A Semantic and Parametric Method for 3D Models used in 3D Cognitive-Information System

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Abstract. The paper presents an innovative semantic and parametric method to build 3D models to be used in cognitive-information systems. We integrated structured geometrical and documentary information resulting from multiple sources with the aim to enhance the knowledge of those sites within the frame of their historical evolution and their institutional management in a 3D GIS/DB. The developed applications were designed for different types of users, with a largely scalable interface, able to support different output devices and to work at different levels of iconicity. The system allows a full comprehension of the buildings in their own context, permitting to discover unknown relationships, to evaluate their architectural occupancy and to quickly access a complex system of information.

Keywords. 3D-GIS; semantic modeling; 3D reality-based modeling; real-time rendering; virtual heritage.

One of the main problems regarding the conservation of architectural and archaeological complex urban systems is the lack of an integrated information system providing both multiple solutions to the information demand from multiple stakeholders and functions: management, preservation, analysis, tourism. Using 3D models it’s possible to build knowledge-based and simulation systems as well as to upgrade the well-known 2D GIS to 3D GIS, satisfying the 3D GIS requirements for complete and continuous information (Gaiani et al, 2002). On the other hand to use computer-generated models efficiently, data must be kept up-to-date, consistent and transparent, based on standards and organized in libraries.

In this context we developed a framework to record, construct, pre-process, manage and visually navigate 3D models of architectural and archaeological heritage sites. Specifically it concerns the field of structuring geometrical and documentary information resulting from multiple sources (reality based, scratch or existing drawings) with the aim to enhance the information system of those sites within the frame of their historical evolution and their institutional management in a 3D GIS/DB (Manferdini et al, 2008). 3D models are conceived to be displayed in real-time with high-quality rendering, as tools to manage, work, study, promote restoration or redevelopment of existing assets. In this direction the framework presents several innovations and robust methods to have high quality shading and/or photorealistic visualization of the models in real-time. To improve the retrieval of 3D objects and related information within the repository, we annotated
each shape as a whole and as sub-parts, linked to attributes and relationships between them.

From a technical point of view, our system was based on two major components linked through a query layer:

- an efficient storage module for multi-dimensional data with a joint concept-based representation module for the objects identified in the data;
- a set of models semantically built.

We experienced our framework in two different scenarios:

1. a joint project with the Scuola Normale Superiore of Pisa to assist the local Superintendence of archaeological excavations and heritage of Pompeii for digital reconstruction, classification, management and visualization of findings inside an advanced 3D web-based repository of reality based data (Benedetti et al, 2008);
2. a web-based information system designed – as a kind of prototype – to make available on the Google Earth platform the complete Palladian corpus documentation (Gaiani 2008) implemented by the Centro Internazionale di Studi di Architettura Andrea Palladio di Vicenza (Figure 1).

Both applications have been developed in order to have a largely scalable interface, able to support different output devices and to work at different levels of iconicity. Applying this new methodology, our system allowed the full comprehension of the buildings in the territory and in their own urban context, permitting to discover unknown relationships with the environment, to evaluate their architectural occupancy and to quickly access a complex system of information.

The paper is organized in the following eight sections. A short description of 3D modeling for 3D Web GIS system state of the art is reported in section 2. Section 3 explains 3D modeling construction
pipeline. Section 4 reports the different techniques and procedures we applied to model in 3D artifacts from real-world data. Section 5 describes our pipeline to build high resolution 3D models from 2D drawings. Section 6 illustrates our 3D model semantic organization. Section 7 is devoted to our database description. Concluding remarks are reported in section 8.

3D modeling for Web GIS system: state of the art

The key point in overcoming the difficulties that characterize a 3D Web GIS (conceptual model, data collection, visualization, navigation and user interface development, Internet access, spatial analysis) is the efficient topological organization of spatial data. Ellul and Haklay (2006) identified and reviewed a list of requirements for topology in 3D applications. Three key areas were studied to identify system requirements, namely existing 2D topological systems, 3D visualization and 3D analysis requirements supported by topology. This is a particularly demanding set of requirements; for this reason GIS software that handles reality-based 3D data are very rare. The problem is even amplified for data defined by a large number of polygons, the typical case of high-resolution architectural and archeological models. Over the last few years we have seen an increasing amount of work in the fields of modeling and managing geospatial 3D objects. Recent projects employed object-relational concepts to address these issues (Zlatanova et al, 2002).

In a geospatial model a 3D geospatial object can be defined by its geometric or topological representation, or by using both representations (Breuning and Zlatanova, 2006). Today geospatial models represent a large number of objects, mostly in 2D/2.5D, with simple geometric representations. Recently 3D information models have been developed for representing real world objects. A notable example is CityGML (Kolbe 2009), a technology that represents a great improvement over previous applications and a comprehensive framework, even if it does not seem to be enough robust for high resolution architectural models and the geometry is still limited to simple representations. The DILAS (Digital Landscape Server) project (Nebiker 2003) partially addressed our issue focusing on object semantics, complex object geometries and photo-realistic textures, integration of existing (geospatial) databases and temporal aspects and combining an object-oriented topological 3D data model with an XML-based 3D object storage in an object-relational DBMS. However, these projects revealed a number of unsolved problems associated with the process of creating high-resolution 3D models typical of cultural heritage objects (Enggard and Zlatanova, 2008).

3D modeling construction pipeline

Several ways and methods exist to acquire geometrical and semantic information from real objects and to represent it within the 3D geospatial environment. However, none of these methods appear to be appropriate in the field of archaeology and monumental architecture since archaeological/architectural data are extremely complex from a geometric point of view and the existing methods lead to large simplifications and consequently to the loss of information.

In our framework using different levels of detail (LOD), each model could be used as a mold or as a metaphor of the real object in order to convey other information and to guarantee the maximum quality while observing details near the observer, but also allowing faster visualization of large views, with a more effective use of resources.

The framework also deals with the problem of standardization of reality-based or 2D-to-3D modeling. It’s known that it is practically impossible to build 3D models reality-based of a large archaeological site or of the entire built heritage with a single acquisition and restitution campaign. Therefore different artifacts are modeled by different operators, working in different places and times and often
using different methods and technologies. In addition, 3D modeling from real-world data is not a standardized procedure: survey and modeling methods strictly depend on the characteristics of the object, on the level of representation detail and on communicative aims. To be sure that our information system will be efficient and consistent in all its parts, we defined a-priori and verified a-posteriori widely shared standardized characteristics of 3D models.

Among the most effective techniques available to detect and survey architectural or archaeological artifacts, we used digital photogrammetry and/or terrestrial laser scanners (triangulation and TOF) or traditional techniques starting from surveying data and engineering drawings. Using the first technologies we obtained models that include all fine details of the original artifact such as a photo-realistic representation of the surface; with the second one we created models characterized by geometric/dimensional and detail approximation. Therefore our model construction pipeline consists of six steps (Figure 2):

- acquisition of metric, formal and surface data of the artifacts/buildings;
- 3D modeling;
- editing;
- texture/shader mapping;
- post-processing;
- visualization/positioning in 3D-GIS.

3D models were conceived with the purpose to uniquely identify the buildings/artifacts and their related resources (images, 3D models, text, etc.) as elements connected with the 3D geometry. This requirement was met by constraining the final model to allow a semantic reading of the real object and the design intents throughout the interpretation of the shapes described by the model itself. From an operative point of view our approach used semantic modeling for descriptors as common denominator between heterogeneous information, possible representations of the building, and parametric modeling for data modeled from scratch, existing drawings or photos. Mostly in these fields we presented important innovations including a term-based approach to name each architectural part of the model based on a robust thesaurus.

**Reality-based 3D modeling**

Our reality-based models were designed as a ‘replica’ of the original object with the purpose to build a ‘master model’ from which a multi-resolution representation arises.

The working assumption we formulated for the ‘master model’ development was a thoughtful read of weaknesses and key steps of the different techniques available today aimed at maintaining

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**Figure 2**

The flow chart describing the processing from the real object to the 3D model with textures
the model quality throughout its production pipeline. We also ensured consistency for reality-based modeling by performing an accurate analysis and typological mapping of the artifacts (geometric, surface properties, semantic), identifying case studies representative of most archaeological sites or architectural buildings. In detail, we considered:

- Shape and material characteristics of each finding;
- Recurrence of the identified shape and material characteristics;
- Tools and methods available and suitable for data capture and model construction;
- Relationship between the artifact environment and the acquisition conditions.

Along this pipeline the following step was to perform the analysis of each type of artifact in order to describe its characteristics and to define survey accuracy, tolerances, methods and output. In choosing the most appropriate technique for each finding, we assessed the following issues:

- Object characteristics: maximum size (bounding box), possible prevalence of one dimension over others, size threshold at micro- and macro-scale, material characteristics (i.e. material behavior not lambertian);
- Capture instrument characteristics as function of (a) minimum accuracy and geometric resolution required, (b) recovery area dimensions, (c) range, (d) lighting conditions, (e) presence of non-lambertian materials, (f) instrument manageability;
- Aim of the survey: size and minimum level of detail to be returned; distinction between different levels of detail;
- Boundary conditions: availability of work areas free from impediments.

We took into consideration additional parameters such as tool usability and time needed for data acquisition and model development. Additional important factors considered were the skills of operators and the object location. Overall, the acquisition pipeline is a standard pipeline including scanning laser range data and/or photogrammetry processing.

The geometric model obtained was then textured for photorealistic visualization (Figure 3).

In order to add more details to geometry, for models obtained from photogrammetry, we developed a method to use normal mapping techniques to simulate irregularities (Cohen et al, 1998). The pipeline ends with the generation of semantic 3D models segmenting the acquired mesh. For some models new surfaces have been introduced in order to rebuild hidden volumes.

**From drawing to 3D modeling**

To obtain a complete description of shapes and silhouette renderings from existing 2D handmade drawing survey (2D-to-3D modeling) we ‘evolved’ in 3D the typical features of 2D drawings. We interpreted this system by building the semantic model at a level corresponding to the desired LOD and highlighting the masses by imposing a texture of Ambient Occlusion (AO). The *Corpus dei rilievi delle fabbriche palladiane* was used to build the Palladian 3D models with an accuracy range of ±1,75÷±3,5 cm, employing operators with different skills and utilizing different commercial software, with the only constraint of NURBS or polygons for boundary representation, to ensure geometric interoperability.

Architectural apparatus (orders, moldings, balusters, etc.) were modeled by defining three LODs in accordance with those defined and applied for reality-based models, characterized by a large variability in the total amount of triangles. In order to bring out volumes from flat Palladian drawings and, at the same time, solve another typical problem of displaying 3D models in GIS system (i.e. GoogleEarth viewer provide a simple Gouraud shading), we applied a render-to-texture illumination using AO pre-calculated techniques (Figure 4).

All 3D models were structured according to the criteria of semantic organization ensuring consistency along all post-processing phases and consistency switching from a LOD to another. In the last step we generated the 3D model in KMZ format - a single
root KML document and a series of referenced files DAE, that describes geometry and includes mapping information - in order to geo-reference the model in the Geodatabase.

3D model semantic organization

The topological information is a major issue in the 3D model construction since it describes the spatial relationships between geo-objects and the capability of the models to be used into a 3D GIS. On the other hand 3D models are an excellent mean for understanding architecture, describable as a collection of structural objects, and identified through a precise architectural vocabulary. The availability of 3D semantic models organized as cognitive systems allows to have geo-object items in a 3D GIS and an improved topological control that allows a semantic approach to the classical problem of model LODs generation. Many projects presented a methodological approach to the semantic description of architectural elements (De Luca et al, 2007), or defined a method able to describe the shape of 3D objects (Ullrich et al, 2008) or showed how attribute grammar formalism can be used as a 3D modeling language (Schmittwilken et al, 2009).

The 3D modeling system we defined is based on the accepted and general convention whereby structures are described as a series of structured objects using a specific architectural lexicon. Following the classification method of Tzonis and Oorschot (1987) the architectural space is subdivided according to
their level of ‘abstraction’ (clustering, topological and metric). Then the component parts were reassembled using a 3D extension of the ‘put-together’ method reported by Stiny and Mitchell (1978) and adopting a ‘shape grammars’ that uses a pre-established set of tree-shaped formal rules which indicate a clear purpose and an evident structure. The obtained semantic models, ready-to-use as a knowledge system, allow to manage the 3D models as multi-resolution models and to subdivide them in consistent and hierarchically related subsets of a defined number of triangles/polygons in order to be included inside the tested 3D GIS. Due to the different typologies of objects we defined two different groups of interpretation and structural formulation for the final architectural/archeological complex (Figure 5):

1. A first group (2D-to-3D modeling) consisting of individual elements derived from pure geometric primitives (architectural lexicon) and built up using unambiguous logic. The primitives were put together mechanically in a pre-ordered manner to become objects like bases, capitals, shafts etc. and when assembled co-axially, they appear as a column or a series of columns supporting an entablature, etc;

2. A second group (reality-based modeling) referred to the construction of complex parts, i.e. an architectural whole (cornice, window, basement, internal and external volumes etc.) or to the anastylosis of archaeological finds. Any complex system comprising similar elements was hierarchized in order to determine which parts should undergo transformations.

Figure 5
Corinthian Order: segmentation and acyclic graph of the corresponding structure - 2D to 3D modeling (left) and reality-based 3D modeling (right)
The semantic classification led to the identification of classical orders, building functions and materials through its naming. The naming of each single sub-element and of the classes in which they can be grouped is an important phase that strictly depends on archaeological and architectural widely shared interpretations. Considering that each single sub-element has to be analyzed regardless of its context, the name can be derived from classical orders only if specific morphological analysis can be performed; in other cases the name itself should suggest the function or the material that constitutes it, as well as extra information, such as geo-location and numbering that uniquely indicate a single element within the entire set of finds, in order to allow more general and versatile interpretations.

The qualification of this problem can’t be an automated procedure requiring the support of archaeologist or architects in order to recognize transitions between different elements composing the artifact.

3D data organization and GIS implementation

3D digital models were conceived to be displayed in real-time with high-quality rendering and using a web browser plug-in compatible with Google Earth. Semantic organization allows studying every single element without context. Furthermore, this classification was a useful instrument for the excavation administration or superintendence that permitted to check the consistency of the archaeological site or monument and to program restoration and conservation interventions. In order to preserve the consistency and interoperability, data were described in the Collada file format and structured following the organization of a typical scene-graph organized in nodes (Lindbergh 2006).

The method organized each single sub-element as a node, which was linked to a file that can be stored separately from others belonging to the same artifact. All geometry-parts were associated with a semantic meaning, and each semantic item was further described with specific attributes. Each part was then connected to series of information created to facilitate the retrieval process in a semantic-based context. Furthermore a semantic driven visualization enhanced model usability. Semantic structure was then exploited to obtain multi-resolution representations. The link between 3D models and 2D documentation was bi-directional, using the same web based interface, and the system could be easily linked with any kind of database available on web.

The two information/cognitive systems where the 3D models were used, have been designed and developed to satisfy both internal (cataloguing, documentation, preservation, management of archaeological heritage) and external (communication through the web portal) purposes. The first was developed in order to have a web-based system that uses Open Source software and complies with national and international standards in one

Figure 6
"Palladio 3D Geodatabase", the architecture of the cognitive system
inter-operative platform different kinds of resources pertaining to a certain (archaeological or architectural) heritage. The second one, Palladio - 3D Geodatabase is an application organized as a Rich Internet Application (RIA), with typical client-server architecture and components in both sides (Figure 6). Both systems present at their core our storage module encoding and managing different and multiple 2D and 3D data:

- model Level-of-Detail (polygon number, texture size, management complexity) classified according to use. Our system provides 3 LOD;
- texture LOD (color, normal, etc.). Our system provides 3 LOD;
- 1D and 2D documentation attached to each element.

Without requiring a 3D file interpretation, the database can rebuild the nodes frame and can access to sub-node or to the entire 3D model.

Conclusions and future works

In this paper we presented a new semantic and parametric method for building 3D models used in a 3D cognitive-information system. The developed methodology is divided into three steps, which are mutually connected one to each other (modeling, segmentation and visualization) that allow (a) to reproduce photo-realistic and reality-based 3D models, (b) to classify them into levels, and (c) to assign to each archaeological and architectural element additional information other than the geometric and surface quality properties.

Future developments will concern specific applications able to:

- show chronological evolution/transformation undergone by the building;
- highlight the architectural, historical, artistic or peculiar features of the building.

References


