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3D VIRTUAL RECONSTRUCTION OF ARCHAEOLOGICAL MONUMENTS

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ABSTRACT

3D Virtual Models are the future of the representation of the existing and destroyed architectural heritage. The term reconstruction defines the re-building of a monument to its state at the time of its history chosen for that particular representation. In recent years the evolution of the technology, has contributed significantly in many aspects of the field of cultural heritage preservation and recording. Techniques like digital image processing, digital orthophoto production, terrestrial laser scanning and 3D model processing have enabled the production of such alternative products. In this paper two characteristic cases of 3D virtual reconstruction of non-existing monuments are presented: The Middle Stoa in the Athens Agora and the Church of San Prudencio's Monastery in Spain. All data collected were evaluated and used appropriately for the final products. It is evident that the data collected do not all belong to the target periods and not all the data necessary to built up the models are available today. Therefore, one needs to carefully select the data corresponding to the period of study and complete them with suitable hypotheses. It is imperative that both tasks must be done in collaboration with archaeologists and architects. In this context a data hierarchy was developed, based on their reliability and correctness. The data were categorized for their reliability after careful evaluation their accuracy depending on the source. In this paper a 'Reliability' matrix for creation of digital models for cultural heritage research is presented. Sometimes the data appear in more than one source; in this case they must be checked for correspondence. All different sources should be evaluated and used accordingly for the final product. The procedures followed are briefly described and the results are presented and assessed for their reliability and usefulness.

KEYWORDS: Virtual Reconstruction, 3D models, Digital Cultural Heritage, ICT tools

1. INTRODUCTION

Nowadays, the rapid advances of Digital Technologies also referred to as Information Communication Technology (ICT), have provided scientists with new powerful tools. Especially in the field of Cultural Heritage Documentation, we are now able to acquire, store, process, manage and present any kind of information in digital form. Nowadays this may be done faster, more accurately and more completely and in this way a larger base of interested individuals is built that this information may reach.

The use of Digital Technologies in preservation and curation in general of cultural heritage is also mandated by UNESCO. With the *Charter on the Preservation of the Digital Cultural Heritage* (http://portal.unesco.org/en/ev.php-URL_ID=17721&URL_DO=DO_TOPIC&URL_SECTION=201.html) this global organization proclaims the basic principles of Digital Cultural Heritage for all civilized countries of the world. At the same time numerous international efforts are underway with the scope to digitize all aspects of Cultural heritage, be it large monuments, or tangible artefacts or even intangible articles of the world's legacy.

2. MOTIVATION

The involvement of contemporary Digital Technologies (ICT) in the domain of Cultural Heritage has increased the gap between *Providers*, i.e. those who master these techniques and are able to apply them and the *Users*, i.e. those scholars traditionally concerned with the Cultural Heritage. This gap was caused mainly due to the mistrust of the latter towards contemporary technologies and lately ICT. However systematic efforts have been applied, like RecorDIM by CIPA, i.e. the International Committee of Architectural Photogrammetry formed by ICOMOS and ISPRS (International Society for Photogrammetry and Remote Sensing (http://cipa.icomos.org/index. php?id=43) which have managed to narrow if not bridge this gap.

This current effort concerned with the 3D virtual reconstruction of monuments is motivated exactly by this endeavour to bridge this gap. This will only be done through deep understanding of each other's needs and through proper exploitation of ICT with the benefit of Cultural Heritage always in mind. In addition, the notion of virtual reconstruction is introduced and its use for bringing the reconstructed monuments into a museum environment is investigated.

3. ICT TOOLS

3.1 Definition

The available contemporary digital tools include mainly instrumentation for digital data acquisition, such as terrestrial laser scanners, structured light scanners, digital optical, thermal and range cameras, digital total stations etc., software for processing and managing the collected data, such as structure from motion (SfM) and -of course- computer hardware, for running the demanding software, storing the data and presenting them in various forms.

3.2 Impact

Already the introduction of digital technologies has altered the way we perceive fundamental notions like *indigenous, artefact, heritage, 3D space, ecology* etc. At the same time they tend to transform the traditional work of archaeologists and museums as they are known so far. In other words Digital Technologies redefine the relationship to Cultural Heritage, as they enable universal access to it and they also connect traditional cultural institutions to new "audiences". Finally traditional museums and archaeological sites through the use of contemporary technologies appeal to new generations, as the latter are, by default, computer literate.

3.3 New products, possibilities and uses

The impact of digital technologies to the domain of Cultural Heritage has enhanced speed and automation of the procedures which involve processing of the digital data and presentation of the results. At the same time accuracy and reliability has been substantially enhanced.

However, most important is the ability to provide to the users new and alternative products, which include two dimensional and three dimensional products, such as orthophotos and 3D models. All in all the digitization of the world's Cultural Heritage, be it tangible or intangible is now possible.

3D modelling, on the other hand, is the process of virtually constructing the three-dimensional representation of an object. The use of 3D models is highly increased nowadays in many aspects of everyday life (cinema, advertisements, museums, medicine etc). This paper focuses on their use for representing, reviving, interacting and studying Cultural Heritage in an interactive way.

3.4 3D Digital Data

Digital data acquisition is nowadays performed with (a) geodetic digital total stations, which produce 3D coordinates of single points in space, (b) digital image processing, which produces 2D or 3D products and (c) with digital scanning devices, which produce 3D point clouds of the objects.

The common attribute of the above is the three dimensional data acquisition, which enables the development of 3D virtual models. It is these 3D models that have made the 3D virtual reconstructions possible.

3D models can be simple linear vector models or they can consist of complex textured surfaces depending on the object and their final use. As the specific technology advanced, 3D models were used for multiple purposes. Initially they simply served as means for visualization. Gradually, however, they contributed to other uses, such as study, description purposes and restoration interventions and lately for virtual reconstruction and engineering applications (Valanis et al. 2009).

Technological advances have provided 3D modelling software with numerous capabilities, which enable them to go beyond the simple representation of an architectural structure. They can provide information regarding the materials used and the realistic texture of the surfaces and also be interconnected with a data base for storing, managing and exploiting diverse information. Typical implementations of 3D modelling can be found in modern museums and educational foundations helping their visitors and students to communicate in a special way with the monument or site of interest as they can 'walk' through it or fly over it and thus examine it better, having always in mind its level of accuracy and likelihood. Researchers are also using 3D data acquisition to not only conserve excavation sites, but to reconstruct the actual excavation for real-time analyses (Levy 2013).

4. 3D VIRTUAL RECONSTRUCTION

The term reconstruction implies the re-building of a monument to its state at a particular time moment of its past life, chosen for the representation. The term has similar meaning with the terms *anastylosis* and *restoration*, with the difference that the anastylosis is expected to use the authentic material, while for the restoration new material may be used, but both are implemented up to the point where assumptions about the original form of the monument are required. Nowadays archaeologists are extremely reluctant in actually reconstructing a monument for a number of reasons.

Digital technologies have enabled the *virtual* reconstruction (Matini et al. 2008, Lentini 2009, Matini et al. 2009, Patay-Horvath 2011, Vico & Vassalo 2008). This term implies that the representation takes place in a three dimensional space, which is usually called virtual environment and the final product is usually called a 3D virtual model. It is evident that 3D virtual reconstructions significantly support studies for the eventual real reconstruction of the monument in the future. A virtual reconstruction would also enable the examination of various alternative solutions and help decisions for the suitable use of the salvaged members today.

In case of monuments preserving most of their characteristics, or having been restored in the past, descriptive 3D models apply. In this case a geometric documentation with simple and suitable methods can generate 3D products which are good enough for visualization and can be obtained with varying degree of accuracy and detail. On the other hand, when we deal with objects that have few or practically no evidence of their past form and appearance, modelling is more complicated and needs hypotheses with different degrees of likelihood.

There are many kinds of virtual reconstruction, mainly focussing on the verisimilitude of data used (Valle Melon et al. 2005, De Fuentes et al. 2010). This implies that data should be ranked according to their reliability and accuracy and given appropriate likelihood (Gkintzou et al. 2012, Kontogianni et al. 2013). All data collected are evaluated and used appropriately for the reconstruction. It is evident that, on one hand, the data collected do not all belong to the target period and, on the other, not all the data necessary to built up the model are available today. Therefore careful selection should always be done of the data corresponding to the period of study and complete them with suitable hypotheses.

Usually the different data are illustrated with different colours, every colour representing different data source. Another way of representation is that the object parts are illustrated with different transparency level according to the reliability of original source. In this case important role plays the data date, their accuracy and their likelihood. The differentiation may also represent the knowledge about the original construction material.

The application of the texture must be carried out carefully, because it is necessary to texture the virtual model of the monument correctly and make it look as real as possible. Very often, special decisions should be made during the progress of the 3D reconstruction, such as interpreting the geometry of the architectural elements like symmetry and the construction method of each element or section of the monument.

Symmetry, which is a very important element in architecture, may also be represented and interpreted with the virtual reconstruction, while building the geometry of the architectural elements, like windows, doors, arcs etc. Another important element is the representation of the construction method of each element or section of the monument. Hence, the process of virtual reconstruction must be done very carefully in order to create the virtual model correctly both geometrically and photorealistically.

5. VIRTUAL RECONSTRUCTION

Three examples of virtual reconstruction will be presented in order to illustrate their usefulness and great potential. All projects have been performed by the Laboratory of Photogrammetry of the National Technical University of Athens (NTUA). The first example is a standard virtual reconstruction of a monument which is ruined today. The second example is a case of a modern monument, which was restored on the basis of its virtual reconstruction. The final example is a case of a monument of which today nothing is salvaged, but its foundations and very few artifacts of the initial construction. They form a complete set of various cases of virtual reconstruction, which have been used for various purposes for the benefit of Cultural Heritage.

5.1 The Monastery of San Prudencio

The Monastery of San Prudencio is located at the province of La Rioja in Spain. The three dimensional virtual restoration and reconstruction of the

Figure 1: The Church of San Prudencio today

church of the Monastery was performed within the framework of a larger project (Gkintzou et al. 2012). As the monument is almost completely ruined (Fig. 1), many additional sources were used for the reconstruction.

It was decided to produce a 3D virtual model with surfaces in order to convey as much information as possible and represent the church as it probably was during the 14th-15th century according to historical sources that are available and other essential information selected in collaboration with archaeologists and architects. The restoration was also based on the detailed documentation of the current situation of the monument that conserves parts of the target phase. The documentation products were surveying measurements, Digital Surface Models (DSM), orthophotos, and laser scanner point clouds. The documentation of the current situation was needed for two reasons. Firstly because it provides information about the past of the monument and it is recommended for all related projects. Secondly, it includes existing elements, which will serve as the basis for the reconstruction phase. As far as the current situation is concerned digital images were acquired, which were used in order to generate Digital Surface Models (DSM) and orthophotos. In addition, surveying measurements and some laser scanner data were also collected. These images were taken from different angles and they aimed to record as completely as possible the relative position of the various remaining structural elements and the materials on the wall. In general, they served as valuable reference, but they do not have any metric accuracy and they are not suitable for 3D modeling.

It is evident that the data collected do not all belong to the target period and not all the data necessary to built up the model are available today. Therefore, we need to carefully select the data corresponding to the period of study and complete them with suitable hypotheses. It is imperative that both tasks must be done in collaboration of the archaeologists and architects. In this context a hierarchy of the data was developed, based on their reliability as far as their "correctness" is concerned (Table 1).

Table 1: Reliability of data *(1-10 decreasing)*

Sources	Reliability
Written Documents	2
Images	6
Drawings-Paintings	6
Surveying Measurements	3
Orthophotos	5
DSM	4
3D Line Drawings (Laser Scanner)	4
Archaeological Assumptions	1

Reliability measure, as depicted in Table 1, does not have anything to do with the accuracy of the surveying and photogrammetric measurements. Hence, the archaeological and architectural experts' opinion and assumptions are considered as most reliable. Similarly, the rest of the various sources were evaluated by the interdisciplinary group. Written sources are high in the reliability scale, while drawings and paintings have a higher degree of subjectivity and are graded low in reliability. Surveying measurements and surface descriptions (DSM) as well as orthophotos are in the middle of the scale, as they do not describe only the specific era of reconstruction.

The final 3D model was constructed by also taking into account the criterion of accuracy. In this case, there were three sources giving information about an arc on the southern wall of the church. These sources were the DSM, the orthophotos and the 3D line drawings as they were extracted from the laser scanner data. As it was expected, they do not coincide as their accuracy differs. Consequently a second table was created (Table 2) representing the hierarchy of the data based on the criterion of accuracy.

Table 2: Accuracy of data *(1-10 decreasing)*

Sources	Geometric Accuracy
Written Documents	5
Photos	7
Drawings-Paintings	8
Surveying Measurements	1
Orthophotos	2
DSM	3
3D Line Drawings (Laser Scanner)	4
Archaeological Assumptions	6

It is clear that 3D Virtual models representing reconstructed objects, that do not exist today, include elements with different levels of accuracy and likelihood. It has to be mentioned that the likelihood expresses the possibility of each element to exist during the period of reconstruction as it is presented at the model, while the accuracy describes the certainty related to the absolute and relative position of the elements. There are elements for example that can be represented with better accuracy than others, because they still exist but one cannot be so sure about their existence during the reconstruction period. In this case these two characteristics (likelihood and accuracy) of the representation coincided as the likelihood was depended on the kind of sources present for every element just like the accuracy level. If a more complete architecture and archaeological study were available this two characteristics may differ for some elements. All the data were examined critically in order to approximate the form and the structure of the church as well as the textures too. At the end, it was decided that the materials and textures did not need to be defined yet and, therefore, we will wait until the architectural and archaeological studies go further after deciding about them.

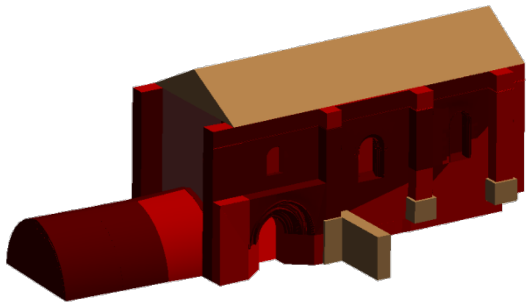


Figure 2: Virtual reconstruction with differentiation of data reliability

In this way the final reconstruction (Fig. 2) reflects the various reliability grades, thus helping the potential user to comprehend it in a better way. This significantly differentiates this alternative virtual reconstruction approach, as it adds the reliability aspect.

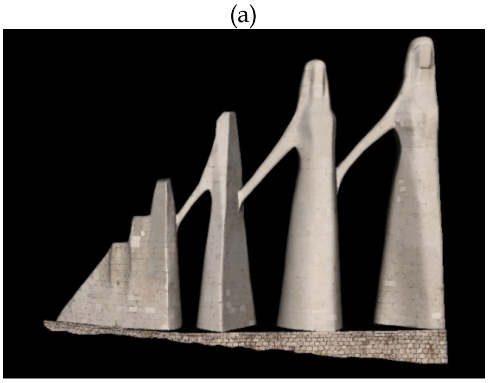
5.2 The Zalongon Sculpture

The monument of Zalongon is a huge complex of sculptures, 15m tall and 18m long, built in the 1950's and located on top and at the edge of an 80m high cliff in north-western Greece. The monument commemorates the sacrifice of the Souli village women, who in 1803 preferred death from humiliation by the Ottoman conqueror. The restoration work that was carried out involved the cleaning of the sculpture's surface, the extraction and replacement of large pieces that have suffered damages from harsh weather and were deteriorating rather quickly, and the restoration of parts that have been destroyed by frost.

The data required to build high resolution 3D textured models include, 3D scans, geodetic measurements and a significant number of images. The detailed geometric documentation of the current situation of the monument included the production of 2D drawings, orthophotos and an accurate 3D model (Valanis et al. 2009).

Engineers who are involved in restoration are greatly facilitated if they can interact with a 3D model and immediately obtain various kinds of information by measuring various distances, areas, volumes, by creating cross-sections, outlines or even by formulating and adding missing parts. However, in cases where the formulation and addition of 3D data is desired different methods and algorithms are required. This was also the case for the monument of Zalongon, where the upper parts of the two tallest figures were almost destroyed. Two main categories of data were extracted, namely the part of the surface that was healthy and would be retained and the broken part that was recorded only in order to help reconstruct what was missing.

(a)



(b)

Figure 3: The 3D model before (a) and after (b) restoration

Efforts were also made to completely restore the original surface virtually. However, in order to obtain a better result, another approach was preferred. The partially completed surfaces were used for the creation of analogue models of a scale 1:5 and an artist, a sculptor, was assigned with the task of completing the forms based on the existing model and old photographs and sketches made by the original sculptor. The new plaster models were scanned with an XYZRGB SL2™ structured light scanner and the data acquired were registered with the 3D model. The final mesh was exported, appropriately scaled and in such a form to enable masonry experts to reproduce exactly the missing parts and to actually restore the monument (Fig. 3).

5.3 The Middle Stoa in the Athenian Agora

The Ancient Athenian Agora is today one of the most important archaeological sites in Athens and is situated at the northern foot of the Acropolis hill. It was a large open space to the south of Eridanos River and served as the administrative, philosophical, educational, social and economical centre of the town of Athens for many centuries.

Figure 4: The foundations of the Middle Stoa

The Middle Stoa was an elongated building 147m by 17.5m, which ran east–west across the old square, dividing it into two unequal halves. This large building was constructed with Doric colonnades at both the north and south sides as well as an Ionic colonnade along the middle. The original steps and three columns remain *in situ* at its eastern end; to the west, only the heavy foundations of reddish conglomerate survive. The Middle Stoa was built between ca. 180 and 140 B.C. and it was continuously used even during of the Roman era (www.agathe.gr). Foreign architects were responsible for its construction; hence it presents particular design and construction elements not usual for that time in the area. Today only the foundations of this majestic building and some individual parts of it are visible in the site (Fig. 4).

For the virtual reconstruction several different data were available. Artifacts from the initial construction in the museum, drawings from scholars who had studied thoroughly the monument (Travlos 1971, Muller-Wiener, 1995), survey measurements of the foundations which are visible today and artists' reproductions of pertinent descriptions from travellers of the past. All data were evaluated (Table 3) for their reliability and accuracy before usage for the final virtual reconstruction (Fig. 5)

Table 3: Data evaluation

Data Source	Characteristics		
	Year	Accuracy	Like-lihood
3D Model	2010, 2012	1	1
Archit. plans	1963, 1966	2	2
Other plans	Varies	3	3
Images	Varies	5	5
Literature	Varies	4	4
Assumptions	-	6	6

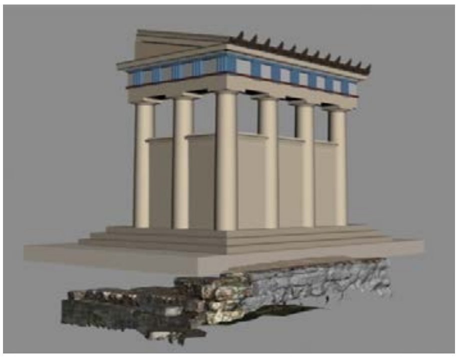


Figure 5: The reconstructed Middle Stoa

This final product reconstructs a building that does not exist today. The visitor may only see the foundations of the building, which at the time of its peak (2nd c. BC) were buried in the ground. Consequently the virtual reconstruction is a combination of existing detailed architectural drawings, of sketches, descriptions, digitization of real artefacts and other minor sources of information. Of utmost importance were the discussions and suggestions of scientists who have studied the monument from an historical and archaeological point of view, proving once again that a reconstruction is a multi disciplinary process.

6. CONCLUDING REMARKS

The final products are virtual reconstructions of buildings that do not exist today. Consequently virtual reconstructions are combinations of existing detailed architectural drawings, of sketches, descriptions, digitization of real artefacts and other minor sources of information. Of utmost importance are the discussions and suggestions of scientists who have studied the monuments from an historical and archaeological point of view, proving once again that reconstructions are a multi disciplinary process.

Virtual reconstructions on the other hand support many other disciplines involved in cultural heritage. They help architects in their work for monuments especially in cases of restoration, anastylosis etc. Archaeologists and Conservationists have a very good tool at their disposal for their studies. Many applications can be generated from a virtual reconstruction like virtual video tours of the monument for educational and other purposes for use by schools, museums and other organizations, for incorporation into a geographical information system (GIS) for archaeological sites, for the design of virtual museums and the creation of numerous applications for mobile devices (e.g. mobile phones, tablets etc).

Virtual reconstructions have the undeniable advantage that they do not harm the existing architectural elements and, most importantly, they may be reproduced in many different ways depicting each time a different solution to the inevitable questions that arise during a reconstruction process. Thus they could be a very powerful tool for in depth studies of our Cultural heritage.

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