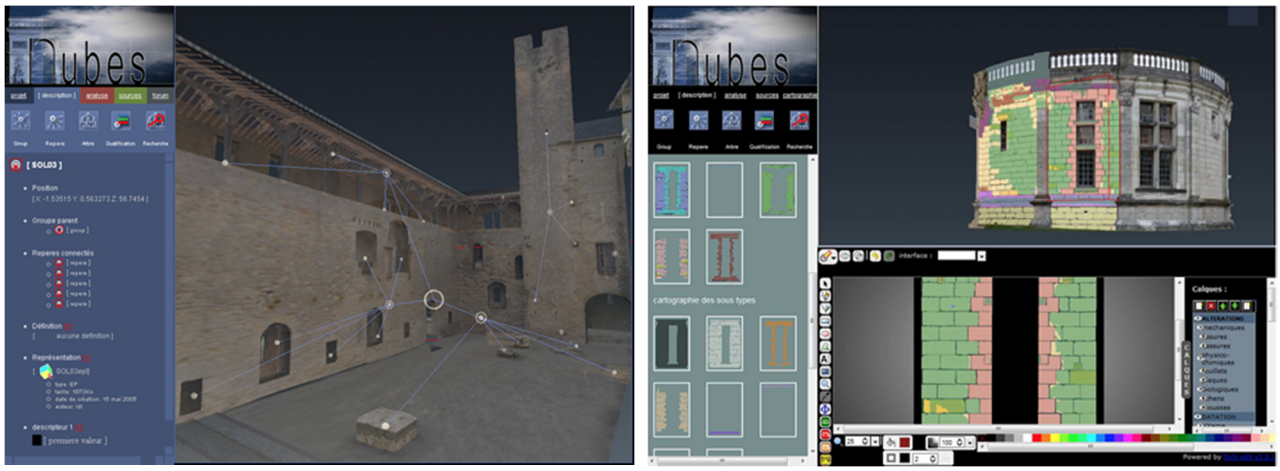

Figure 6: Screenshots of the NUBES web platform. On the left, the semantic annotation and structuring of building's parts and sub-parts. On the right, the semantic annotation of surface regions for documenting the conservation state.

4.1. Representing semantics

Our first experiments on structuring heterogeneous data around the description of the morphology, did emerge a parallel issue concerning the possibility of visually explain the relationship between the 3D representation of a building and its conceptual description by means of *graphs of concepts* (Valentino Losciale et al., 2012). We started from the premise that, in the context of the morphological description of a heritage artefact, the 3D representation could be definitely a solution for visualizing and / or archiving geometric information, but also a way to organize and spatialise cognitive data (Moles, 1973). In this sense, we explored new modalities for *visually unveiling* the relationships between *shape* and *information* of compositive logics of architectural buildings.
In order to view and interact with the mass of concepts (and relationships) composing the semantic description of the building's morphology, we build interactive graphs of concepts interconnected to

a related real-time 3D representation. These conceptual graphs are organized according to different *levels of abstraction* (Tzonis et al., 1986; Goulette, 1999). The construction of the graph starts with an automatic analysis of the 3D representation aimed to extract dimensional, hierarchical and topological attributes that can structure *nodes* and *relationships* representing the architectural composition (see fig. 7). Bilateral links between the 3D representation and the conceptual graph determine the displacement of the observation point into the 3D scene (in order to *focus* on a specific element or group of elements) by selecting a node of the description graph and vice-versa.

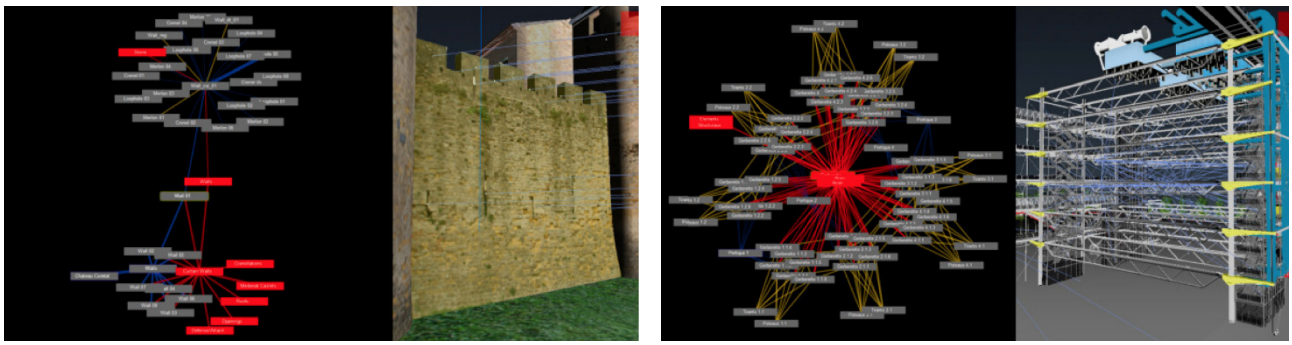

Figure 7: Conceptual description graph and related 3D scene of two architectural buildings: on the left, the Comtal Castle in Carcassonne; on the right, the Centre Pompidou in Paris.

4.2. Propogating semantics towards multiple representations and overtime

Regarding the linking of the model with other graphical documents, today several works are exploring the spatial referencing of iconographic data (such as photographs, drawings, paintings, etc.). These research works can lay on manual methods based on the knowledge and on the registration of the position of the cameras (Kadobayashi et al., 2005), on semi-automatic methods based camera pose estimation (Tsai, 1996) or still on automatic methods based on camera calibration and orientation (Snavely et al., 2006). Clearly, these works have shown that the retrieval of the body of knowledge fostering the comprehension and analysis of heritage buildings can be significantly improved, on one hand, by connecting the iconographic collection to the building, and on the other hand, by semantically annotating the morphology of buildings non only as a whole, but also in terms of their parts and subparts, their attributes and relations. However, one major issue remains open. Today the semantic relation between the 3D model and the collection of spatially oriented images is lacking. The use of semantics-driven approached could become a support for displaying measurements made on the accurate 3D-model, information collected about analytical data, or the conservation state of the building. The main idea of our approach concerning this issue is to organise the iconographic documentation and to link it to a semantically structured 3D model, characterised by elements defined by geometric information hierarchically structured, classified, and having assigned temporal attributes. Therefore, the iconographic spatialised sources inherit a semantic annotation from the 3D model by means of a semantic enrichment method, which permits:

- Structuring the 3D-model according to spatial and temporal criteria by assigning attributes, which describe the building's morphological transformations (see fig. 8, left);
- Referencing iconography in space and in time, basing on the knowledge of the geometric models of the cameras, and on the association of temporal attributes depending on the period of the sources (see fig. 8, right);
- Annotating iconography from a semantic point of view by exploiting the projective relations between the 3D model and the 2D sources (see fig. 9).

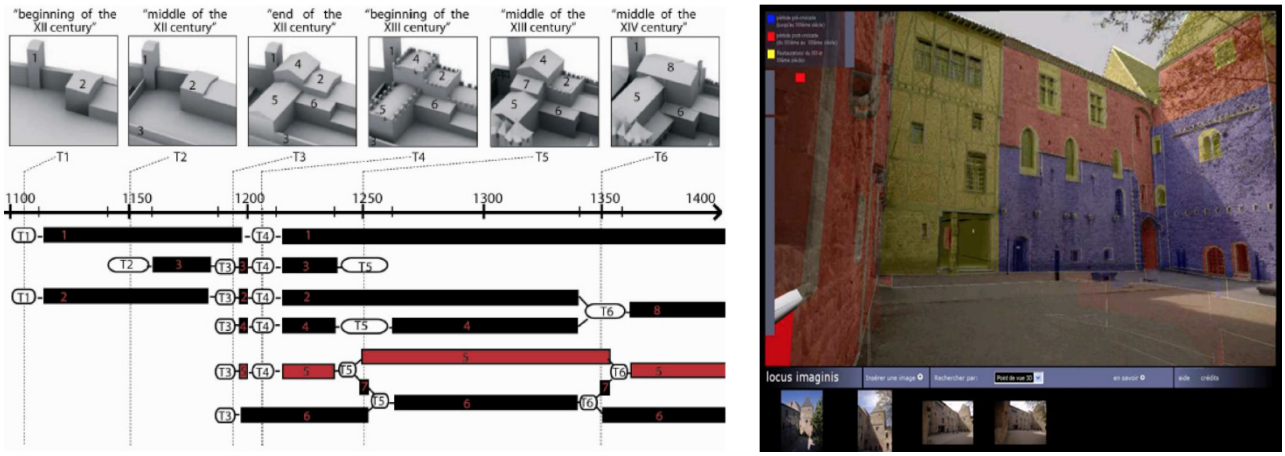

Figure 8: Spatio-temporal modelling of building's transformations. On the left, the temporal graph describing transformations in a time-line; on the right, temporal layers overlapped on a spatially-oriented iconographic source.

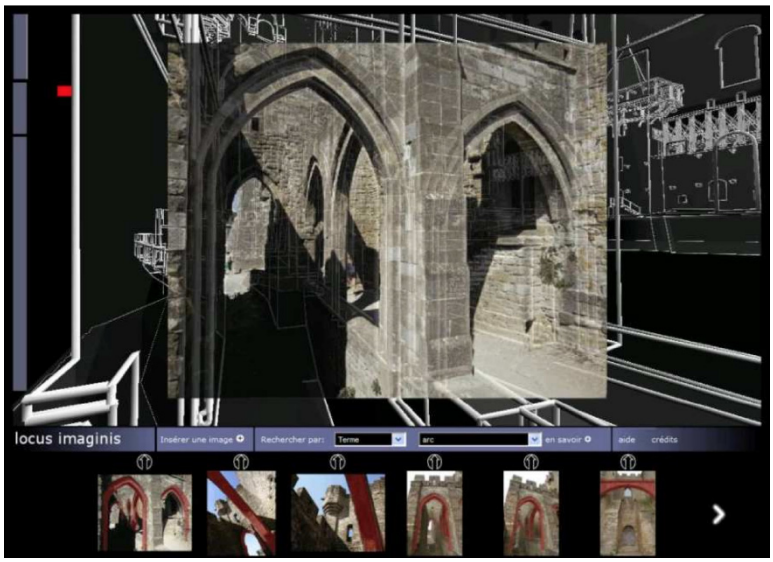

Figure 9: Search by vocabulary terms. Semantic annotations related to the selected term (arc) are projected from the semantically-enriched 3D model to the spatially oriented 2D images.

In contrast with the works in this area, our approach on semantic annotation of images (Stefani et al., 2012; Locus Imaginis) does not lean on the direct annotation of semantic concepts on specific areas of each image. Semantically-annotated 3D models are used as medium to propagate/distribute semantic layers directly to iconographic sources. The relation between 3D models and 2D images is created by means of procedures for the spatial referencing of images (spatial resection, camera calibration and orientation). By aligning images to the 3D model, the 3D model contour (according to its morphological segmentation) is automatically projected on the 2D image with the goal of superposing a semantic layer on the original iconography. This layer is produced by projecting the spatial extension of each morphological entity (eventually organized in parts and subparts) according to the image's internal and external orientation parameters (see fig. 9). Each projection (computed through a vector rendering technique) is processed as a 2D polygonal region associated with the identifier of the related 3D entity. At the functional level, this method allows positioning iconographic sources on a reality-based 3D representation of the related building. So, the developed database allows querying for images according to three main criteria: search by viewpoints into the 3D scene or by semantic attributes (see fig. 9).

5. CONCLUSIONS

Our research activity focuses on tools, methods and models integrated within cross-cutting approaches aiming to drive the design and the development of innovative representation systems for the digital documentation of the architectural heritage. The most original aspect of our approach is probably the comprehensive and coherent management of existing interrelationships between all phases of a digital documentation process, by starting from the acquisition of spatial data and by ending with the development of information systems at an architectural scale. By questioning existing information technologies and formalisms, or by introducing innovative methods and tools, our approach is characterized by two key contributions.
First, the integration of the architectural modelling logic with the analysis practices of the heritage documentation domain. In this way, the artefact morphology plays the role of *anchor point* that can structure heterogeneous documents, by giving to the 3D model the status of *interface* for querying databases.
Then, the implementation of theoretical models and graphic representations answering to specific requirements of the heritage documentation within the framework of an interdisciplinary study approach able to explore in-depth technical issues from a critical observation of the methodological issues.

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