Semantic 3D Media and Content

A semantic-based platform for the digital analysis of architectural heritage

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A B S T R A C T

This essay focuses on the fields of architectural documentation and digital representation. We present a research paper concerning the development of an information system at the scale of architecture, taking into account the relationships that can be established between the representation of buildings (shape, dimension, state of conservation, hypothetical restitution) and heterogeneous information about various fields (such as the technical, the documentary or still the historical one). The proposed approach aims to organize multiple representations (and associated information) around a semantic description model with the goal of defining a system for the multi-field analysis of buildings.

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Architectural heritage
Semantic description
Multiple representations
Information systems
Internet

1. Introduction

1.1. 3D digitizing of architectural heritage

In recent years, the field of architectural survey and representation took advantage from the use of the third dimension in the graphic documentation about cultural heritage. Various tools and emerging technologies [1,2] have been integrated into approaches for the 3D reconstruction of buildings in order to reproduce the morphological complexity of heritage buildings and to support different analysis requirements [3].

These reconstruction strategies permit both to collect and organize information issue from architectural survey and to produce multiple representations of buildings. To date various reconstruction methods have been developed. Firstly, some approaches are inclined to represent the geometric accuracy of 3D models [4]: they mainly base on the standard methods of automatic meshing starting from 3D laser scanning. Secondly, other approaches are based on descriptions that are specific to particular kinds of analysis [5]: they are characterized by data acquisition and data processing strategies consistent with specific representation goals. Thirdly, other techniques focus on reproducing the visual appearance of the surfaces forming the object [6], by taking into account photometric information. Finally, other approaches concentrate on the simultaneous representation of multiple factors at multiple scales: for this goal, they use different technical procedures in a complementary way [7,8].

However, beyond three-dimensional data, a large amount of heterogeneous data is collected during the analysis of buildings. Moreover all this data often comes from different branches and relies on different media. Various studies are carried out on heritage buildings for a variety of purposes including analysis of documentary sources, building maintenance and monitoring, formulation of assumptions and cultural diffusion. In addition to architectural survey, the development of qualitative descriptions of buildings is a larger research area. For this reason, today it seems essential to examine how quantitative information (extracted from survey) and qualitative information (produced by interpretation of data acquired during the analysis of documentary sources), can be analyzed and displayed within a unique integrated platform.

2. Related works

In recent years, the scientific analysis of documentary resources has benefited informatics solutions about how to organize and manage data. Many solutions have been developed in order to improve the management of digital contents [9], other works tend to define a formal structure for describing implicit and explicit concepts and relationships used in cultural heritage documentation [10]. A research consortium [11] also worked on the definition of metadata and paradata related to procedures for acquiring and processing data.

If many works focused on the semantic characterization of generic 3D shapes [12], very few works seem to deal with integrating heterogeneous data in a display device referring to the building morphology [13]. In this area, researches focus on how heterogeneous data is linked to the building morphology or to its graphic

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representation. In the panorama of published studies, some systems associate information to the entire building [14], other ones associate information to entities belonging to a 2D representation [15] or to a 3D representation [16,17] and finally other systems organize information according to a model description [18]. However, if the goal is, starting from architectural survey, to establish a link between the phases of description, analysis and documentation of buildings, several problems should be taken into account.

The first problem concerns the need to manage information collected about measurement, analysis and interpretation of building shapes. Systems organizing information around a single representation limit the consultation of building current states to a single analysis support such as plans, cross sections and orthophotos (in a two-dimensional plane) or triangles (in 3D models). In this sense, it is important to stress the difference between building representations deriving from data acquisition and representations obtained from data interpretation.

The second problem concerns the possibility of making available to various users (scientists, administrators, public, etc.) collected data and information. To this end, an important requirement is to express the various "viewpoints" of the disciplines involved in the study, preservation and enhancement of buildings. As a result of a wide range of analysis, it is required to manage multiple consulting modes, each one based both on a specific strategy for organizing data and on a specific representation system. However, systems structuring information around a building description model are effective just for one kind of analysis at a time. Actually, concepts organized for describing building shapes can just express the needs of a single disciplinary area.

The third problem deals with the access to collected information. It is necessary to consider technical solutions to share both acquired data and produced analysis. This requires, on one hand, to structure information according to different user profiles, and on the other hand, to build a specific documentation for each type of analysis. In this sense, the system should be adapted to collecting and organizing specific and a priori unstructured information.

3. General approach

Organizing the graphical documentation according to the building morphology requires integrating a purely geometric level to a semantic representation one. Actually, 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 [19]. Architectural objects have a shape (spatial extension), they can be described by structures (entity collections and part–whole relationship), they have quality attributes (colors, textures, terms, etc.) and they always have an interaction with time; finally various kinds of sources can describe their aspects.

Our approach discusses three main issues:

- Producing and managing multiple representations of buildings according to different analysis needs (see Section 3.1).
- Establishing links between the 3D morphology of buildings and the collection of 2D iconographic sources used for their study (see Section 3.2).
- Analyzing and representing building transformations over time (see Section 3.3).

Our approach is based on the idea that digital models can be considered as the interface of preferential access to various kinds of cultural heritage data: firstly, the ones related to the building current state, secondly, the ones related to its geometry interpretation and finally, the ones concerning to the formulation of assumptions on its past states.

3.1. Semantic description

Our platform uses a semantic description model as a common denominator between the possible representations of buildings and the related information. We build a description model defined by three distinct levels concerning the building morphology: the semantic, the structure and the representation one. An article details the used formalism [20]: the semantic level allows concepts (description terms) to be isolated and parts of the shape to be associated. The structural level provides for the establishment of relation graphs among these concepts in order to organize the elements of the scene according to a specific description need. The representation level allows one or more geometric representations to be associated to each isolated concept. Temporal dimension is joined to these three levels of the description. Temporal notion allows descriptive entities to be enriched with the concept of transformation (see Section 3.3).

3.1.1. Semantic level

The building description starts with a morphological decomposition consisting of organizing the elements of the scene in a compartment structure in which geometry is associated to each unitary concept. As knowledge involved in the semantic structuring of the building morphology is always in relation with the goal of the analysis, the description phase can start at different levels of the decomposition according to the size of entities composing the architectural complex: the body of the building (e.g. towers, curtains, etc.) or architectural elements (e.g. walls, roofs, windows, etc.).

3.1.2. Structural level

To support the phase of semantic description of the building morphology, the part–whole relations established between single elements are represented in the 3D space in a symbolic way. Representation is inspired by the structural approach introduced by Heine [21]. It is about a 3D graph (a tree graph in space) whose configuration depends on the manipulation (hierarchical relations) of a set of terms belonging to a list. Graphs are built using conceptual entities that have been specifically defined (Fig. 1): the morphological entity, the finalized group and the reference mark.

A *morphological entity* resulting from a morphological structuring is a concept, identified by the user for the building description, which can be joined with one or more geometrical representations.

A *finalized group* is a node that includes morphological features and that does not have its own geometric representation. In fact, its spatial extension is due to the union of the envelopes encompassing the entities belonging to it.

A *reference mark* indicates a particular aspect within an entity. For example, moldings or particular aspects on the entity surface (historical figures of a bas-relief, a physical degradation, etc.) can be considered as reference marks.

3.1.3. Representation level

To support the variety of representation techniques available today, the storage of representations has been structured according to three geometric bases.

Point-based representations: This category uses point clouds, if necessary enriched with color attributes. This kind of representation can contain rough data issued from a laser scanning or a photogrammetric restitution. It is the ideal support for measurement, because it is characterized by faithful representations of data acquired during the survey, without any approximation or interpretation.

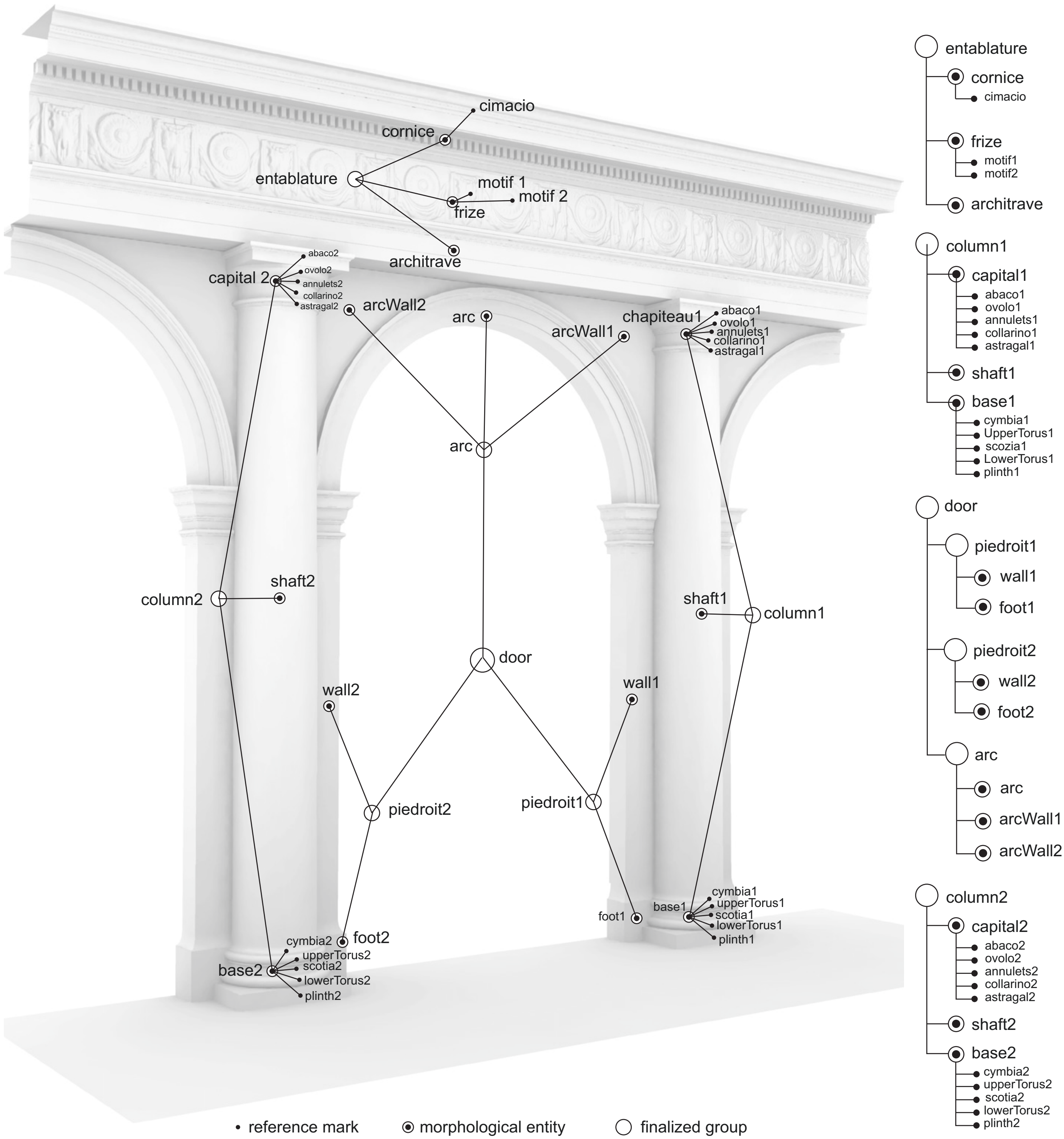

Fig. 1. Semantic description of the building morphology composed by a three-level graph: finalized groups, morphological entities and reference marks.

Curve-based representations: Representations laying on this basis can contain geometric information extracted during the shape analysis step (to name but a few, significant profiles, area boundaries, etc.) or parametric curves of the reconstructed surfaces. Moreover, they are an efficient support for the structuring of dimensional information.

Polygon-based representations: These representations permit the expression of volume and they can enrich it with information reproducing the visual appearance of surfaces. They give important information for the photorealistic rendering of buildings or for estimating the preservation of building materials.

3.1.4. *Points of view on the building*

The three-level description (concerning semantic, structure and representation), combined with the possibility of classifying entities by means of vocabulary terms, allows the construction of what we call “views” on the building (Fig. 2). Logic behind this system is based on the need to decline any description structuring in order to allow a real freedom in organizing data. Three aspects depend on the kind of observation on the building morphology: firstly, the choice of representation kinds, secondly, the structuring strategy of entities and thirdly, the choice of terms qualifying them.

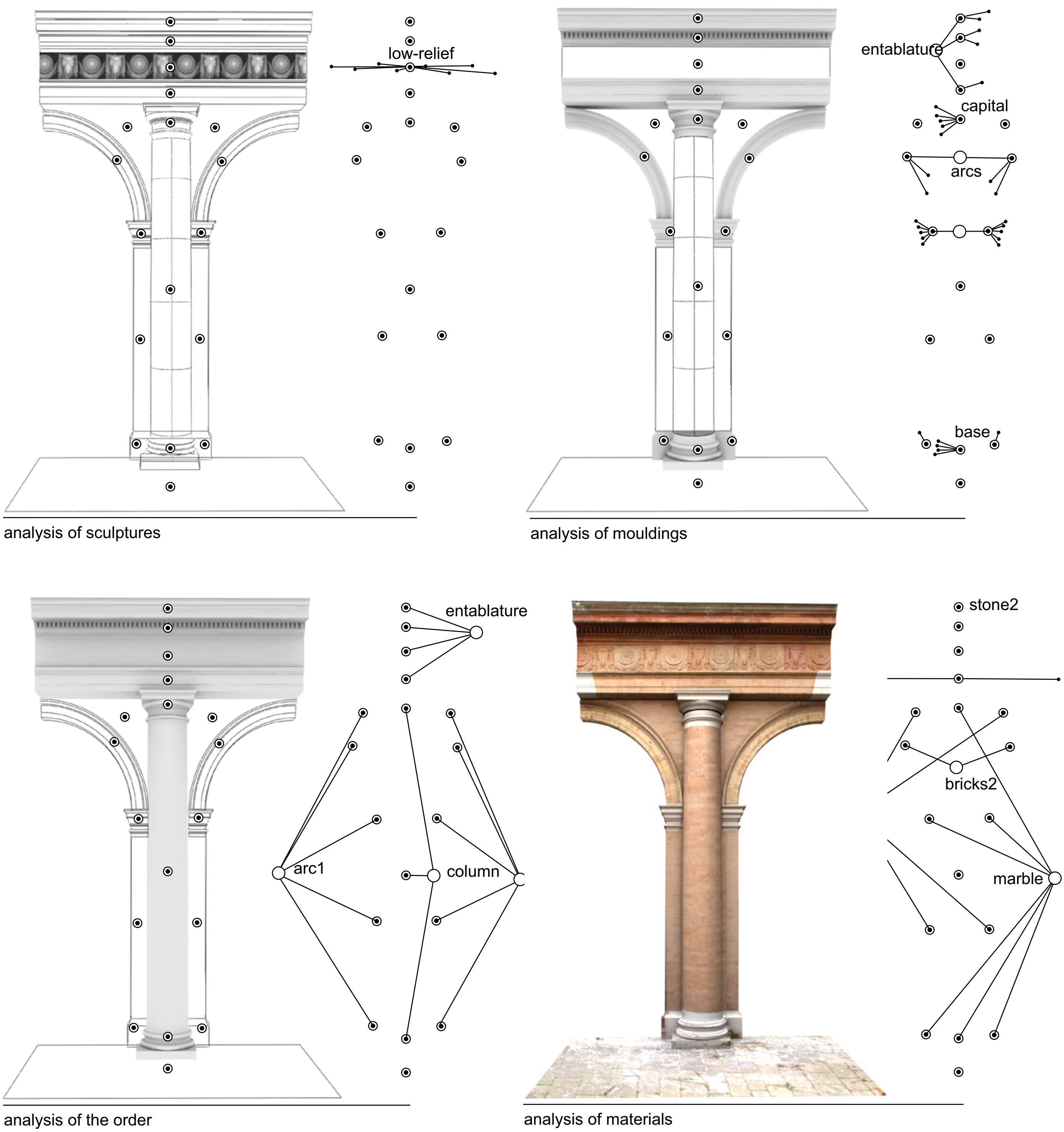

Fig. 2. Four "points of view" on the building morphology composed by three parallel levels of description: semantic, structure and representation. Top-left: analysis of sculptures; top-right: analysis of profiled elements; bottom-left: analysis of the architectural order and bottom-right: analysis of materials.

3.2. Spatial referencing of iconographic sources

3.2.1. Spatial resection of images on 3D models

In order to establish links between the 3D representation of the morphology and the 2D iconographic sources concerning its history, we use the spatial referencing of images. This principle is based on the definition of projective relations between iconographic sources and the 3D model of the current state of the building. Several types of iconographic sources are taken into account (photographs of current and historical states, drawings or paintings in perspective, technical drawings at different scales, etc.).

Regarding photographs, we use a spatial resection procedure [22] to establish a set of correspondences between each picture (2D coordinates) and the 3D model of the current state (3D coordinates). In the case of spatial referencing of historical photographs (representing the building in a state that is different from the current one already restituted in 3D), the spatial resection of the camera poses two problems. Firstly, information acquired during

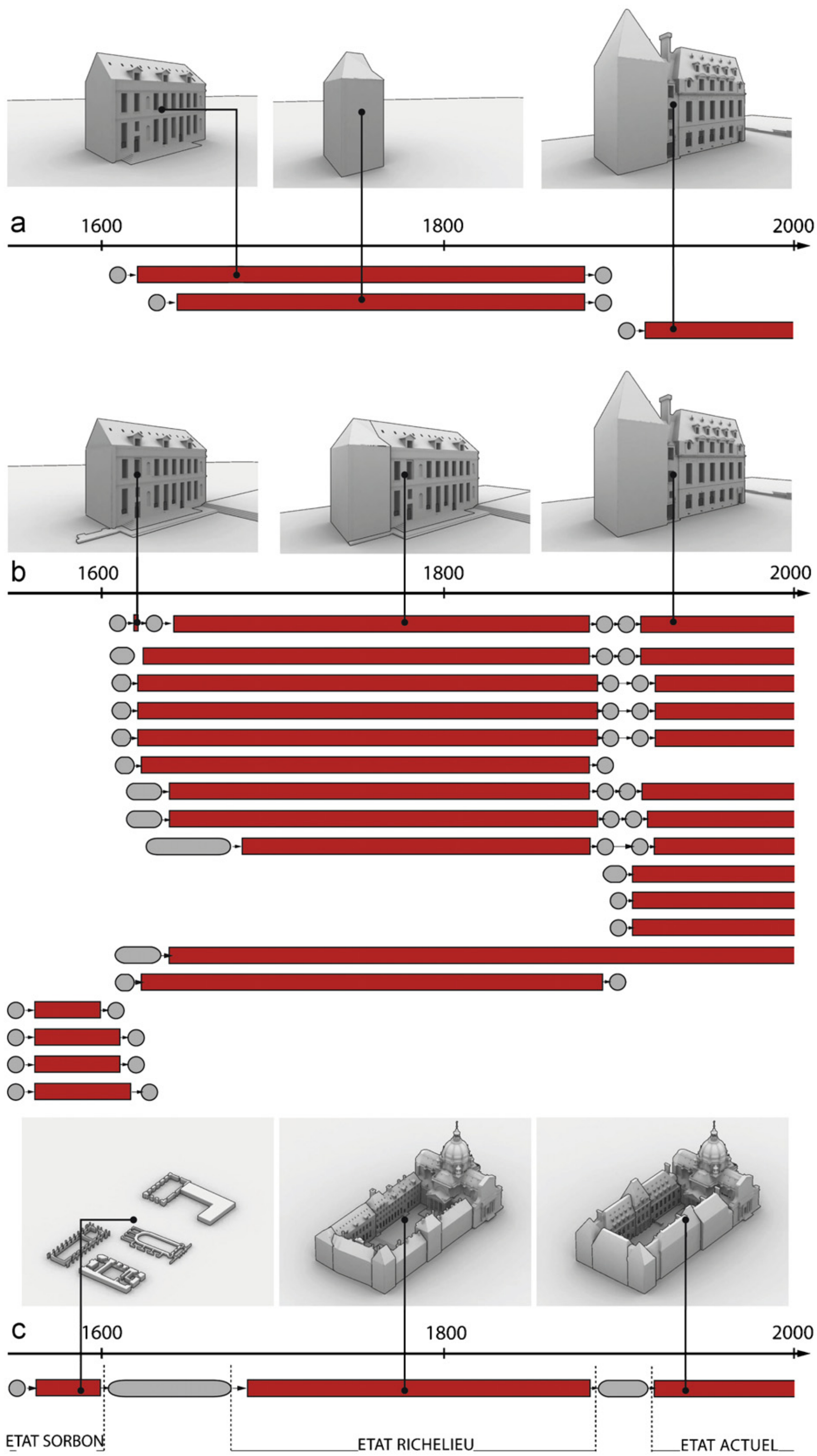

Fig. 3. Spatial resolutions applied to the courtyard of the Sorbonne. Each graph describes: (a) a single temporal unit, (b) single buildings and (c) evolutions of the architectural complex.

the shooting time is often unknown (focal length and distortion) and the image size sometimes is modified. Secondly, the current state of the building (resulting from a 3D scanning) and the past one described by historical sources are often very different. This divergence can make a proper distribution of 2D and 3D correspondences more difficult. On the basis of these constraints, we calculate the spatial resection by simultaneous estimation of intrinsic and extrinsic camera parameters [23] through the selection of a set of 2D/3D correspondences.

In all cases described above, spatial resection lies in associating, to each iconographic source, information on the camera geometric model at shooting time: the translation and orientation of the camera, and the focal length and distortion of the objective. In the case of iconographic sources based on the use of manual techniques (drawings, paintings, engravings, etc.) we use a manual spatial referencing based on a procedure consisting in an interactive superposition of a 3D scene viewpoint (in cylindrical or perspective projection) on the iconographic source used as the image plane.

3.2.2. 2D–3D projective relations

The projective relation established between the 3D geometric representation of the building and the iconographic sources is used in two contexts: semantic annotation of iconography by structuring the 3D scene (see Section 4.1), and searching the iconography according to spatial and semantic criteria (see Section 5.4).

3.3. The temporal dimension

In the case we are interested in studying changes undergone by buildings over time, the semantic structuring of the building morphology according to its current state is not sufficient. The examination of its morphology evolution throughout its lifecycle is required. In this case, the semantic structuring on one side, should take into account the temporal fragmentation, and on the other, should be integrated with a model capable of managing, storing and representing building history over time.

We start from the statement that building lifecycles are characterized by a series of transitions (representing artifact physical changes) and sets of states (indicating time periods, in which the artifact does not undergo any change) [24]. In addition, some of these changes concern the entire building lifecycle (construction, demolition, reconstruction, union, division, redistribution), on the contrary others involve only some parts of its morphology (such as variation, displacement, degradation, facing).

3.3.1. The historic graphs

Starting from the work of Renolen [25], we describe building transformations using a system of graphic notation [26]. At a graphic level, this model describes changes through a succession of states (rectangles) and transitions (smoothed rectangles). Our model deals with six types of transformations (creation, destruction, alteration, union, division, reconstruction) having different lengths (shorter or longer, or even sudden). Sudden changes, corresponding to events with zero duration (i.e. a change of ownership) are displayed with circles; gradual changes are described using smoothed rectangles whose lengths depend on the transformation interval. If change is gradual over a long time period, transition is broken by rectangles. This model has been adapted to display other changes characterizing historical heritage (displacement, covering, slow degradation, reallocation, change of function, of identity and ownership). If transformations do not cause any change in shape, some features are simply added to the graphical metaphor used for the six primary transformations: some symbols (i/f/p) are overlapped on the graphic system to underline change.

This model is well-adapted to represent multiple objects and transformations having different dimensions (corresponding to different spatial and temporal resolutions). Depending on the purpose of the analysis, several resolutions can be used. The computation on the resolution level follows the criterion of priority of changes over states.

3.3.2. Spatial resolution

According to this resolution, graphs can provide information at various levels of detail: the simple components of a building, the building or a selected group of buildings. In the upper part of Fig. 3, each rectangle corresponds to a single temporal entity designated according to the model structuring. This representation is possible by affecting temporal attributes of creation and demolition (the last one is attached to entities no longer existing) characterizing each entity. At this level, graphs are reduced to simple diagrams. In the middle part of the same figure, the concepts represented by rectangles are entire buildings. A single graph retains the evolution history of all components belonging to a building. By analogy, if we need to generalize the representation, each graph can retain the history of several buildings. For example, the graph at the bottom of Fig. 3 describes the building complex characterizing history of the courtyard of the Sorbonne. This type of representation allows the courtyard history to be detected: history is marked by three major states: the state of "Sorbon", the state of "Richelieu" and finally the current one. Each *macro-variation* corresponds to all changes of the building complex: macro-transitions summarize all the construction periods (from the beginning to the completion of the construction period of each building).

3.3.3. Temporal resolution

Similarly, the succession of states and transitions can be generalized according to the time scale of the analysis. Depending on the displayed temporal interval, it is possible to represent all changes characterizing the building (Fig. 4) or just a macro-variation, e.g., if such changes result too close together for everything to be displayed. This kind of simplification involves the disappearance of some intermediate states, which are displayed just to a more reduced scale.

4. Semantics, temporal dimension and spatial referencing as complementary features

In the previous paragraph we presented the main principles of our platform: the semantic description of the building morphology, the spatio-temporal analysis of its transformations and the spatial referencing of iconographic sources. These three aspects are logically related and can be joined in a complementary way in order to develop new approaches for documenting and studying architectural heritage. We have explored two possible intersections:

- Intersection between morphological description of 3D models and spatial referencing of iconographic sources. This research topic allows images to be semantically annotated (see Section 4.1).
- Integration between the semantic description, the spatio-temporal analysis and the spatial referencing of iconographic sources. This axis is the basis of a modeling approach that uses a set of photographs as historical support for building the hypothetical representation of missing temporal past states (see Section 4.2).

4.1. Semantic annotation of iconography

In contrast with various works in this field, our approach on semantic annotation of images does not lean on the direct relation between semantic concepts and specific areas of the image. We use semantized 3D representations of building morphology (see Section 3.1) as a support between these two kinds of information. The relation between 3D models and 2D images is created by means of procedures for the spatial referencing of images (see Section 3.2). By aligning images and the 3D model, the 3D model profile is projected on the 2D image with the goal of superposing a semantic layer on the original image. This layer is produced by projecting the spatial extension of the representations associated with the morphological entities of the semantic description (see Section 3.1).

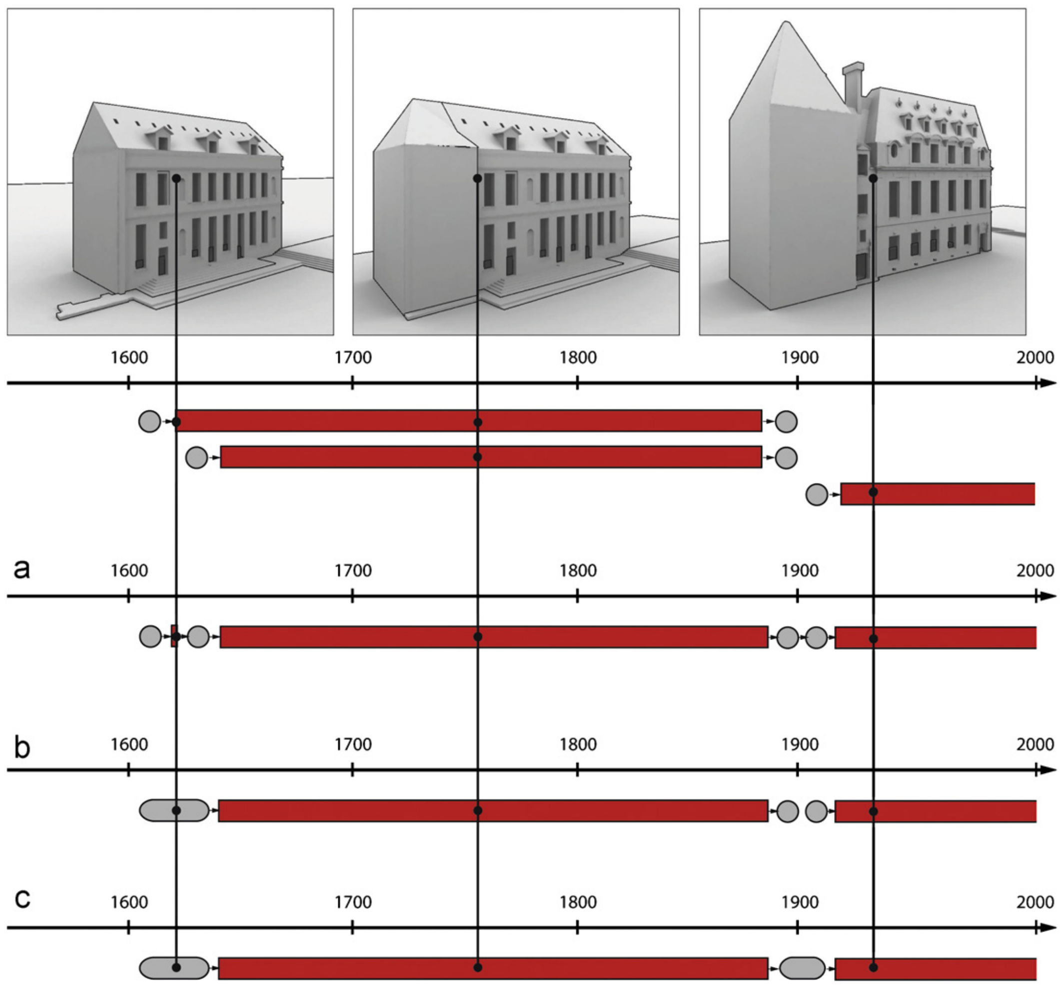

Fig. 4. Temporal resolutions applied to the courtyard of the Sorbonne, displaying: (a) all variations and (b)–(c) simplifications of variations.

Each projection (computed through a vector rendering technique) is processed as a 2D polygon associated with the identifier of the related 3D entity.

The projective relation between 3D representations and the spatialized iconographic sources provides automatic procedures for adding and updating semantic annotations (Fig. 5):

- In the case of addition or change of the 3D morphological description, the new structuring description is re-projected on images.
- In the case of spatial referencing of a new image, the building morphological description will be automatically projected on images.

Semantic annotation of images by projection generates structured data well-adapted for searching iconographic sources relating to architectural elements composing buildings (see Section 5.4.2).

4.2. *Iconography-based modeling approach*

Starting from the spatial referencing of a set of iconographic sources (see Section 3.2) describing historic buildings, the spatio-temporal reconstruction approach is based on three main phases:

- the construction of a geometric model of historical states based both on survey data and historical sources;

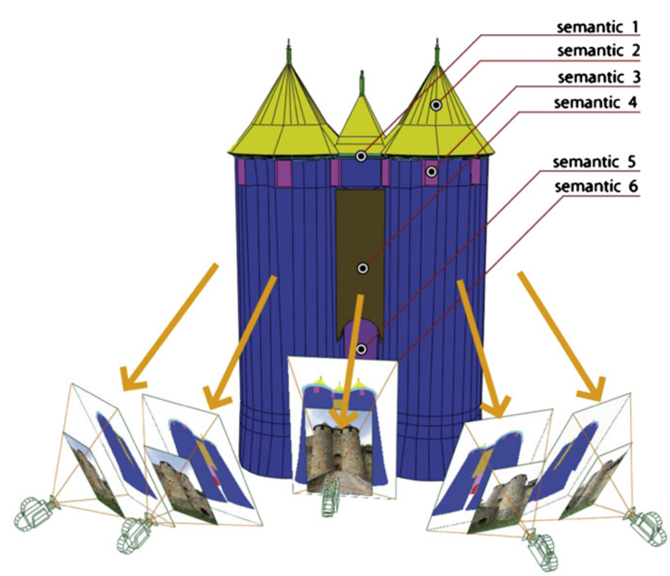

Fig. 5. Semantic annotation of photographs by projecting the building morphology organized according to the chosen description structuring. Segmentation of the 3D representation is mapped on oriented images structured as semantic layers.

- the semantic structuring of the 3D model to organize representations over time, taking into account the variety of hypothetical restitutions that sometimes exist on the same site;

- the enrichment of the structured geometric model through attributes describing time, the hypothetical value of the reconstruction and its reliability according to the iconography used for the restitution.

A detailed description of this approach is presented in [27]. The approach leans on the idea that only the current state can be reconstructed exactly using mixed techniques of survey and photogrammetry; on the contrary, past states are conditioned by a certain number of missing elements whose morphology and temporality can remain uncertain. In this sense, in order to interpret and restitute shapes, it is necessary to base on knowledge about architectural shapes. In fact, on one hand, classical architectural shapes are known and they have been documented by many architectural treatises of the first century BC. On the other hand, the three-dimensional restitution of missing states based on excavations and iconography leaves an important role to interpretation (based on analogy with other sites and on deduction from incomplete shapes). Therefore, the three-dimensional reconstruction is initially based on the geometric acquisition of a few existing elements; in a second step it is based on interpretation of sources (that can reveal inaccurate from a formal and graphical point of view), at last, it relies on composition relations deduced from knowledge of architecture. Historical sources are a fundamental constraint as they determine the 3D modeling approach, the metric quality and its reliability level.

4.2.1. Geometric modeling of temporal states

The construction of a geometric model of past periods by means of historical sources is based on the comparison between two historical stages: the perspective projection (2D) of a past state and the 3D representation (of the actual state or the already modeled past state). Three modeling operations allow geometry of architectural entities to be restituted according to the temporal distribution of events: creation, alteration and deletion of entities. Their position and orientation is based both on the projected image and on geometric information provided by the 3D model.

Creation of new geometric entities: This task permits to add entities that are visible on the iconographic source but that have not been modeled yet. Geometric entities are created by inserting geometric primitives or by copying identical geometric entities; according to the iconographical information provided, their position can be adjusted through translation and rotation tools.

Modification of geometric entities: This action consists of identifying the 3D geometric entities already created in another state (for comparison) and to modify them according to the visual appearance in the analyzed source. This tool allows entities to be split, joined or deformed according to the temporal fragmentation.

Deletion of geometric entities: This action is possible when entities do not exist in the analyzed temporal state. It is based on the assignment of a temporal attribute hiding the selected entity without deleting its geometry.

4.2.2. Qualification of hypothetic restitutions

In order to formulate temporal queries based on semantic structure, geometric entities are enriched with attributes concerning temporality and reliability. These aspects, integrating the three fundamental levels of semantic, structuring and representation, have been presented in Section 3.1.

Temporal level: The temporal qualification process is based on the temporal referencing of iconographic sources and entities, and on the definition of relations concerning their evolutions. Regarding geometric entities, to save the history of each morphological element, two operations must be performed: on one hand, entities must be qualified according to their temporal characteristics; on the other hand, the kind of relations established during the building lifecycle should be declared. Two kinds of attributes are affected to each group or sub-group: firstly, the temporal attributes identifying the analyzed period (characterized by the source attributes) and secondly, the relation attributes, describing entity transformations in relation with the previous period (simple morphological variation or deeper change of the artifact-division, union or reconstruction). The attributes associated with groups are applied to lower elements of the hierarchic structure.

Reliability level: Each hypothetical reconstruction is qualified by attributes representing the confidence level of the geometric 3D model. Firstly, each reconstruction is classified according to *certainty*. Each entity or group is characterized by an attribute identifying if the morphology is certain (in this case, sources, which reconstruction is based on are certain) or hypothetical (we assume that hypothetical reconstruction depends on interpretation and is validated by experts). Secondly, the *type of uncertainty* is described. Reconstructions are qualified by indices revealing if fuzziness is related to spatial aspects (entity shape or position) or to temporal ones (period of creation, existence, alteration, demolition of artifacts). Spatial uncertainty (Fig. 6) is determined by the presence/absence of entities in the source, by the source quality (state of preservation, image resolution, etc.), by the geometric resolution level (depending on the source level of detail) and by the certainty level of the archaeological reasoning. Temporal uncertainty is determined by temporal information about the source,

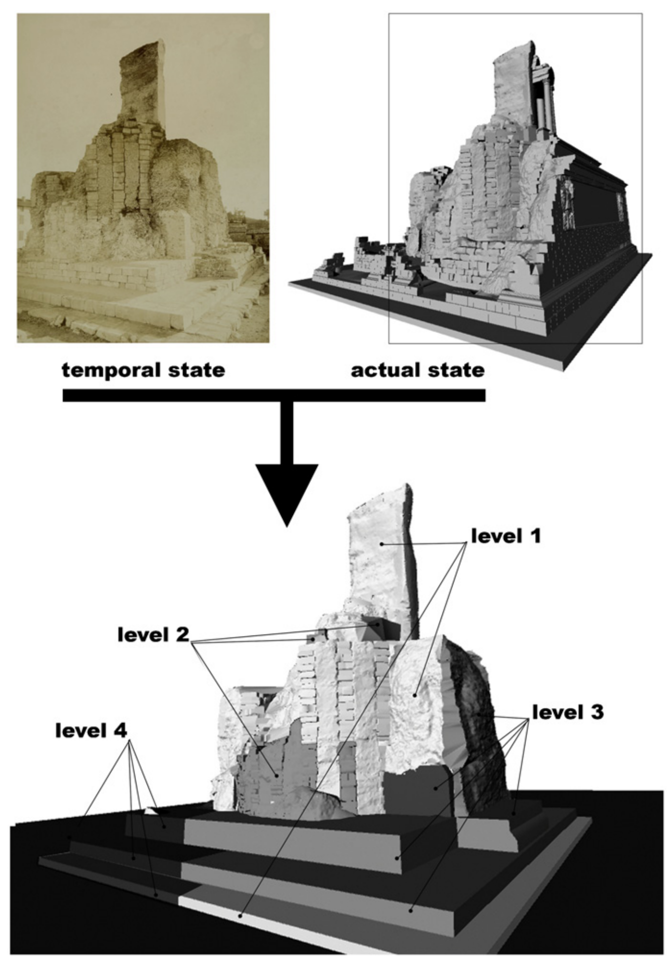

Fig. 6. Visual coding of uncertainty applied to the hypothetical representation of a temporal state. By comparing the original documentary source with a relevant 3D reconstruction, the user can assign a certainty level to elements or parts according to spatial and metric information included in the source.

the temporal granularity qualifying time intervals on states and transitions (including the period of creation, existence, modification and demolition of artifacts) and the certainty level of archaeological reasoning. Finally, in the case of hypothetical representations, reconstruction can be classified according to the type of interpretation (analogy, deduction or a mixed approach).

The model structuring allows temporal changes to be displayed by means of automatic generation of historic graphs (see Section 3.3). The reliability level and the temporal evolutions can be queried in a web application (see Section 5.3).

5. Informatics implementation

Our platform, called Nubes [28], consists currently of four tools:

- *Archivium*, a database for storing 3D representations.
- *Tempus*, for structuring and displaying temporal changes.
- *Imago*, for the spatial referencing and semantic annotation of iconographic sources.
- *Visum*, for the construction of "viewpoints" joining 3D representations, iconographic sources and sets of attributes configured by the user.

These tools are intended primarily for specialists in the field of architectural heritage conservation and valorization. Experts can qualify 2D and 3D representations according to their analysis needs. Users can actually access the platform only like clients in two ways: standard user (semantic annotation and characterization of a pre-loaded 3D description) and super user (upload and structuring of new 3D descriptions and representations).

5.1. Platform architecture

Our system consists of a web application based on a three-part architecture. From the technical point of view, this system joins three separate requirements.

- Storage of heterogeneous data: A database developed in MySQL organizes rough data deriving from survey, multiple representations and associated information according to the different user profiles.
- Manipulation of three-dimensional geometric representations in real time: A 3D interactive scene developed in Virtools DEV allows 3D representations to be downloaded, viewed and manipulated.
- Consultation and management of online data: The application is developed in PHP, a website that allows the user to access data stored in the database and provides the dialogue between the 3D scene and the database.

In order to handle geometric representations, specific functions permitting to interact with entities have been developed: tools for spatial navigation, procedures for downloading geometric representations from database, tools for measurement and profile extraction, procedures for spatial geometric intersection of entities and finally procedures for the position and orientation interpolation of the camera viewpoint.

The web application is based on the dialogue between the relational SQL database and the Virtools 3D scene, through PHP and Javascript, by means of table synchronization. At each interaction in the 3D scene, information on the manipulated entities is updated in the SQL database and vice versa. Some visual devices for the semantic annotation of images and the temporal graphs are developed in SVG.

For sustainability data requirements, all geometric representations are stored in database in the binary format (.NMO via 3D player) for compression purpose, and in ASCII (coordinates of point clouds and of B-splines control points, Collada for polygonal representations and materials).

5.2. Visum: qualifying and structuring semantic entities

Visum allows viewpoints on objects to be built (Fig. 7). It permits, firstly, to define attributes describing entities (such as terms in one or more thesauri), secondly, to establish hierarchical relations between entities and finally, to choose the suited representation according to the needs of consultation, analysis or communication. Starting from imported morphological entities, to which a basic geometric representation is associated, the user can interactively build a description graph by inserting finalized groups or reference marks in the 3D scene. The creation of a group corresponds to create a concept joining together a collection of entities: in the graph, a 3D symbol is then created and displayed in the barycentre of the envelope encompassing all the morphologically selected entities. The reference mark creation is made by selecting a point on the morphological entity geometric representation. The link between the 3D scene and the web application provides the update of the structure that is so displayed as a hierarchy of entities belonging to a list. In fact, the representation of spatial relations is calculated in real time by a procedure generating a chain of 3D connections: connections are established according to the recognition of the hierarchy levels expressed in the term list. As a consequence, each entity of the description graph can be described by a thesaurus containing terms and definitions of the architectural vocabulary. Actually we use a simple vocabulary, based on the official thesaurus of the French Ministry of Culture [29]. In order to qualify entities characterizing the description graph, we are planning to implement several thesauri depending on the different disciplinary areas (specific vocabularies for particular types of buildings, construction techniques, degradation types, etc.). We plan to construct thesauri using known schemas and models in order to facilitate the sharing process [10].

The use of three-dimensional graphs to organize entities describing the building morphology provides the main advantage of spatially locating all information (qualification attributes, definitions, dimensions, etc.). Amount of information is still accessible in the database by formulating queries. Each entity belonging to the graph is linked to three separate blocks of information: general information about items (such as position, entities, etc.), information on the vocabulary term defining entities and information related to their current geometric representation (e.g., volume for polyhedral representations, dimension for profile representations). We are currently implementing a fourth block of information regarding a set of attributes freely configurable by users.

By means of bilateral relations established between information and morphological components, it is possible to perform searches in two ways: searches relying on the entities selected in the 3D scene and entity searches in the 3D scene by means of form queries executed on the database.

Different criteria allow filtering entities in space: searches by thesaurus, by dimension, by representation type or still by temporal attribute. Search results are displayed in three steps. Firstly, records responding to the PHP page criteria are displayed as a list. Secondly, selected entities are identifies in the 3D space. Lastly, a procedure calculates automatically the camera movement so that the observation point is positioned in front of the searched entity.

Moreover, Visum allows relations established among entities to be displayed by two-dimensional hierarchical graphs (Fig. 8). In this way, a privileged link between 3D representations and the

Fig. 7. Semantic qualification of a 3D representation in Nubes Visum. The user can select a morphological entity, assign a vocabulary term, choose a type of representation (point cloud, profiles, polygons, etc.), qualify entities by custom attributes and create related reference marks.

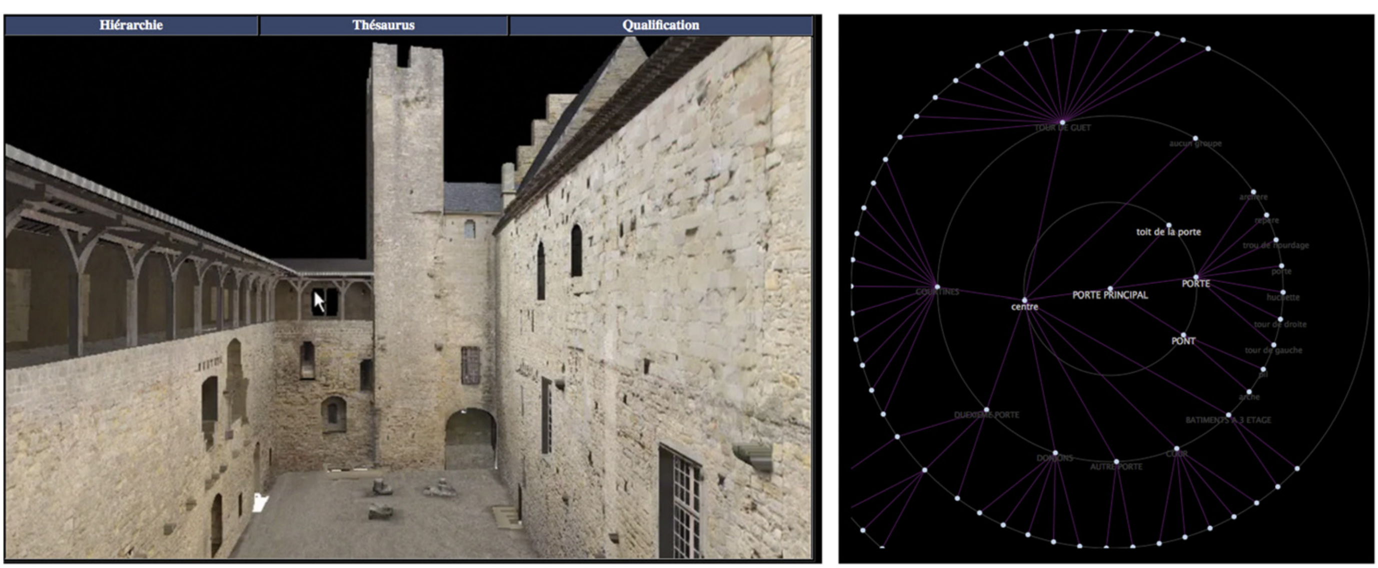

Fig. 8. Hierarchical graph representation according to viewpoints defined by users. In this visualization system, the user can navigate in the 3D scene (left) and the graph scene (right) structuring the vocabulary terms used for the description. When a term is selected on the graph, the navigation camera flies to the related element in the 3D scene.

concepts describing them is established in the world of knowledge. Graphs, representing how specialists have described buildings according to their "viewpoints", are interactively constructed in SVG format, leaning on the attributes assigned by the user (thesaurus or arbitrary qualification).

5.3. *Tempus: semantic-based temporal queries*

After the modeling and referencing stages previously described, on one side, changes over time are dynamically displayed through historic graphs, on the other side, visual information is presented on the model in order to describe the restitution type. The following queries, based on the temporal structuring, are possible:

Visualizing information about changes: In the previous section, we have illustrated the 3D model structuring approach according to time. On the one hand, the semantic description allows entities to be organized around groups according to temporal criteria: the semantic graph establishes the link between space and time. On the other one, the historic graph notation plays a complementary role to the one of group. This notation (Fig. 9) reflects the history of each group: the temporal position of geometric entities and the sequence of events. Then, entities composing the conceptual graph can become the common denominator linking hypothetical representations to the documentary sources justifying them.

Displaying temporal states: By means of temporal attributes affected to morphological entities, color coding is used to better distinguish building components having different temporalities (Fig. 10 (a)). Color tones should be adopted according to the specific site context (Fig. 10 (b)): it could be necessary to display the architectural elements according to a proportional or not proportional ratio between date and color ranges. For instance, if dates are too close one another, visualization by colors proportional to dates will not offer useful results. A procedure calculates the number of construction dates and assigns color and saturation parameters to geometric elements according to their temporal construction period.

Displaying assumptions: A *transparency* parameter is associated with the model to differentiate the hypothetical shapes (existing or destroyed) whose iconographic sources are known (Fig. 10 (c)). This representation is achieved through a procedure that reduces opacity of hypothetical entities. Moreover, if various assumptions are possible, a color is assigned to each assumption in order to distinguish them.

Displaying spatial uncertainties: To distinguish the kind of uncertainty, we use different diffusion levels: 3D representations can display the actual state of knowledge about time periods (Fig. 10 (f)). The uncertainty degree is expressed through a visual coding related to shading properties and to light diffusion material properties of entities. The diffuse color parameter is set according to the certainty attribute affected by the geometric entity. In function of the reconstruction method employed, four levels of diffusion are used: reconstructions based on survey data acquisition, such as laser or photogrammetry (diffuse color: 100%); reconstructions based on images in conic or cylindric projection (diffuse color: 75%), reconstructions based on images in pseudo-perspective, pseudo-axonometry or sketches (diffuse color: 50%) and finally reconstructions without iconographic support or survey data (diffuse color: 25%).

5.4. Imago: spatial searching of iconography

Regarding the search of graphic sources, we focused on the use of spatial relations established between building morphology and photographs by means of the methods listed below.

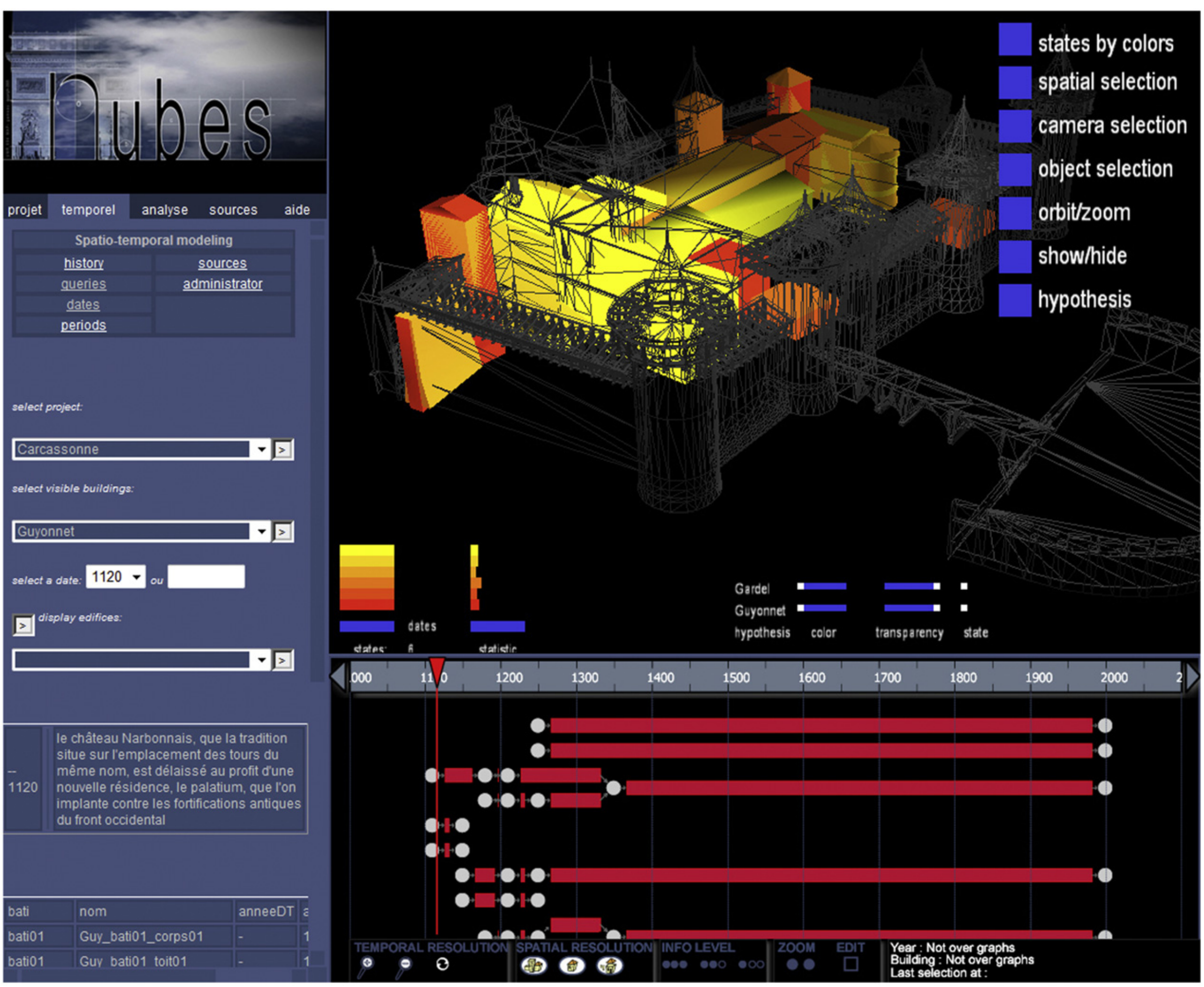

Fig. 9. Semantic-based temporal query interface. In this visualization system, the user can formulate temporal queries (left), display buildings according to their ancientness, isolate and compare assumptions (top) and display transformations by means of historic graphs (bottom). When a 3D element is selected, its history is displayed and vice versa, at the graph selection, the corresponding 3D elements are displayed.

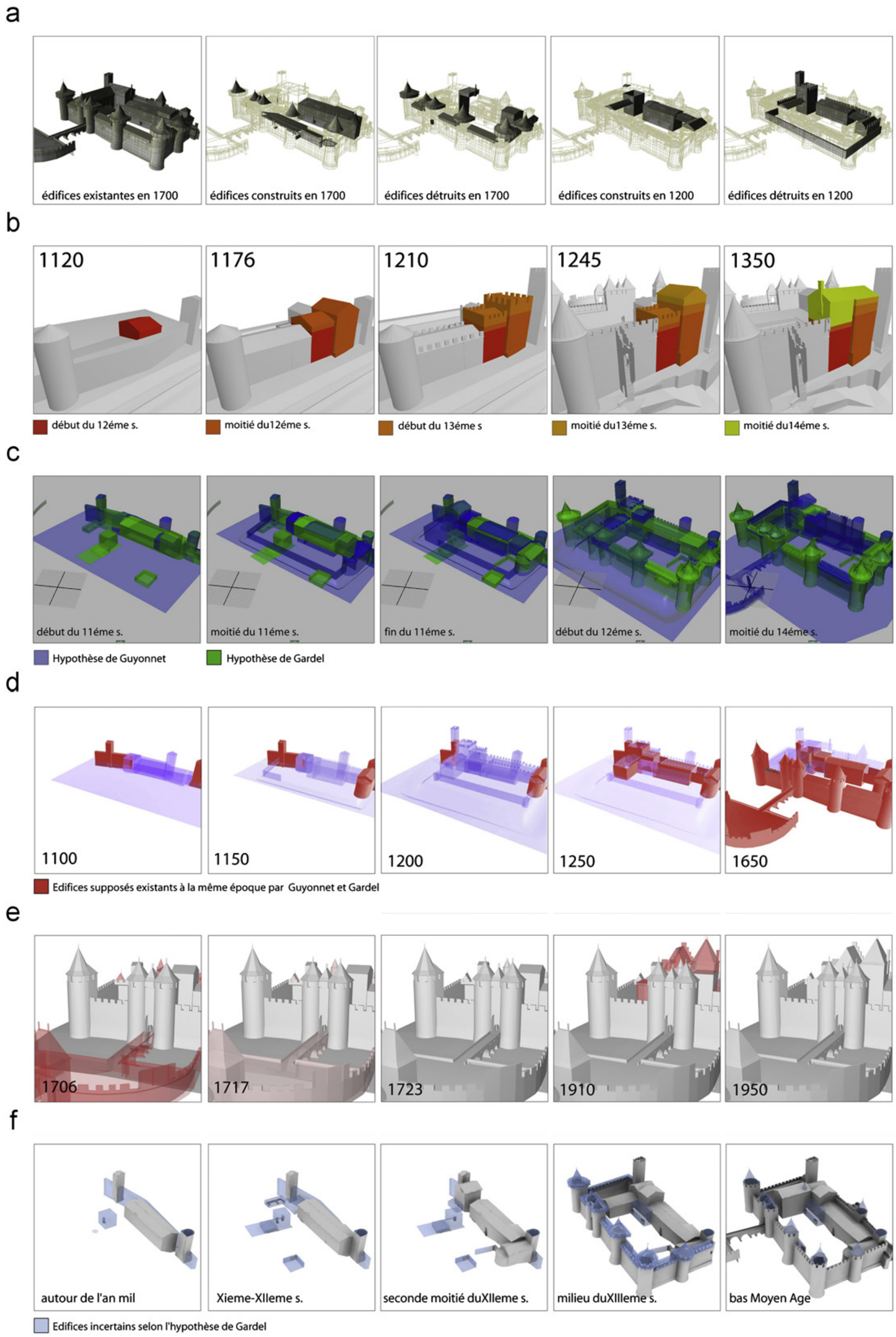

Fig. 10. Semantic-based temporal queries displaying, for various past states: (a) temporal selections, (b) building ancientness, (c) assumptions, (d) assumption comparison, (e) temporal uncertainty and (f) spatial reliability level.

5.4.1. Viewpoint-based photograph searching

This search method allows a database query to be formulated according to the camera viewpoint (the current position of the navigation camera) in the scene [30]. It relies on the intersection between the visual pyramid of the browser camera and that of each photo stored in the database. Intersection computing between the visual pyramids considers three main criteria: the browser camera field (size of the visual pyramid), the distance between the browser camera position and the optical center of each camera linked to photographs and the angular difference (around the vertical axis) between the orientation of the camera browser and that of photographs. These three criteria can be configured at any time by the user during navigation of the scene to better filter the query. The user can choose the camera view angle between 50° and 120°, the distance from 0.5 to 50 m, the angle from 0° to more or less than 180°.

All information related to the camera geometric models concerning photographs are controlled by a table. This table is internal to the 3D scene, to allow real-time camera detection. Furthermore, at any time, in the interface an indicator displays the number of detected photographs. Once the camera viewpoint is fixed, a query is launched to the SQL database, using the identifiers of the photographs displayed in the PHP page. The display order of results is calculated as a function of the distance and orientation deviations between the viewpoint and the detected photographs (Fig. 11).

By knowing the camera parameters of photographs stored in the database, one last feature allows the photograph's viewpoint to be found in the 3D scene. This function is based on a linear interpolation between the extrinsic and intrinsic parameters of the camera navigation and those of the selected photograph. This corresponds to a displacement and a rotation of the navigation camera in order to reach the optical center associated with the photograph. Once the shifting is completed, firstly the focal length of the navigation camera is adjusted to that of the photograph; secondly, a plane orthogonal to the main camera axis is generated and finally it is distorted according to the film back proportions of the photo. A final procedure downloads the photo (at small size) from the database and displays it as a texture of that plane in the 3D scene.

5.4.2. Entity-based photograph searching

This search method allows users firstly to select architectural elements in the 3D scene and finally to launch a query in order to find photos corresponding to the selected object in the database (Fig. 12). Once a morphological entity is selected (whatever is geometric representation), a function seeks all photographs displaying the entity. The function is structured as follows: for each camera associated with the photographs stored in the database, it is verified whether the object is present in the associated semantic layer (SVG) produced by projection (see Section 4.1).

Precision between the polygon resulting from the semantic layer projection and the represented shape in the original image depends on the results of the spatial referencing process. The following process computes the area of visible elements in the image (expressed as percentages) and provides values to sort results: the image in which the selected entity occupies the largest area will be displayed first. The semantic layer overlapped by the image is enhanced by an interactive behavior (in Javascript) permitting discovery of the semantic segmentation of the image as mouse passes over (Fig. 13). The interactive SVG images are hybrid representations combining three types of information: the 2D image, the structure of the 3D scene and the terms used for describing the elements of the 3D scene. This richness of information allows taking into account image searching by element classes or by specific attributes. For instance, it is possible to search in the database all photographs representing a specific type of architectural element or any element affected by a specific kind of degradation.

6. Conclusions and future works

In this paper, we presented an integrated platform to manage digital representations of buildings for architectural applications related to the analysis and the documentation of cultural heritage.

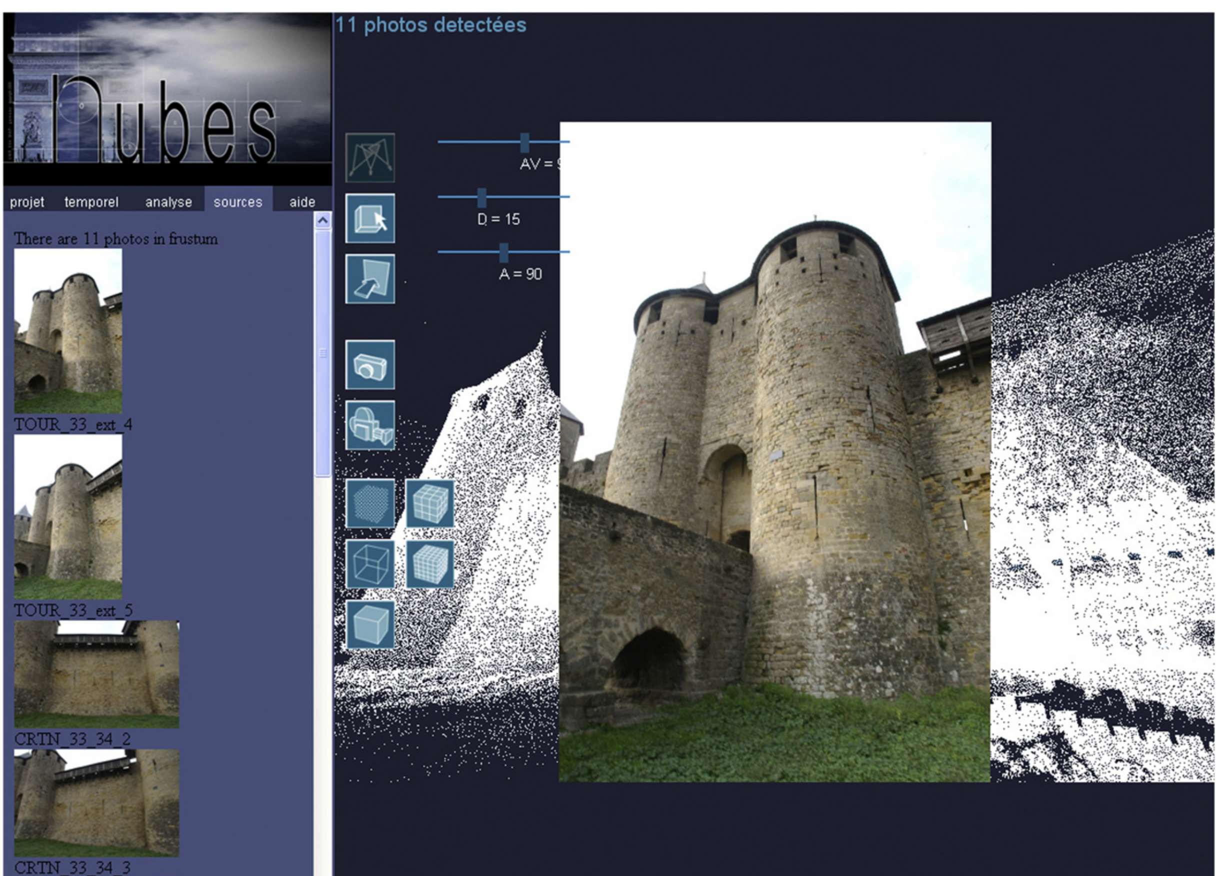

Fig. 11. Viewpoint-based image searching in the 3D scene. During the navigation in the 3D scene (right) and photos according to the observation point (in real time) are listed on the left of the interface. When the user selects a photo on this list, the navigation camera flies to the corresponding point of view showing the selected image in the 3D scene.

Fig. 12. Entity-based images searching in the 3D scene. When one or more 3D entities are selected in the 3D scene, all photographs in which these elements are present are listed. The semantic layer related to the selected elements (mapped on photos as a SVG mask) is highlighted.

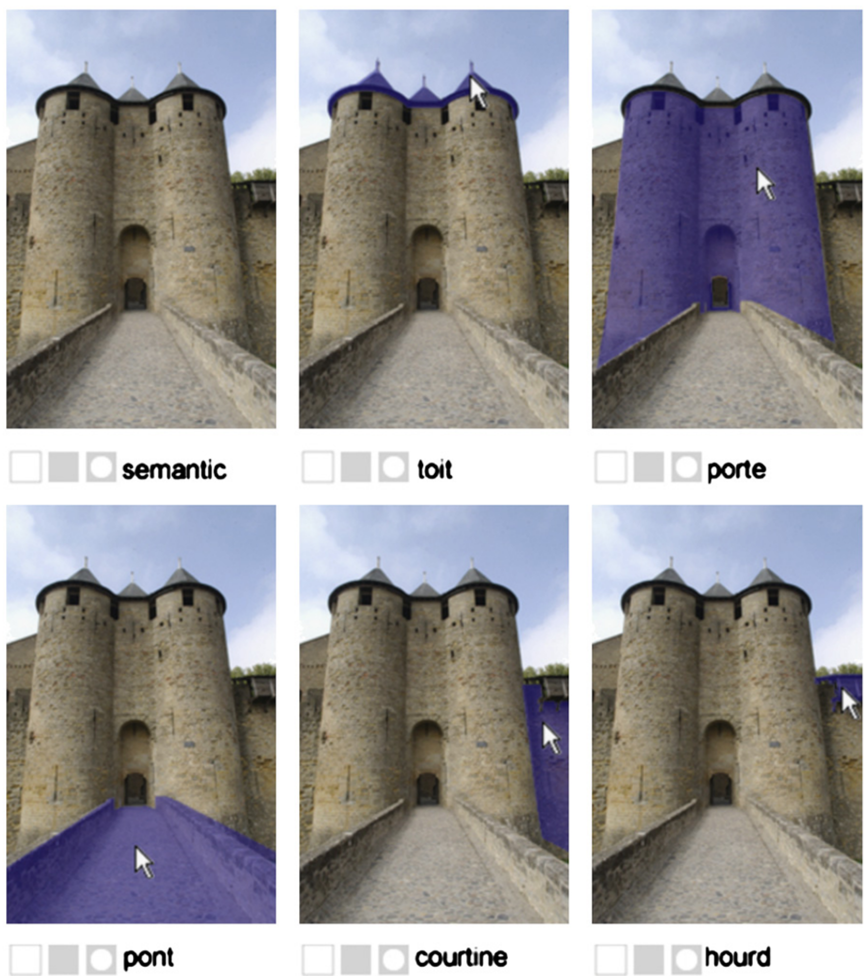

Fig. 13. Interactivity of semantic layers associated to images. Moving the cursor on photos, the semantics coming from the 3D model is highlighted showing vocabulary terms (on the bottom of each image) related to the selected entities.

Various fundamental problems have been explained and various informatics developments have been presented. We are actually working with some specialists in conservation that use our platform in order to organize the 3D representation of artifacts and heterogeneous data coming from analysis of degradation. Two papers discuss these applications [31,32].

After the results were obtained, different research perspectives open. A first perspective concerns the link between 2D and 3D visualization. By using the method conceived for structuring 3D models, an extension would consist of creating links (projection of graphic and alphanumeric information) between two-dimensional analysis supports (i.e. visualization of profiles, depth-maps, thermography, etc.) and 3D models of buildings. Beyond the methodological problems that only a multidisciplinary approach could tackle (i.e. formalization tools for the analysis of material degradation), various technical challenges must be evaluated: for instance, it should be necessary to define projective transformation procedures required to attach graphical entities (symbols, polygonal areas, etc.) to 3D representations; moreover, it could be important to dynamically display and control simultaneously several thematic layers and their topological consistency in the 3D scene.

A second perspective concerns the generation of a semantic description graph starting from a morphological analysis of 3D elements. It is based on the capability of classifying the elements composing buildings by dimension, by orientation, by similarities in order both to extract the composition rules and to distinguish the vocabulary and the grammar concerning buildings.

Finally, at this moment most of the operations to provide content are based on manual process. We plan to automatize some of these (especially the semantic annotation and the image registration) making use of the image-geometry mutual relation [33]. Readers can find a lot of resources about our platform in the following web page: http://www.map.archi.fr/nubes

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