An Iconography-Based Modeling Approach
for the Spatio-Temporal Analysis of Architectural Heritage

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Abstract—**The study of historic buildings is usually based on the collection and analysis of iconographic sources such as photographs, drawings, engravings, paintings or sketches. This paper describes a methodological approach to make use of the existing iconographic corpus for the analysis and the 3D management of building transformations.**

Iconography is used for different goals. Firstly, it's a source of geometric information (image-based-modeling of anterior states); secondly, it's used for the re-creation of visual appearance (image-based texture extraction); thirdly it's a proof of the temporal distribution of shape transformations (spatio-temporal modeling); finally it becomes a visual support for the study of building transformations (visual comparison between different temporal states).

The aim is to establish a relation between the iconography used for the hypothetical reconstruction and the 3D representation that depends on it. This approach relates to the idea of using 3D representations like visualization systems capable of reflecting the amount of knowledge developed by the study of a historic building

Keywords : Iconography, Image-based-modeling, shape transformation, uncertainty representation, information visualization, architectural heritage.

I. INTRODUCTION

The etymology of the "iconography" term comes from the old Greek "ikon" (image) and "graphein" (to write). As a field of study, Iconography is the branch of art history that studies the identification, the description, and the interpretation of the image content. In the specific field of architectural heritage, this term is used to indicate the set of representations related to the same subject. The study of building transformations over time is generally based on the gathering and analysis of iconographic sources (photographs, drawings, engravings, paintings, etc). On one hand this corpus can be considered as the visual proof of the state of a building at a given time, on the other hand it is at the basis of hypothetical restitutions formulated by historians and archaeologists and sometimes represented in 3D by means of computer graphics techniques. The combined use of 3D reconstructions and traditional 2D documentation is today an efficient way to display and verify historical site analysis and interpretation. However, this widespread approach has many limits if we consider the possibility of using computer graphics techniques in order to analyze, manage and display scientific content related to the building history .

Firstly, building shape is usually not constant in time: it can undergo significant modifications or even disappear. 3D reconstructions of heritage buildings focus normally on existing states and not on the management of historical evolutions or fuzzy elements. Most studies propose static restitutions where buildings are represented in one historic moment that is usually the current one or the original one, but not its transition or declining state.

Secondly, if on one side iconographic sources are generally used like visual memory of a building temporal state to be restored graphically, on the other side few works today focus on the use of all metric and visual information contained in sources. For example, an old photograph could allow the restoration of dimensional and geometrical data related to the shape of disappeared elements. Furthermore, it can sometimes provide accurate information on the visual appearance of the materials composing the building.

At last, iconographic documentation concerning building past states is sometimes contradictory, dubious and incomplete. As a consequence, an important issue relates to the capability both to manage site historical evolutions and to highlight uncertainties, contradictions and gaps in information used for the 3D reconstruction. The issue relates to the idea of using historical building 3D models like a visualization system able to reflect the amount of knowledge resulting from its investigation.

This paper describes a methodological approach to make use of the existing iconographic corpus for the analysis and the reconstruction of the buildings transformations.

Our approach is built joining three main aspects in a complete workflow:

- the spatial and temporal referencing of 2D iconographic sources for the 3D reconstruction of disappeared building states;

- the analysis of building transformations by means of a temporal state distribution;

- the use of spatial relations established between 2D iconography and 3D representation for the visual browsing of information based on spatio-temporal criteria.

The approach definition is illustrated by the study of a roman monument: the "Trophée des Alpes" in "La Turbie", in the south of France.

II. RELATED WORKS

Today modeling software enables users to obtain particularly rich and complex geometries with a high level of detail. Moreover, according to [1], computer graphics offers a vast range of visualizations (wireframe, transparency, broken lines or various rending modes) which leads us to think that architectures are always described in a correct, objective and complete way. In the panorama of current researches, various information representation approaches are proposed. In some works [2], historical reconstructions are geographically well integrated; however the result is a set of photorealistic images showing an historical site that does not exist anymore. The historical state is so detailed that the public is led to believe that the site was very similar to the restituted one. In other works, hypothetical parts and historical states are displayed by color coding [3], by transparency [4], wireframe or broken lines [1], as the goal is to distinguish the certainty levels. However, uncertainty interpretation is limited to the 3D scene: parts are shown with different transparency levels but data cannot be fully manipulated and information cannot be fully extracted [5]. Other researches propose mixed approaches combining the 3D scene with temporal diagrams [6]. Uncertainties and historical states are clearer, however lack of information and building transformations are not taken into account.

In order to make use of iconography for the 3D reconstruction of building prior states, we analyze some interesting research works related to image-based-modeling and spatio-temporal modeling.

A. Image-based modeling and rendering

Image-based modeling and rendering techniques are used more and more for 3D building reconstruction [7]. Multi-images solutions are based on establishing projective relations between a set of photographs of a single scene in order to extract characteristic points for the 3D reconstruction workflow [8,9]. Single-image solutions make use of knowledge related to the geometric invariants of some primitives in order to estimate the elements composition in the photographed scene [10]. Other more flexible solutions are also employed for the 3D model reconstruction starting from paintings with correct perspective [11].

B. Spatio-temporal modeling

For a long time, in the field of cultural heritage and GIS, researchers have only been concentrated on the manipulation of spatial geometries, describing them in terms of position and form. Interactive processes managing spatial queries have been developed; whereas temporal aspects have often been disregarded as less important attributes [12]. However, any change in space also implies the passage from the instant of time 0 to 1. Therefore, temporal notions play an essential role in the description of transformations. Mainly within the context of historical heritage, buildings may modify their mutual relations over time. Lately researchers [13] in similar fields have started considering spatial and temporal transformations as joint concepts.

C. Critical analysis of related works

This paper discusses an original topic that joins the spatio-temporal modeling with image-based modeling. Few researchers worked in this joint problem. Given an unordered collection of photos (related to different periods) the temporal ordering of images is inferred by reasoning about the visibility of 3D structure in each image in [14]. The 4D Cities project [15] aims at building time-varying 3D models that can serve to pull together large collections of images pertaining to the appearance, evolution, and events surrounding places or artifacts over time.

Concerning image-based-modeling, the presented techniques can be applied to the 3D reconstruction both of building current states (using specific photographic shooting techniques) and of prior states (using old photographs or other kind of images). In its last case the available geometric information level is rarely exhaustive for the full modeling of a building. Firstly, having many photos of the same building from different viewpoints at a past historical period is unlikely. Secondly, having information related to the used cameras (such as the focal length and distortion) is complicated. Finally, old image geometry is often modified by trimming or reproduction process.

Concerning the temporal dimension, in a general way, visualizing site evolutions is difficult. In the community, the historical site recollection is often fixed to a precise state, the current one or the past one. Moreover, people are inclined to reinterpret images and to reduce complex shapes to simpler and preferably symmetrical ones [16]. As a result, site evolution is often represented as running images describing buildings in fixed states. Particularly, in the case of buildings, the following aspects strongly affect their transformations and their mutual relations: the typologies of transformation and their duration.

Categories of transformations. Potential transformations of a building throughout its existence are abundant and various. In fact a building can undergo both physical transformations and qualitative ones. On one hand, buildings are built, destroyed, or rebuilt. They may also be extended, attached to other ones, or divided into several buildings. They may undergo simple or minor geometrical modifications, too. Less frequently, buildings can be entirely or partially moved and rebuilt somewhere else. On the other hand, their destination can change over time, as well as their owner or identity.

The duration of transformations. Changes involving buildings can be sudden or gradual. For instance, a change of property is a sudden event. On the other hand changes may be progressive: for example, building demolition is a short event but the construction site of a Gothic cathedral is a long event that lasts several centuries. Furthermore, historical building deteriorations may take centuries or millennia.

III. GENERAL OVERVIEW OF THE APPROACH

In order to conceive a complete methodological In order to conceive a complete methodological approach for the iconography-based 3D reconstruction of historic

building, we integrate different techniques of surveying, modeling, rendering and structuring into a coherent workflow based on three main steps.

Iconography-based 3D reconstruction (section 4)
- 3D surveying of the current state of the building
- Spatial and temporal referencing of iconography sources
- Image-based reconstruction of prior states starting from iconography

Spatio-temporal modeling (section 5)
- Temporal distribution of transformation events
- Time-based model organization

Visual browsing in space and in time (section 6)
- Spatio-temporal queries
- Visual comparison of temporal states

Iconography is used for different goals. Firstly, it's a source of geometric information (image-based-modeling of anterior states); secondly, it's used for the simulation of the visual appearance (image-based texture extraction); thirdly it's a proof of the temporal distribution of shape transformations (spatio-temporal modeling); finally it becomes a visual support for the study of building transformations (visual comparison between different temporal states).

The presented functions are integrated (or in development) in the NUBES platform, developed at the MAP-Gamsau Laboratory. In particular, it deals with NUBES Forma, a 3D reconstruction tool based on point-clouds and photogrammetry, developed as a Maya Plug-in in MEL (Maya Embedded Language) and C++. It is displayed in NUBES Visum, a 3D Web Information System at the architectural scale, developed in PHP/MySQL and VirtoolsDEV.

IV. ICONOGRAPHY-BASED 3D RECONSTRUCTION

Our method starts with the elaboration of an accurate 3D model of the building current state (see Fig.1).

This step, which we will not detail in this paper, is based on a hybrid acquisition (3D laser scanning and phogrammetry), followed by a reconstruction approach previously described in [17]. This 3D model makes up the general support for the following operations of space-time iconography referencing like for the semantic structuring step. In order to manage the temporal structuring, this 3D model was produced by taking into account requirements of structure disassembling (block per block) .

A. Iconography recovering and interpretation

In the study of historical buildings, the collection of sources describing their past states is often contradictory, heterogeneous, dubious and incomplete. As a consequence, building transformations are sometimes difficult to interpret. In fact, a certainty degree and a quality level characterize each source. These two aspects depend on a human component and on representation tools [18]. The certainty degree depends on the author of the source. In

general the author can express his or her own point of view, or sometimes represent un-built projects. In isolated cases, certain sources can reveal contradictions.
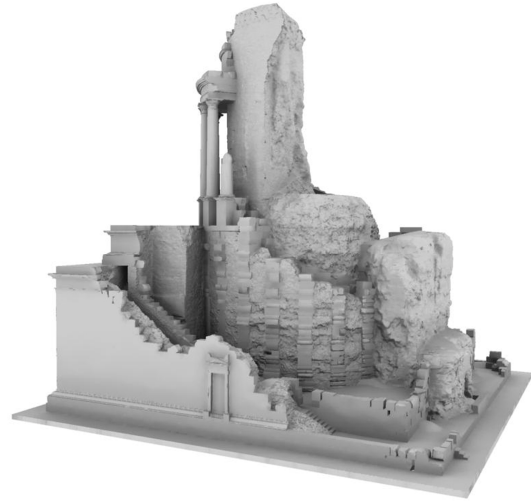

Figure 1. 3D model of the current state of the building elaborated with a hybrid modeling approach mixing laser scanning and photogrammetry techniques.

The quality level depends on the preservation state of the source, on the adopted representation tools and on the description goal. These three aspects play an important role in determining the relevancy level.

Essentially, iconographic sources of building past and disappeared states can be classified according to the quality of information (graphical, dimensional, geometrical, etc.) that they contain. The difficulty is to establish a relation between the kind of iconography and the 3D representation one can effectively extract from it. In relation with our purpose, one can classify iconographic sources according to the projection type (perspective or orthographic) and to the technique of graphic execution (from a human sketch to a machinery-based image generation).

Regarding graphical sources like drawings or paintings, usually this typology does not contain unquestionable dimensional information, except for some correct perspective representations based on machinery. Firstly, this kind of sources can provide information about the general morphology of a building. Secondly, the 3D modeling starting from a graphical source (combined with information coming from the real artifact) always introduces an interpretative factor (that of the user).

Finally, the typology of sources helps structure the 3D representation but it does not determine it: each representation is always a compromise between many parameters (metric, quantitative, visual, etc.). For all these reasons, iconographic sources are so heterogeneous that establishing a univocal relation is almost impossible.

Considering photographs, the problem is different because the generation of this kind of images is linked to a technical process that can be formalized from a geometrical point of view [19]. In the next paragraphs we focus principally on these kinds of sources so that the iconography-based modeling approach will be used with

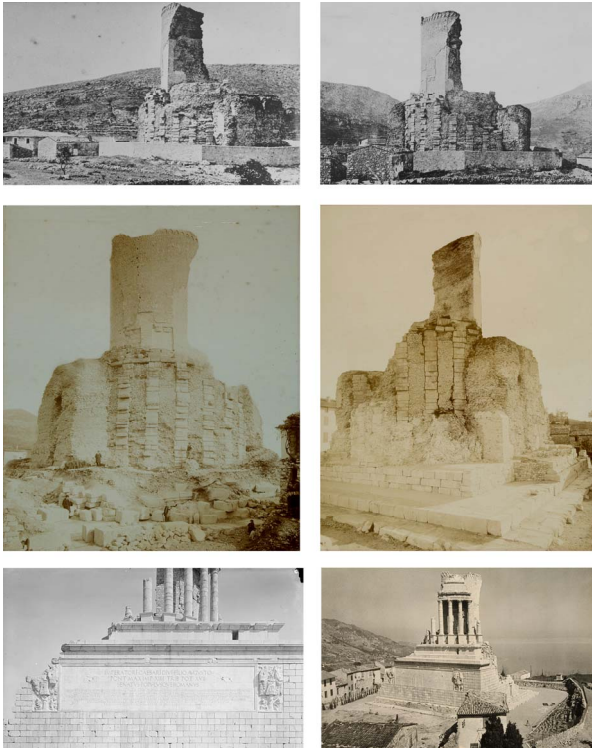consistent sources at least from the geometrical point of view (see Fig. 2).

Figure 2. A set of photographs of the "Trophée des Alpes" in "La Turbie" related to different historic periods.

B. Image-based modeling from iconography

Our iconography-based modeling approach is based on image-based-modeling and rendering techniques. We distinguish three different steps:

- Spatial referencing of photographs on the 3D model of the current building state;

- 3D modeling of building prior states starting from old photographs;

- Visual enrichment of the reconstructed geometry by texture extraction and projection starting from photographs.

1) Spatial referencing of iconography

In order to establish a projective relation between old photographs and the 3D model of the building current state, we use a spatial resection procedure. Starting from a set of correspondences established between the photograph (2D) and the current state model (3D), one determines the camera geometrical model associated to the photograph [20]. It deals with the intrinsic (focal length and distortion) and extrinsic (translation and orientation) parameters related to the image geometrical model. The spatial resection of old photographs poses two main problems.

The first one covers the lack of information related the camera used at the shooting time and the lower precision degree concerning the image format (that can be modified or trimmed). In this case, intrinsic parameters estimation becomes the most difficult task.

The second one addresses the possible morphological incoherence between the building state at the shooting time (photographs) and that one at the surveying time (3D model). That introduces various problems in the 2D/3D correspondences selection step. The solution consists in leading this step using the unmodified parts of the building.

For the estimation of the spatial resection we use a versatile camera calibration algorithm [21] needing at least 11 2D/3D correspondences with the intent of providing intrinsic and extrinsic parameters of the camera. In order to obtain a better parameter estimation, characteristic points are accurately selected so to distribute homogeneously the 2D/3D correspondences from the viewpoint both of the image maximal extension and of the maximal depth range of the 3D scene. For the illustrated experience, six old photographs with global errors (average of re-projection errors) included between 6 and 25 pixels have been superposed (see Fig.3).
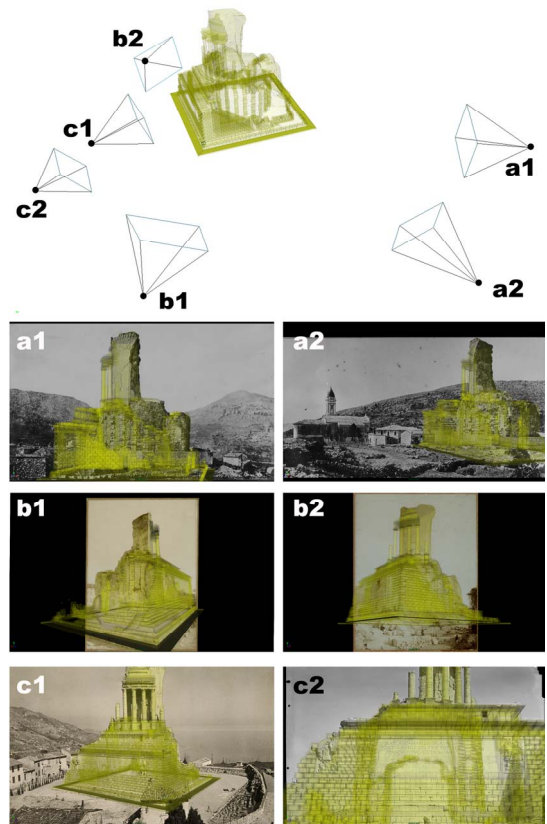

Figure 3. Fig. 3. Spatial referencing of historical photos on the 3D model of the current state of the building.

2) Image-based modeling of a temporal state

Elaboration of 3D representations of building states starting from historic photographs is generally based on the comparison between two temporal states: the 3D representation of the existing state and a 2D perspective projection of a prior state.

Starting from a reference description of the entities in the 3D scene (building current state), we customize three common modeling operations related to the temporal distribution of transformation events (discussed in the next section of the paper):

Adding (3D modeling of entities existing in the analyzed temporal state but missing in the current state or in other past ones);

Modifying (splitting, joining or deforming geometrical entities related to other temporal states);

Deleting (hiding entities which do not exist in the analyzed temporal state).

For the operation of *adding* geometrical entities, the image-based-modeling capabilities are used: the control of the positioning and orientation of geometrical primitives laying on the perspective projection on the image. In the specific case of the developed working environment (see Fig.4), we make use of geometric information coming also from the current state 3D model. That provides a rich support to the reconstruction stage (coordinates, straights, reference planes, etc.). In fact, the spatial resection of the photo generates a working environment which allows to recover the position of the characteristic points defining the shapes to reconstruct.
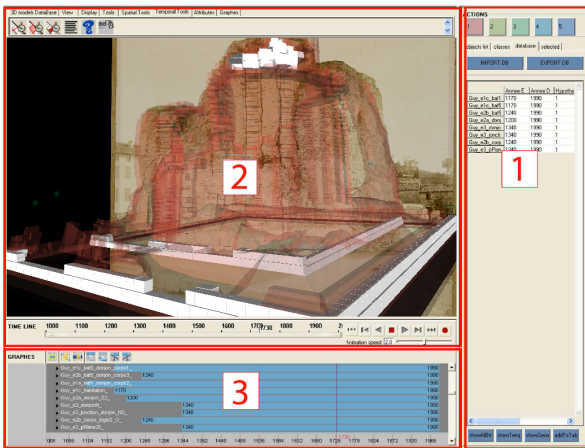

Figure 4. A screenshot of the developed working environment: 1) transformation event management; 2) image-based modeling; 3) temporal diagrams.

In order to take into account the information lack due to the absence of historical contemporary images or to the geometric inconsistencies between two states, different interactive modeling solutions were explored using the intersection principle:

- intersection of two projection lines corresponding to homologous points selected on two images (both of them related to the same temporal state or two different ones).

- intersection between the projection line of a selected point on the image and an axis of the 3D scene general pivot.

- intersection between the projection line of a selected point on the image and a reference plane previously defined in the 3D scene.

The characteristic points extracted from the shapes are used in order to position, handle and deform geometric entities. Different interactive modeling techniques are used: primitive adjusting, face extrusion, meshing, etc. When geometric information about shapes is missing or uncertain, standard geometric properties of architectural shapes - i.e. parallelism, orthogonally, symmetry, etc. - are taken into account.

Concerning entity *modification* - starting by existing modeling tools - we define three editing functions:

Splitting, allowing geometric entity parts to be separated in order to hide them in the chosen temporal state;

Joining, allowing geometric entities belonging to different temporal states to be combined in an unique one;

Deforming, allowing instances of existing geometric entities to be generated in order to modify their shape according to the selected temporal state.

Entity *deletion* is based on the assignment of a temporal attribute hiding the selected entity in the analyzed temporal state. These three operations are related to the temporal referencing of the iconography (in our case, spatialized old photographs): *adding*, *modifying* or *deleting* entities correspond to specific temporal attribute assignments. The interface developed allows the display of elements related to a temporal state (iconography and 3D elements) according to the time position selected on a time cursor.

V. SPATIO-TEMPORAL MODELING

A. The historic graph as temporal notation

Among several approaches managing spatio-temporal transformations [22], Renolen's historic graphs [23] represent a suitable notation for the field of historical heritage. Transformations such as building creation, union, division, demolition and reconstruction can be represented through this system. Such an object oriented approach reveals this kind of building transformations by showing the relations between entities and their lifespan. A notation graph facilitates transformation understanding.

According to our modeling approach, we can formalize 6 types of physical transformations (see Fig. 5): creation (*adding*), demolition (*deleting*), union (*joining*), division (*splitting*), reconstruction (*deleting/adding*), modification (*deforming*).
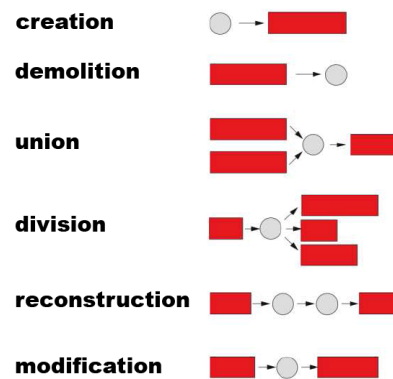

Figure 5. Transformation events formalized for temporal modeling.

Starting from these transformation events, a graph is created during the modeling process in order to dynamically visualize the temporal structuring of modeled entities. This graph can be modified in two different ways:

- a new independent entity (*adding* function) and its temporal attributes (temporal referencing of the iconographic sources) are created, and new temporal values are thus inserted;

- the temporal attributes of the existing entity are modified.

The nature of the links among entities is dynamically modified when modification implies division (*splitting*), union (*joining*) or reconstruction (*deleting/adding*).

B. Spatial and temporal resolution

In a previous work [24] we have demonstrated that building transformations can be formalized by means of historic graphs fitted to different spatial and temporal resolutions.

1) Spatial resolution

Various spatial resolutions can be applied to entities according to the goal of the analysis. From groups of buildings to single building components, resolution will be progressively higher. The concept of graphing can have different meanings. Rectangles can stand for single buildings. However, at a higher resolution level, each rectangle could symbolize the various parts composing a building (see Fig. 6a): walls, roofs and blocks belonging to the same construction built at different temporal periods. Lastly, at a lower level, each rectangle can be related to a group of buildings (see Fig. 6c) whose transformations are grouped together.
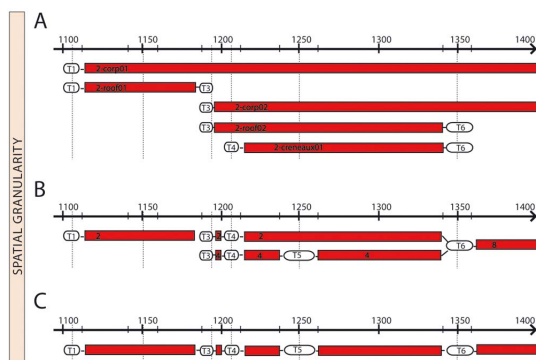

Figure 6. Example of spatial resolution applied to three different scales : building components (a); building (b); groups of buildings (c).

2) Temporal resolution

In the same way, temporal resolution varies for graph visualization according to the « temporal scale » analysis. As a result, each transition (smoothed rectangle) can reveal only one change of the building state (see Fig. 7a). However, in a wide-ranging analysis, a smoothed rectangle can stand for multiple and complex transformations such as extremely small, close or overlapping changes (see Fig. 7b,c).
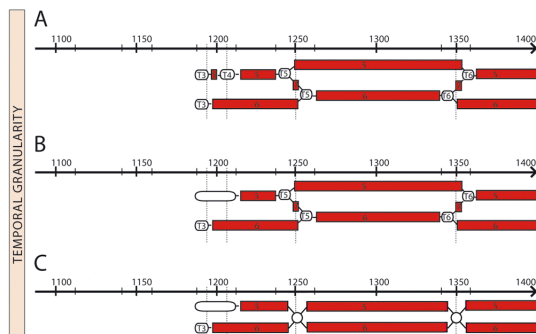

Figure 7. Example of temporal resolution: all transitions (a), transition simplification (b and c).

C. Space-time digital mock-up structuring

This section deals with two fundamental topics: space structuring and the relation between space and time. Building description is one of the most delicate aspects to take into account in a spatio-temporal formalization. Buildings are rather complex entities, comprised of many functional elements, each of them having specific characteristics, materials and functions. Furthermore, when buildings undergo morphological variations through time, the type of structuring depends on temporal fragmentation. The study of an historic building reveals several stratifications throughout time. As a consequence of this, a simple façade cannot be considered as a single entity. Time becomes the fourth dimension in the morphological structuring: shape is conceived at a certain time, but it can last for different periods of time.
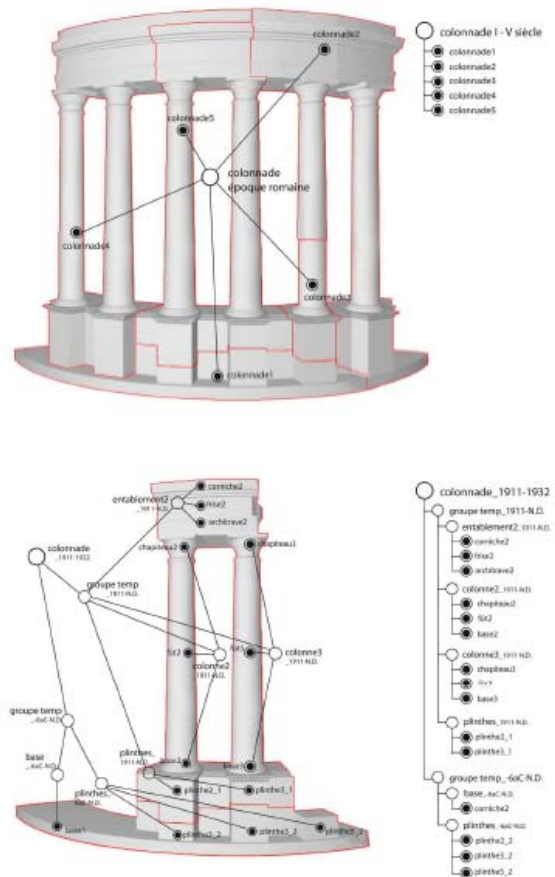
Figure 8. Model structuring according to different temporal states

For this reason, structuring digital models in space according to temporal organization is a complex task. The following paragraphs focus on the semantic description of the building in order to build a time-based morphological organization of its entities.

1) Semantic description

This aspect deals with the spatial structuring of virtual models in order to allow multiple restitutions. These reflections are in line with a previous work [25] in which we established how to transform general data into

significant and structured spatial information on buildings. The solution consists of three phases: firstly the classification of building components according to selected « points of view » (by function, by material), secondly the morphological building decomposition and thirdly the creation of associations of concepts by means of description graphs. Such graphs provide a semantic value to the morphological representation of architectural objects.

In the specific case discussed in this paper, the goal is to integrate the temporal notion into the 3D-model structuring. The chosen « point of view » will be that of Time. Data are therefore structured according to the following four-level-hierarchy:

- *classes,* macro groups that encompass historical building complexes;

- *groups,* corresponding to buildings and their major components (ground, walls, bays, roofs, etc.) belonging to the same time period;

- *entities,* standing for the functional/temporal 3D-model elements;

- *reference marks,* representing the lowest-level elements which sources are fixed to.

2) Time-based morphological organization

Using this formalism, two main parameters condition the morphological structuring of the building: the transformation scale (concerning the whole building or its components) and the chosen « point of view ».

Then the time-based morphological segmentation can be executed at different levels: if the viewpoint is only that of time, each building is structured without taking into account other division strategies.

On the contrary, if the organization criteria are those of function or material, temporal decomposition is overlapped to other criteria. Graphs will be anchored to elements structured according to a hybrid decomposition (functional and temporal) and temporal attributes will be attached to the hierarchy of these graphs. The goal of the analysis is to define both the morphological segmentation and the relations between concepts (describing shapes) according to temporal criteria. For example, groups can reassemble simple temporal entities (see Fig. 8a) ; otherwise, if both temporal and spatial concepts are described at the same time, sub-groups can link elements related to the same category (see Fig. 8b). Temporal description can be therefore associated to other hierarchical organizations of entities.

D. Implementation

In section 3 we argued that the process starts from a photogrammetric or laser-based reconstruction of the current state; previous states are manually built up with primitives based upon earlier iconography and interpretations.

The user determines physical changes over time laying on iconography. Temporal referencing is easier when analyzing consecutive temporal states, however 3D model modifications can be performed without following a specific time-related order: if a temporal state is inserted in the middle of the process, a procedure allows to update

links with previous and following temporal entities. The tasks characterizing implementation are listed here below.

1) Iconography insertion and referencing.

Once iconography is inserted into the system, a procedure allows the user to attach temporal attributes, including the snapshot time and the state described by the snapshot. Each state represents a period which artifact does not undergo changes in, it is therefore characterized by starting and ending dates (see Fig. 9).

```
6   //create existence/demolition date : 1911-1933
7   addAttr -ln snapshotTime -at long -dv 1920 photo1;
8   setAttr -e -keyable true photo1.snapshotTime;
9   addAttr -ln startingDate -at long -dv 1911 photo1;
10  setAttr -e -keyable true photo1.startingDate;
11  addAttr -ln endingDate -at long  -dv 1933 photo1;
12  setAttr -e -keyable true photo1.endingDate;
```

Figure 9.   Mel script for referencing iconography.

2) Entity spatial referencing: defining classes and groups.

For each state, entities are manually structured according to the chosen viewpoint, by means of procedures for creating groups and subgroups. Each entity is defined by a symbol representing it in its barycentre, thus expressed by three spatial coordinates x, y, z.

3) Entity temporal referencing: defining temporal and relation attributes.

Each referenced source becomes the guide for temporal structuring. Entity temporal referencing is based on the comparison between reconstructed elements and the source taken into account. Automatic procedures (see Fig. 10) associate each group, subgroup or entity with:

- *temporal attributes* identifying groups or entity life cycles. Attributes attached to groups/subgroups are shared out also to hierarchy lower-level entities. If, according to sources, morphological entities exist along several states, a procedure allows temporal attributes to be updated.

- *relation attributes*, describing transformation history of entities according to their relation to their previous state. These attributes specify the type of transformations undergone by classes, groups and entities over time. An automatic procedure stores transformation dates, duration and entities concerning changes. Artifact transformations can be simple morphological variations or more important changes such as building division, union or reconstruction.

```
6   //create existence/demolition date : 1911-1933
7   addAttr -ln ExistYear -at long -dv 1911 colonnade;
8   setAttr -e -keyable true colonnade.ExistYear;
9   addAttr -ln DestrYear -at long -dv 1933 colonnade;
10  setAttr -e -keyable true colonnade. DestrYear;
11
12  //update attribute value according to source value:
13  //select the picture first, and then the object
14  string $sel[]=`ls -sl`;
15  $newAttr = `getAttr ($sel[0]+".endingDate")`;
16  setAttr ($sel[1]+".DestrYear") $newAttr;
```

Concerning temporal and relation attribute definition, the operations described in session 4.2 are implemented as follows.

Creating. Temporal attributes relating to the life cycle are associated to single entities (see Fig. 11) or groups by means of procedures. Moreover, attributes can be manually modified by the user at anytime, i.e. when the entity life cycle is extended to other states according to other sources.

Splitting. This procedure allows an entity or a group to be separated into several entities or groups keeping the same temporal attributes. In order to modify attributes, it is sufficient to link the new entity or group to the related source.

Union. This procedure combines several entities or groups in a given temporal state. This can be performed only if their temporal attributes are identical or not yet defined. Otherwise, in case of inconsistency, a procedure guides the user in entity attribute verification.

Adding. By this action, entities or groups are attached to other existing entities/groups thus acquiring their attributes.

Deleting. This action sets the demolition date of entities, groups or classes. A procedure hides entities when their life cycle is finished (see Fig. 11).

Reconstruction. This action identifies a link between two groups or entities that are not simultaneous.

```
6    //create attributes for entities
7    addAttr -ln ExistYear -at long  -dv 1300 Entity;
8    setAttr -e -keyable true Entity.ExistYear;
9
10   //deleting
11   hide $csObjsDate[$i];
12   setKeyframe -breakdown 1 -hierarchy none
13   -controlPoints 0 -shape 0 $csObjsDate[$i];
```

Figure 11. Mel script for referencing iconography.

4) *Qualifying entity uncertainty*

Each created or modified entity is connected to an attribute that defines its degree of certainty. User can assign a value (selected between pre-established levels) according to the criteria defined in section 6.1 (b).

5) *Exporting temporal information and transformation history.*

Once the structuring has been carried out for all sources, automatic procedures allow the export of attributes relating to entities, groups and classes in the form of a .txt format file that can be used for other web applications. Data can be exported for a MySQL database to view evolution of the 3D-model through the historical graphs previously described (paragraph 5.1.).

VI. VISUAL BROWSING IN SPACE AND IN TIME

In the domain of the architectural heritage, uncertainty concerning prior periods strongly influences the knowledge on building life cycle. Our approach aims at underlining notions such as uncertainty and ambiguity, in order to analyze the actual relevance of processed spatial and temporal data. Moreover, entities composing our conceptual graphs become the common denominator linking hypothetical 3D representations and the iconographic sources that justify them. Geometry is not sufficient to understand historical site transformations. The 3D scene remains the main visualization and comprehension tool, but other visualization supports [13,26] are needed to understand relations among artifacts and to manipulate geometries. With the aim to build a visual interface for understanding spatio-temporal building transformations, we are working on the development of a visual browsing system that connects iconography sources to the 3D-model by means of a temporal graphic notation and a spatial search engine. Our web system (actually in development) is based on a three parts architecture:

```
for each building DO
calculate the list of unique dates concerning
        all its components in ascending order
for each date DO
    switch to decide which transformation
            corresponds to date
    case date = creation date:
        create circle/ellipse, arrow, rectangle
        End Case
    case date = destruction date
        create arrow, circle/ellipse
        End Case
    case date = union date
        for each building to be unified DO
            jump to the next building
            end for
        if building is the one after union than
            create diagonal arrows, circle/ellipse,
                    arrow (0°), rectangle
            end if
        End Case
    case date = division date
        if building is the first after division than
            create arrow (0°), circle,
                    diagonal arrows, rectangle
        else
            create rectangle
            end if
        End Case
    case date = reconstruction date
        create arrow, circle, arrow, rectangle
        End Case
    case date = degradation
        create arrow, smoothed rectangle,
                arrow, rectangle
        End Case
    case date = change of function
        create arrow, circle, arrow
        End Case
    case date = variation date
        create arrow, circle, arrow, rectangle
        End Case
    End Switch
End for
End for
```

Figure 12. Pseudo code fragment showing graphs representation.

- *real-time geometry manipulation:* a 3D scene developed in Virtools DEV1 allows the download, display and manipulation of different restitutions;

- *building transformation visualization: a SVG2 interface allows the reading of*

historical transformations by means of server-side dynamic graphs generated with PHP₃ on MySQL;

- **online consultation: a PHP page allows the user to select projects, temporal states, assumptions, and to display of data.**

Data is organized in a MySQL developed relational database, containing information regarding geometric entities (spatial and temporal information and certainty degree). This comprehension tool is detailed in the next paragraphs.

A. Information visualization on geometry

In order to understand fuzzy and contradictory data, the representation system needs to go beyond simple geometric restitution: it is necessary to take into account different visual solutions to understand and compare data. The qualitative attributes that we link to geometrical entities during the modeling stage are used as entries for a dynamic representation system based on Information Visualization techniques. In this paragraph, we discuss various viewpoints needing different kinds of display (in transparency or color coding).

1) Temporal states visualization

Color coding can be useful to better distinguish building components having different temporalities (see Fig. 13). Color tones shall be adopted according to the site context: for instance, if dates are too close to one another, visualization by colors not proportional to dates will offer a more useful result than a proportional visualization.
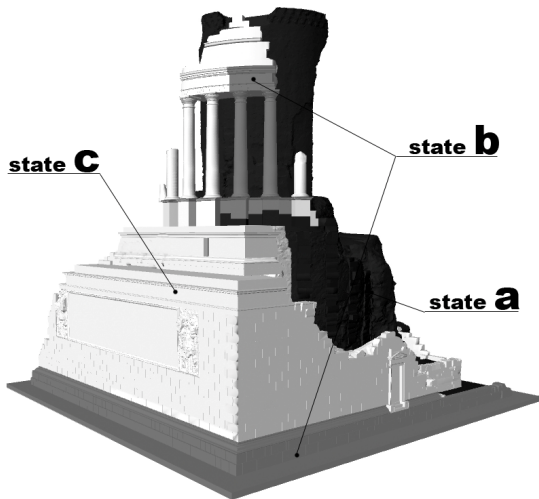

Figure 13. Visual coding of temporalities

2) Displaying uncertainty

To distinguish hypothesis from certain artifacts, assumptions are displayed in various transparency levels. In order to elaborate 3D representations capable to underline the actual knowledge state related to the hypothetical restitution of a temporal state, during the modeling process modeled entities are assigned some

qualitative attributes indicating the level of certainty related to their 3D reconstruction.

Our classification of the certainty levels is based on multiple aspects: presence / absence of the entity in the actual state of the building (initial 3D model); presence / absence of the entity in the iconographic source; accuracy level of the iconographic source (conservation state, image resolution, etc.); level of geometric resolution (according to the accuracy level of the iconographic source); certainty level of the archaeological reasoning.
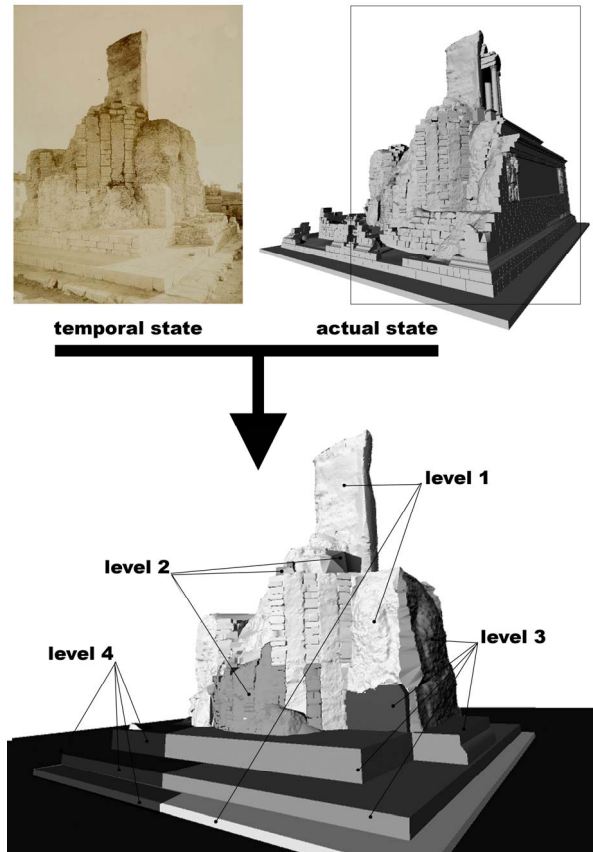

Figure 14. Uncertainty visual coding for the hypothetical representation of a temporal state

The degree of certainty is expressed by a visual coding related to the shading properties of the entities (see Fig. 14). A diffuse color parameter is set according to the certainty attribute assigned to the entity. We use 4 different opacity values:

- Level 1 (diffuse 100%). Entities which exist in the current state and on the iconographic sources concerning a prior temporal state. Shapes are modeled by means of 3D surveying (laser scanning or photogrammetry procedures).

- Level 2 (diffuse 75 %). Entities existing in the current state but whose shape is different at a prior temporal state. Shapes are modeled by *modifying* operators starting from 3D surveying of the building current state.

- Level 3 (diffuse 50%). Entities which are missing in the current state but existing in an iconographic source on a prior temporal state. Shapes are

modeled by *adding* operators which use image-based modeling techniques without metric or geometric support from the 3D surveying of the current state.

- Level 4 (diffuse 25%). Entities which are missing both in the current state and in iconographic sources related to a prior temporal state. Shapes are modeled by deduction, assuming the artifact shape based on fragments, or by analogy, inferring shape on the basis of the known similarity with other artifacts.

B. Graphs as an information visualization tool

In the field of cultural heritage, an information system formulating temporal queries or displaying states is not sufficient. The notation system previously described (see Section 5) achieves different goals.

Firstly, the graphs below a temporal bar allow the display of evolutions and mutual relations among buildings throughout time. Secondly, from building construction to its demolition, each graph retains the transformation history, including complex transformations such as union, division and reconstruction. Thirdly, graphs represent the link between the 3D scene and transformations. They interact with geometry to display transformations both on the scene and in the graphic notation. Finally, the representation scale can be adjusted: transformations are displayed at different scale levels according to the dimension of the selected time period. In this way, some small transformations which are not visible on a great scale, become visible on a smaller one.

In the section 5.3 we have illustrated the concepts of entity grouping according to temporal evolutions. Our semantic description approach allows in fact entity representation to be organized according to temporal criteria. On one hand, the semantic graphs establish the link between space and time and on the other hand, the notation graph represents the temporal positioning of geometrical entities (see Fig. 15).
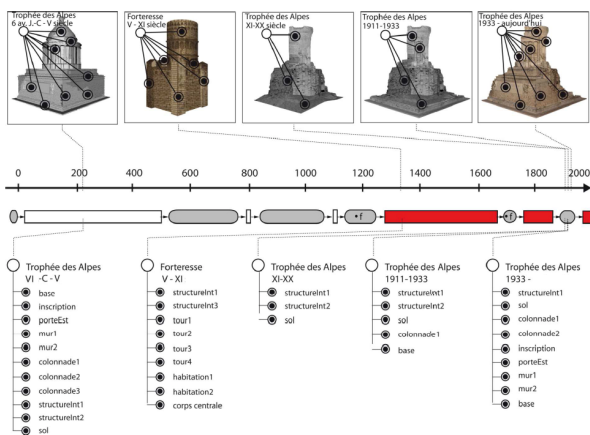

Figure 15. Spatio-temporal representation of building transformations. On the top: 3D representation and semantic graph; on the bottom : the temporal notation graph.

C. Spatial search for iconographic sources

Different researches focus on methods describing how to organize iconographic sources related to 3D representations. An entity-relation connection between iconography and 3D representation (or a part of this) should be preset (generally in an interactive way). Our search engine for iconography retrieval is based on the concept that 3D model allows for the access to information about a building using its morphology as interface [27]. Spatial referencing is used like a way to establish relations between 3D and 2D information [28]. In our specific case, we focus on two main methods: entity-based and viewpoint-based iconography searching.

1) Entity-based iconography searching

Since all iconographic sources in the system database have been spatially referenced to the 3D model in several temporal states (see section 4.2), we use a ray intersection method to determine which images are oriented to which object. The system tests the intersection between each of the camera's frustum related to the stored images and the geometry of a selected entity (taking occlusions into account). Query results are then listed according to two main criteria : the spatial distance (distance between 3D entities and cameras related to iconographic sources in which they can be present) and the temporal distance (distance between the temporal state assigned to the source used for the 3D entity modeling and temporal states related to all other iconographic sources which the selected entity can be present in).

That allows searching the whole of iconographic sources related to a 3D entity by visualizing (with relative precision) the place where it was, or where it should have been, or where it could have been (see Fig. 16).
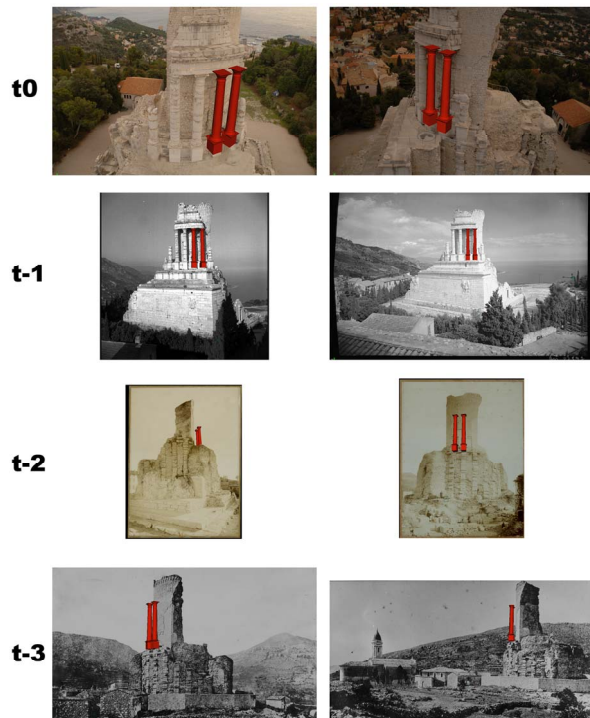

Figure 16. Entity-based searching of iconographic sources

2) Viewpoint-based iconography searching

In order to search iconography close to the current position and orientation of a navigation camera in the 3D scene, we built a 3D representation of the camera visual field associated with each photograph. In this way, we detect iconographic sources by intersecting the spatialized iconography frustums and the observation camera ones. Three parameters are used in order to filter the results of the intersection process: firstly, the distance between the navigation camera and the position of each optical center concerning iconographic sources; secondly, the angle between the orientation of the navigation camera and the orientation of each iconographic source; finally, the distance between the current temporal state (displayed in the 3D scene) and the temporal state concerning the founded iconography.

So, the image that most closely corresponds to the value of the geometrical model of the navigation camera and that is in accord with the nearest temporal state, will be listed first.

3) Visual comparison of temporal states

In order to visually compare two different temporal states we adapt the geometrical parameters of the navigation camera in the 3D scene to those of an iconographic source stored in the database. A 2D plane positioned in front of the navigation camera is textured by the selected image and is placed in the 3D scene. The 3D representation concerning another temporal state can then be displayed in spatial matching (see Fig. 17).

Figure 17. Visual comparison of two different temporal states.

VII. CONCLUSIONS

In this paper we have presented a complete approach for the spatio-temporal analysis of historic building transformations based on an extensive use of iconography. The aim of this approach is to establish a privileged link between the semantic, geometric and temporal representation of an historic building and the iconographic

source(s) allowing for assumptions on its life cycle. A number of important aspects need to be considered in future researches.

Firstly, other kinds of iconographic sources (such as drawings, paintings, etc.) can be used in the image-based-modeling process. This introduces the concept of spatial referencing uncertainty.

Secondly, temporal graphs are actually visualized in a two-dimensional way. However, they should be described directly in a 3D space, where the third dimension would store the history of each graph - i.e. the components of each graph for each historical period [29].

Lastly, image semantics is an interesting subject related to this work. We wish to integrate this concept into our approach in order to associate - by projection - a set of semantic layers to iconographic sources. Layers can be defined according to the spatial, geometric or temporal attributes that qualify 3D entities.

REFERENCES

[1] Strothotte, T., Masuch, M. and Isenberg, T. Visualizing knowledge about virtual reconstructions of ancient architecture. Proceedings of the International Conference on Computer Graphics '99. IEEE Computer Society, 1999.

[2] Bustany-Leca, C. and Bustany D. Vers une vision du forum d'Auguste. Proceedings of Virtual Retrospect, Biarritz, Ausonius editions, 2005.

[3] Theron, R., Gonzalez, A. I., Garcia, F. J. and Santos, P. The use of information visualization to support software configuration management. In Computer Science, volume 4663/2007, Ammersee, Germany, 2007. pp. 317–331.

[4] Kensek, K. M., Swartz Dodd, L. and Cipolla, N. Fantastic reconstructions or reconstructions of the fantastic? tracking and presenting ambiguity, alternatives, and documentation in virtual worlds. Automation in Construction 13, 2004. pp. 175-186.

[5] Pang, A. T., Wittenbrink, C. M. and Lodh, S. K. Approaches to uncertainty visualization. The Visual Computer, 13(8), 1997. pp. 370–390.

[6] Ji-Hyun, L., Hsien-Cheng, C. and Koshak, N. A. Visualization of Spatial-Temporal information for historical sites on GIS. University College London, London, England, 2005.

[7] Debevec, P., Taylor, C. and Malik, J., 1996: Modelling and rendering architecture from photographs: a hybrid geometry and image-based approach. ACM Proceedings of SIGGRAPH'96, pp. 11-20.

[8] Werner, T. and Zisserman, A., 2002: New technique for automated architectural reconstruction from photographs. Proceedings 7th ECCV, Vol.2, pp. 541-555

[9] Vu, H. and Keriven, R. and Labatut, P. and Pons, J.-P Towards high-resolution large-scale multi-view stereo. Conference on Computer Vision and Pattern Recognition (CVPR), Miami, Jun 2009

[10] Taylor, C., Debevec, P. and Malik, J. Reconstructing polyhedral models of architectural scenes from photographs. In Proceedings of 4th European Conference on Computer Vision, Cambridge. Springer-Verlag, 1996.

[11] El-Hakim, S. F., A flexible approach to 3D reconstruction from single images. ACM SIGGRAPH'01 Technical Sketches, 2001.

[12] Wang, S. and Liu, D. Spatial query preprocessing in distributed GIS. In GCC, vol. 3251 of Lecture Notes in Computer Science, Wuhan, China, 2004. pp. 737–744

[13] Kavouras, M. Understanding and modelling spatial change. In Life and Motion of Socio-Economic Units, number 8 in GISDATA, London, 2001

[14] Schindler, G., Dellaert, F. and Kang, SB. Inferring Temporal Order of Images from 3D Structure. CVPR 2007

[15] Sun, M., Schindler, G., Kang, S. B., and Dellaert, F. 4D view synthesis: navigating through time and space. In ACM SIGGRAPH 2007 Posters.

[16] Margaret Boden. Mind As Machine: A History of Cognitive Science. Clarendon Press, 2006.

[17] De Luca, L., Veron P., Florenzano, M. Reverse engineering of architectural buildings based on a hybrid modeling approach. Computers & Graphics, 30(2) Elsevier, 2006, pp. 160-176.

[18] Dudek, I. and Blaise, J.Y. From artefact representation to information visualisation: Genesis of informative modelling. In Smart Graphics, vol 3638 of Lecture Notes in Computer Science, Frauenworth Cloister, Germany, 2005. Springer, LNCS. pp 230–236.

[19] Faugeras, O. Three-Dimensional Computer Vision. The MIT Press, 1993

[20] Hartley, R. I. and Zisserman, A. Multiple View Geometry in Computer Vision. Cambridge University Press, ISBN: 0521623049, 2000.

[21] Tsai, Roger Y. An Efficient and Accurate Camera Calibration Technique for 3D Machine Vision. Proceedings of IEEE Conference on Computer Vision and Pattern Recognition, Miami Beach, FL, 1986, pp. 364-374

[22] Pelekis, N., Theodoulidis, B., Kopanakis, I. and Theodoridis, Y. Literature review of spatio-temporal database models. Knowl. Eng. Rev., 19(3), 2004. pp. 235–274

[23] Renolen, A. Modelling spatiotemporal information: The spatiotemporal object model. Technical report, Department of Surveying and Mapping (IKO), The Norwegian Institute of Technology, 1997.

[24] Stefani, C., De Luca, L., Veron P., Florenzano, M. Reasoning about space-time changes: an approach for modeling the temporal dimension in architectural heritage. Proceedings of IADIS International Conference on Computer Graphics and Visualization. Amsterdam, 2008.

[25] De Luca, L., Veron P., Florenzano, M. A generic formalism for the semantic modeling and representation of architectural elements. The Visual Computer, 23(3) Springer, 2007, pp. 181-205.

[26] Tufte, E. R. The Visual Display of Quantitative Information. Cheshire, CT, graphics press edition, 2001.

[27] Dudek, I. and Blaise, J.Y. New Experimentations of a Generic Framework for Architectural Heritage Data Visualisation. WSCG, 2003.

[28] Busarayat, C., De Luca, L., Veron P., Florenzano, M. A real-time 3D interactive interface for a spatial referencing system. Proceedings of IADIS International Conference on Computer Graphics and Visualization. Amsterdam, 2008.

[29] Shubert, H. Preserving digital archives at the canadian centre for architecture: Greg lynn's embryological house. In Architecture and digital archives. Architecture in the digital age : a question of memory, Infolio edition, 2008.