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LABORATORY FOR THE GEOMETRIC DOCUMENTATION OF HERITAGE'S ARCHIVE

Sección de artículos / Papers section

31

Información general / General information		
TITULO:	Virtual Reconstruction of the Ancient State of a Ruined Church	:TITLE
AUTORES:	Christina GKINTZOU Andreas GEORGOPOULOS José Manuel VALLE MELÓN Álvaro RODRÍGUEZ MIRANDA	:AUTORS
FECHA:	noviembre 2012 / November 2012	:DATE
NUMERO:	LDGP_art_031	:NUMBER
IDIOMA:	inglés / English	:LANGUAGE

Resumen	
TITULO:	Reconstrucción virtual del estado previo de una iglesia en ruinas
RESUMEN:	Los modelos tridimensionales pueden representar tanto los elementos patrimoniales existentes como los ya han dejado de existir. En este proyecto se trata la reconstrucción tridimensional de la iglesia del Monasterio de San Prudencio de Monte Laturce (Clavijo, La Rioja, España) tal como se supone que fue durante el siglo XV. En la actualidad el edificio está arruinado por lo que ha sido necesario realizar una importante reconstrucción virtual basad en hipótesis que han requerido la colaboración de técnicos de diferentes áreas de conocimiento, por ejemplo, se ha contado con un levantamiento topográfico de los restos y del área circundante, datos sobre los materiales e hipótesis arqueológicas y arquitectónicas. Dado que existe información de múltiples fuentes, ha sido necesario incorporar un conjunto de criterios de selección y evaluación de las mismas.
DESCRIPTORES NATURALES:	Fotogrametría, documentación, ortofotografía, reconstrucción virtual, modelo 3D, patrimonio cultural
DESCRIPTORES CONTROLADOS:	(Procedentes del Tesauro UNESCO [http://databases.unesco.org/thessp/]) Patrimonio Cultural, Infografía, Fuente de Información

Abstract	
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NATURAL KEYWORDS:	Photogrammetry, documentation, orthophotos, virtual reconstruction, 3D model, cultural heritage
CONTROLLED KEYWORDS:	(From the UNESCO's thesaurus [http://databases.unesco.org/thesaurus/]) Cultural Heritage, Computer Graphics, Information Sources

Publicación / Publication		
Comunicación en un congreso / Lecture in a congress		
NOMBRE:	**4th International Conference, EuroMed 2012**	:NAME
LUGAR:	Lemessos (Chipre) / Lemessos (Cyprus)	:PLACE
FECHA:	29 octubre – 3 noviembre de 2012 / October 29 – November 3, 2012	:DATE
ACTAS:	Progress in Cultural Heritage Preservation. 4th International Conference, EuroMed 2012, Limassol, Cyprus, October 29 – November 3, 2012. Proceedings. Lecture Notes in Computer Science, Vol. 7616. Information Systems and Applications, incl. Internet/Web, and HCI Publisher: Springer Berlin Heidelberg ISBN: 978-3-642-34233-2 (print). 978-3-642-34234-9 (online) pp. 551-567 DOI: 10.1007/978-3-642-34234-9_57	:PROCEEDINGS
FECHA:	2012	:DATE
WEB:	http://link.springer.com/chapter/10.1007/978-3-642-34234-9_57	:WEB
NOTAS:		:NOTES
Artículo en revista / Journal paper		
NOMBRE:		:NAME
EDITOR:		:EDITOR
NUMERO:		:NUMBER
FECHA:		:DATE
ISBN:		:ISBN
ISSN:		:ISSN
WEB:		:WEB
PAGINAS:		:PAGES
NOTAS:		:NOTES
Otro / Other		
DETALLES:		:DETAILS

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Springer

Title of the Book/Volume/Conference: EuroMed2012 - Cultural Heritage

Volume Editor(s): Marinos Ioannides, Dieter Fritsch, Rosella Caffo, Rob Davies, Fabio Remondino, Johanna Leisner

Title of Contribution: Virtual Reconstruction of the Ancient State of a Ruined Church

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Virtual Reconstruction of the Ancient State of a Ruined Church

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Abstract. Three dimensional virtual models can represent both the existing and the already destroyed architectural heritage. This project deals with the 3D reconstruction and representation of the church of San Prudencio's Monastery in La Rioja (Spain) as it is supposed to be during the 15th century. Today the monument is totally in ruins; hence severe reconstruction was needed. This is an exemplary project of close collaboration of different scientific fields. Surveying data of the monument itself and of the wider area around it, but also architectural and archaeological data were collected in situ. It was not possible from the current situation to conclude about the exact form, style and representation of the monument; hence a large part of the project is based on assumptions which have a sound scientific base. Because of the multisource data there was need to define specific criteria by which every data source was evaluated.

Keywords: Photogrammetry, Documentation, Orthophotos, Virtual Reconstruction, 3D Model, Cultural Heritage

1 Introduction

This work is the result of a collaboration of two universities, the National Technical University of Athens (NTUA) and the University of the Basque Country (UPV/EHU). It is part of a bigger project of the documentation of the Monastery of San Prudencio that is located at the province of Rioja in Spain. This project is undertaken by a team of scholars of the University of the Basque Country with the contribution of five European Universities (National Technical University of Athens, HafenCity University of Hamburg, Polytechnic University of Madrid, University of Studies of Siena, Vilnius Gediminas Technical University) as part of two ERASMUS educational Intensive Programs. These ERASMUS projects aimed to document as completely as possible the whole Monastery by all the appropriate methods with the long-term target to make the great history of the monument known to the inhabitants of the region and the rest of the community. In addition this documentation would serve as the necessary background of the measures that the government should take to protect and conserve the monument.

This paper deals with the 3 dimensional virtual restoration and reconstruction of the church of the Monastery. It was decided to 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. As the monument is almost completely ruined, many sources were used for the reconstruction. The sources were evaluated according to their reliability and the data were categorized accordingly. In this way the final reconstruction reflects the various reliability grades, thus helping the potential user to comprehend it in a better way. This differentiates this reconstruction method, as it adds the reliability aspect.

It is a unique kind of project demanding the collaboration of different scientific fields and the combination of multisource data that were not always in agreement. It also presented a peculiarity regarding the integration of the data needed for the virtual reconstruction. Due to the lack of a thorough architectural and archaeological study at the moment, only a rough image of the structure of the monument was known and some more of its specific characteristics were discovered, noted and dealt with during the modeling phase.

2 Virtual Reconstruction

3D modelling 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 project focuses on their use for representing, reviving and studying Cultural Heritage in an interactive way.

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). In case of monuments preserving most of their characteristics, or have 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.

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.

The case of the church of the San Prudencio Monastery is a typical example of a reconstruction using such a 3D model, as it is completely ruined (Figure 1). It was decided to make a 3D model with surfaces in order to convey as much information as possible. 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.

Fig. 1. The church of San Prudencio's Monastery, current situation

Most of the original materials of the reconstruction phase did not exist. Consequently, for the surfaces to be textured, a thorough study of the existing materials was necessary, together with detailed comparisons with other churches in the area and of similar era. As the necessary time was not available, it was decided to texture the surfaces at a later stage in the future, when such study would be complete.

3 Methodology

The main stages of the work in order to obtain the final 3D model were the following:

- Geometric documentation of the current situation
- Research for the form and the state of the monument in the modeling phase (15th c.)
- Editing of the data
- Evaluation of the multisource data
- 3D model virtual reconstruction

3.1 Geometric Documentation of the Current Situation

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.

For the geometric documentation of the current situation with metric accuracy, correct scale and absolute position DSM and orthophotos were produced. For that purpose, photogrammetric procedures were employed using Photomodeler Scanner® v.6 and ImageMaster®. It should be mentioned that this kind of documentation was made only for the interior part of the church because most of the exterior part is covered and, hence hidden, by a thick layer of debris.

A Canon EOS 5D Mark II camera was used for taking the images and the Leica TCR307 total station for measuring the necessary control points. The images were taken with the suitable geometry and correction of the distortion was taken into account. The final DSM consisted of points clouds from Photomodeler Scanner® and Triangulated Irregular Network from ImageMaster®. Both products were coloured.

Fig. 2. Point cloud of the western wall

After creating the DSM, the operator defined the suitable parameters for generating the orthophotos, i.e. ground resolution, GSD, the part of the mesh that is going to be used for the generation of the orthophoto, the projection plane, the initial image which is going to be used for performing the colour interpolation and its algorithm. A scale of 1:50 was decided for the final orthophotos, so that the characteristics of the object, both for the 3D modelling and the needs of the archaeologists, to be visible. As it was impossible to process the whole church at once, the church was separated into small parts and in the end 10 orthophotos were obtained, which were later merged in AutoCAD.

Fig. 3. Orthophoto of the eastern wall

As the DSM and the orthophotos were used in order to draw vectors on them for the final modeling phase, it was necessary to evaluate their accuracy. This was performed by checking the position of the control points. Some of them were used as GCPs and some were reserved as check points. The check points give a more objective estimation of the accuracy. The results of this evaluation are summarized in the table below:

Table 1. Errors of the photogrammetric results.

	Average difference (GCPs)	Average difference (Check points)	Maximum difference
DSM	0.008 m	0.015 m	0.049 m
ORTHOPHOTO	0.008 m	0.011 m	0.032 m

It should be mentioned that in general DSM accuracy achieved is satisfactory, while the orthophotos accuracy is not entirely adequate for their scale. However, it is considered enough for the needs of the 3D reconstruction.

3.2 The State of the Monument in the Modeling Phase

It was decided to virtually reconstruct the church as it was during a specific period in the past (15th c.), as it was known that then the Monastery was at its major peak. For determining how the monument looked like at that time, historical, religious, archaeological and architectural literature was thoroughly studied. This included articles, descriptions literature, drawings etc. Churches of the same period and area were also examined as the architectural style was the same during the specific time and in the particular area.

The historical and construction data, gathered mainly by archaeologists and architects, were verified by field measurements by the surveyors.

3.3 Editing of the Data

The DSM is a useful tool for the reconstruction as it is a 3D product. It provides 3D information which is directly related to the final model. The 3D models were used as a basis for directly constructing 3D drawings having always in mind that they present the current situation and not the elements of the reconstruction phase (15th c).

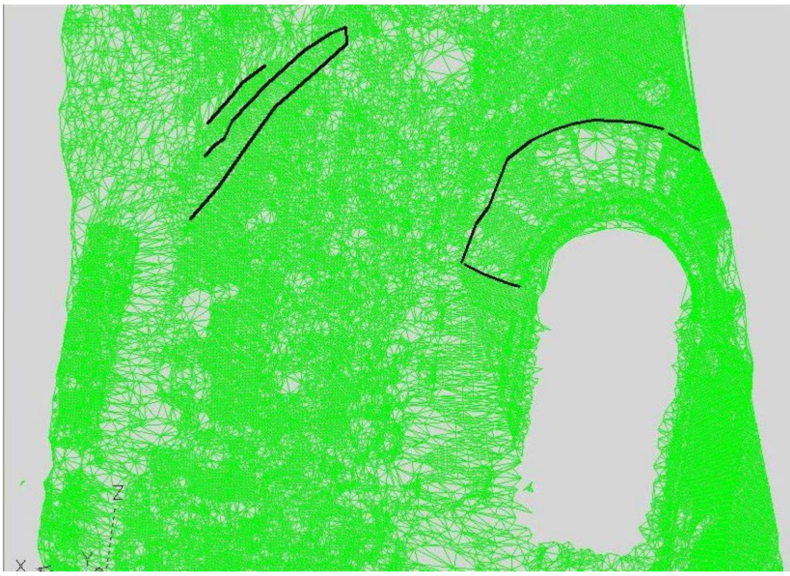

Fig. 4. 3D Drawing on DSM

The orthophotos are of great importance as they provide measuring capabilities. They are useful in order to measure dimensions on their projection plane. They were used as background in order to draw 2D lines on the projection plane of each one of them (Figure 5). These 2D lines were later transformed to 3D lines using the DSM information for the elevations. After suitable editing they were later merged in the final 3D model.

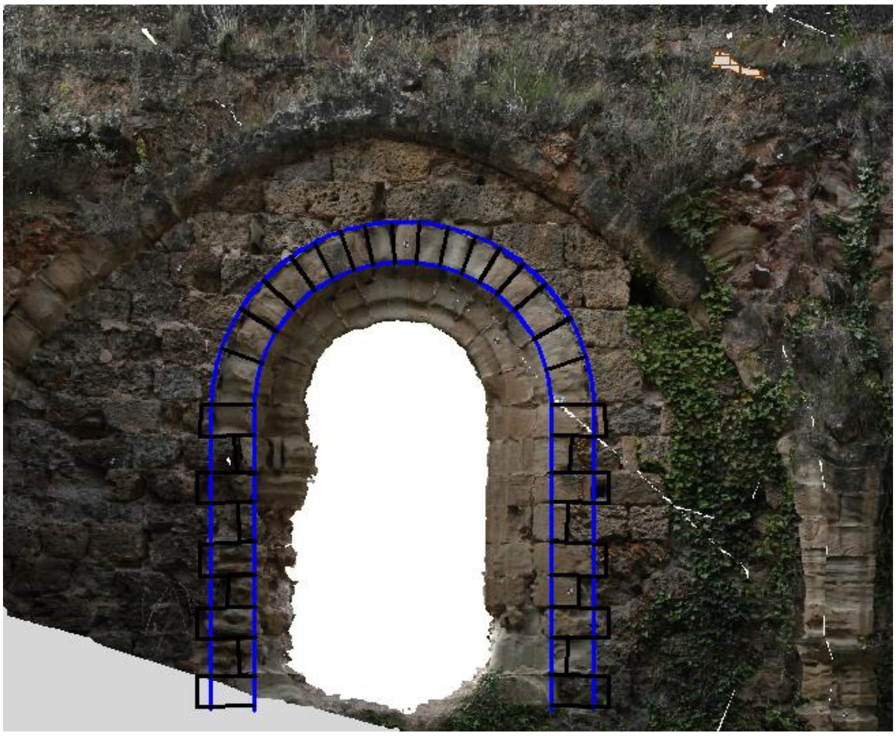

Fig. 5. 2D drawing on an orthophoto

Finally, the scanner data were also used to extract 3D line drawings that were equally important data for the phase of modeling.

Fig. 6. 3D line drawing as it was designed with background laser scanner data

3.4 Evaluation of the Data

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, we need to carefully select -from the previous wire-frame model- 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. The following table shows how reliable each piece of data is evaluated. It refers to the data selected for this project and should not be generalized. For example in other cases a drawing could be more reliable than in this case that its painter is unknown, so it is not a reliable and close to the truth. The photos refer to the current situation are neither very reliable as they include varying scale.

Table 2. Reliability of data (1: most reliable 10: less reliable).

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 2, 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 (cf. grade 1 in Table 2). Similarly, the rest of the various sources were evaluated by the interdisciplinary group. Written sources are high in the reliability scale (cf. grade 2), 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.

After categorizing the data according to their reliability of source, a rough model of the monument was created. In order to pass from the rough model to a more accurate one, data ought to be examined in a second more detailed level. Hence, the final 3D model was constructed by taking into account the criterion of accuracy. This classification refers to data that are not in agreement regarding the position of elements like the example in Figure 7. In this case, there were three sources giving information about an arc on the southern wall of the church. These sources were the relative DSM (light blue line), the orthophoto (black lines) and the 3D line drawings (yellow lines) as they were extracted from the laser scanner data. As it was expected, they do not coincide as their accuracy differs.

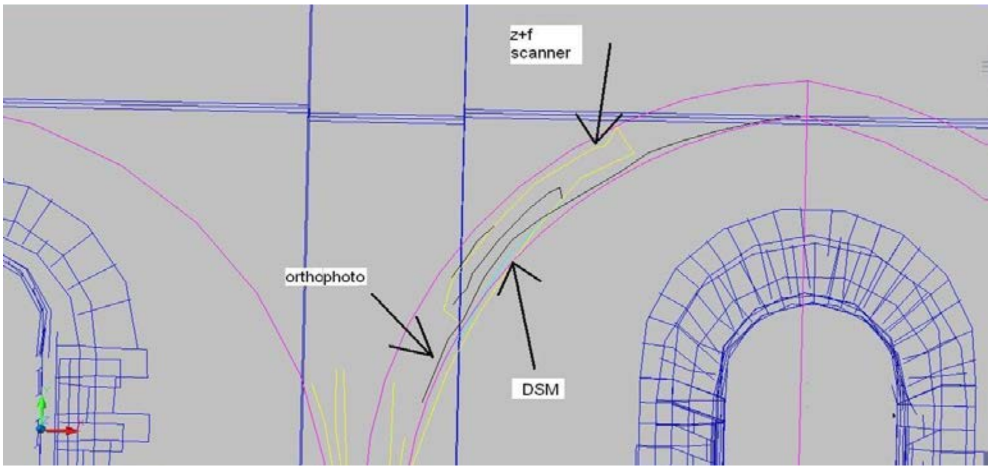

Fig. 7. Data from different sources

Consequently a second table was created (Table 3) representing the hierarchy of the data based on the criterion of accuracy.

Table 3. Accuracy of data (1: most accurate 10: less accurate).

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

Summarizing, Table 2 helps the selection of the elements to be included in the 3D model, while the Table 3 dictates how accurate they will be drawn. The combination of both hierarchies gives a measure of their final likelihood.

3.5 3D Model of the Virtual Reconstruction

The construction of the 3D model was based on all the above data and their evaluation. AutoCAD® was chosen as the construction platform, as it offers good tools for efficient editing of vector drawings, especially in three dimensions. Moreover, no texture was to be applied in the final model, hence a vector editing software was most ideal.

The modeling was based on drawing 3D lines and later applying surfaces to them. Sometimes, surfaces were created directly without the involvement of 3D lines, using useful tools of the software.

3.5.1 Linear Drawings

As already mentioned, the first step of modeling was to create the 3D linear model based on the combined and evaluated data available.
The initial rough design of the church as it was drawn according to the instructions of the experts is shown in Figure 8. It is only a simple sketch of the state of the church.

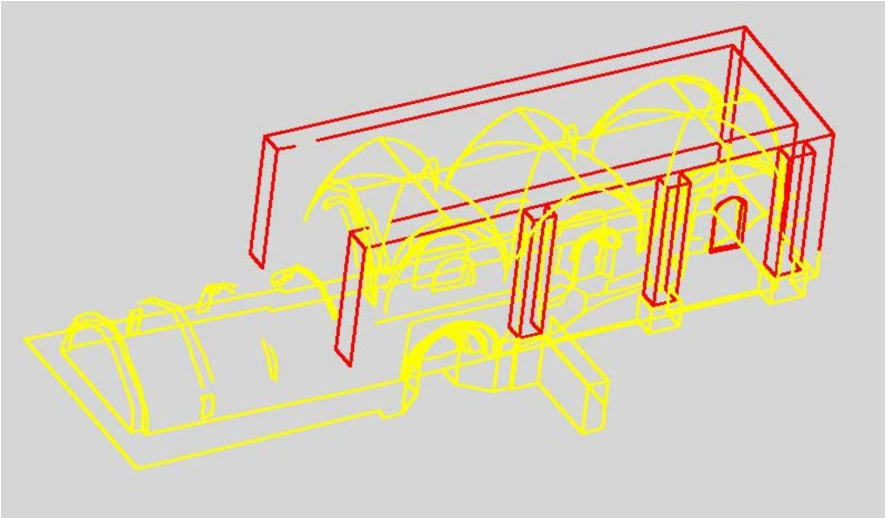

Fig. 8. Initial rough 3D model

Based on this model a more complete one was gradually constructed, i.e. the model is completed progressively. The object had to be separated to many distinct parts that permitted the autonomous drawing, i.e. roof, windows, entrance, parts of the walls etc. and later they were merged to one common file. It was not possible to work simultaneously on the whole object, because the file gradually became larger and difficult to manage. As more lines were added, perception of space became more difficult. Apart from the separation of the object into smaller parts, a multitude of different layers with different colors was employed, in order to help the efficient editing. Creation of surfaces sometimes helped the dubious depth perception.

3.5.2 Completion of the Data

The knowledge of the exact appearance of the monument during the period of interest will always remain incomplete. Consequently, some decisions ought to be made based on observation and assumptions. During the modeling phase, certain geometric observations on the acquired, otherwise not possible, gave sound base to such decisions for the reconstruction. Decisions like that were always discussed and approved by the archaeologists and architects of the team.

Such an example is shown in Figures 9 and 10. Traces of arcs (shown with arrows) have been observed during the phase of drawing on the orthophotos of elements that later would be transferred to the final 3D model. These traces were observed on the southern and western walls of the church. They served as a proof of the existence of a second vaulting system, today totally destroyed, which was constructed higher than the ones apparent today.

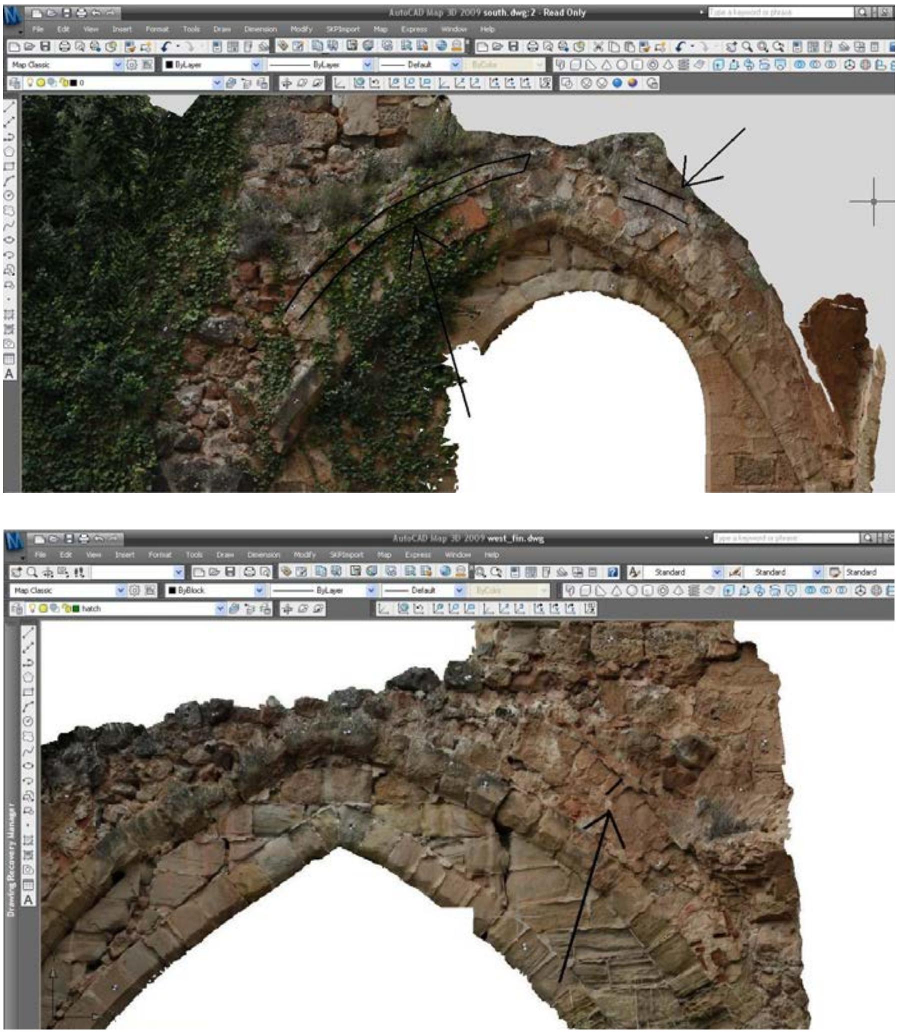

Fig. 9 and 10. Traces of arcs on southern and western wall

In order to improve the realism of the 3D model, surfaces were added based on the lines drawn. Just like in the case of the linear drawing, layers were also used. This stage of surface creation had different levels of difficulty depending on the geometric shapes of the monument.

3.5.3 Level of Details

After creating the general frame that refers to the structure of the object, the more complicated decorative elements were added. In general, the basic elements of the church that could be analyzed to simple geometrical shapes (walls, arcs, windows) were created using useful tools by the drawing software and there was no need to take the level of their detail into consideration, as they have clearly defined shapes. But as far as the decorative elements that were more complex is concerned, there was a lot of subjectivity regarding their design.

For example the figures 11 and 12 show a detail of the middle window of the southern wall. The current situation of this element is damaged and one could not be sure about its initial shape. So it was finally decided to draw the detail with basic criterion the nice aesthetical result (figure 13).

 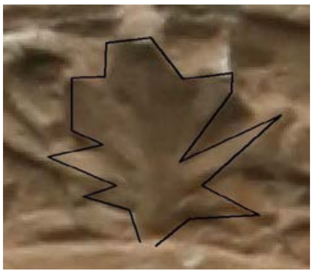 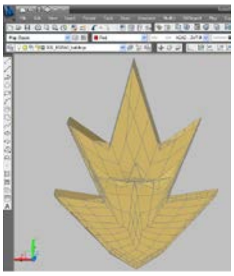

Fig. 11, 12 and 13. Decorative detail

3.5.4 Drawing Difficulties and Decisions

During the modeling many difficulties were encountered, mostly, regarding the connection of different modeled parts of the monument. Unavoidable inaccuracies occurred, mainly due to the different source of the various elements to be combined into the final model. This is more apparent for elements that do not exist and are reconstructed based on other sources, both for their shape and for their exact position. The more accurate solution was to recreate more carefully the parts whose combination was problematic. But once the drawing stage was already advanced it was difficult to change the position and shape of some parts without changing the rest of the structure. So it was decided to change other small elements and not to redraw fundamental parts of the monument.

For example in figure 14 the result of the connection of the vaults of the church with the columns on which they were based is shown. In the floor plan the border of the column is shown with black line and with red color the base of the vault that should be into the column border but it is not. It was quite difficult to reconstruct the vault, so it was decided to make a little bit bigger the diameter of the column, which was a very quick procedure. Regarding the accuracy, it is estimated that practically no accuracy was lost because the widening of the column was so small that it is included within the level of uncertainty allowed for objects non-existent today such as the upper part of the columns.

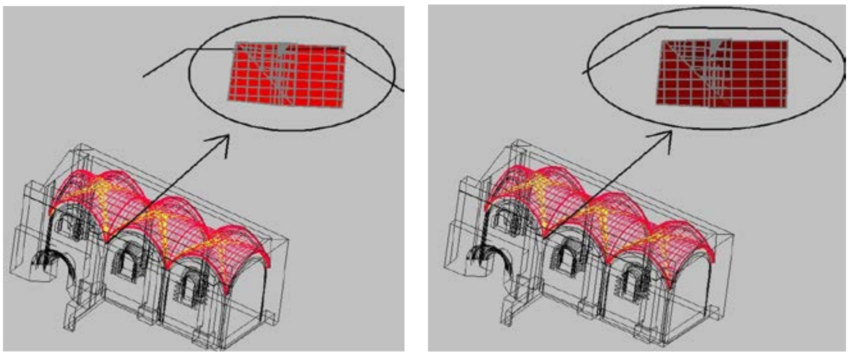

Fig. 14 and 15. Designing problem and solution

4 Results

The final result of this is a 3D Virtual Model representing an hypothetical reconstruction of the church of San Prudencio's Monastery, as it, most probably, could have been the 15th c. The aim was that every interested user would be able to handle it and observe it and focus on the points he is particularly interested in. Of course there are possibilities of producing an animation in a video, which could be used by educational, cultural and touristic organizations that may not use CAD files. Such an animation was produced using Snagit® software, in which the model is moved following a specific route.

In the following some images from the final 3D model are presented. It is a presentation of parts and the entire model with different ways of visualization.

4.1 Vector Drawing

The final 3D line drawing of the church as it is considered to be in 15th c. is presented in Figure 16. Due to lack of surfaces it is not so realistic, but it gives the ability of measuring dimensions and observing certain details.

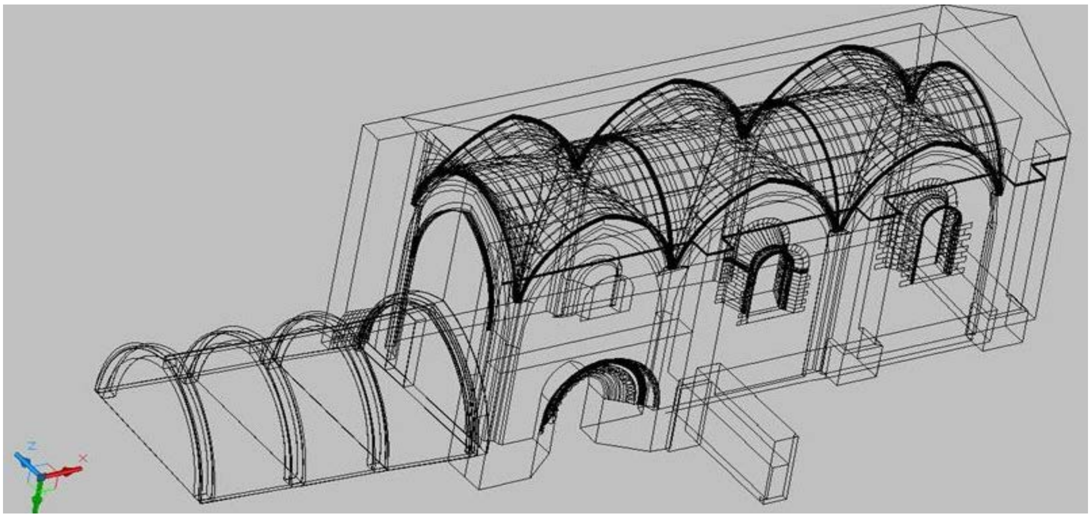

Fig. 16. 3D line drawing

4.2 Surface Drawing

In Figure 17 the church is presented with linear and superficial elements. In the model some details are shown better, but also there are lines visible at this stage that should not be, e.g. the interior ones.

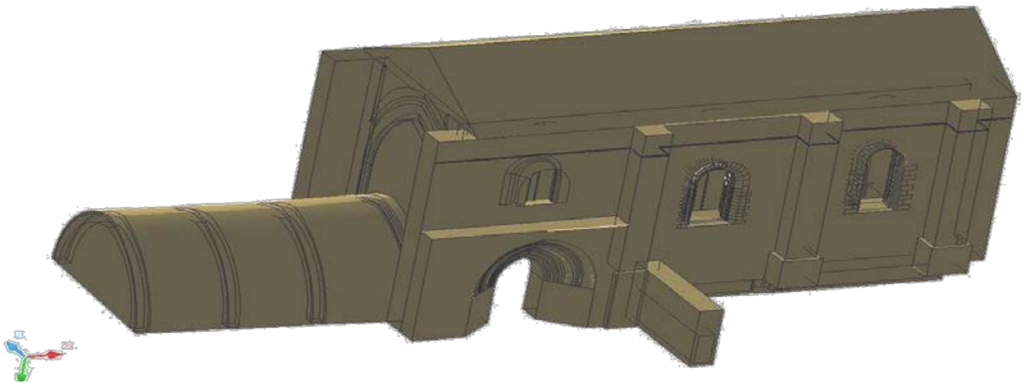

Fig. 17. Initial stage of the 3D model construction

In order to point out some specific parts of the structure, their differentiation by a different color is suggested.

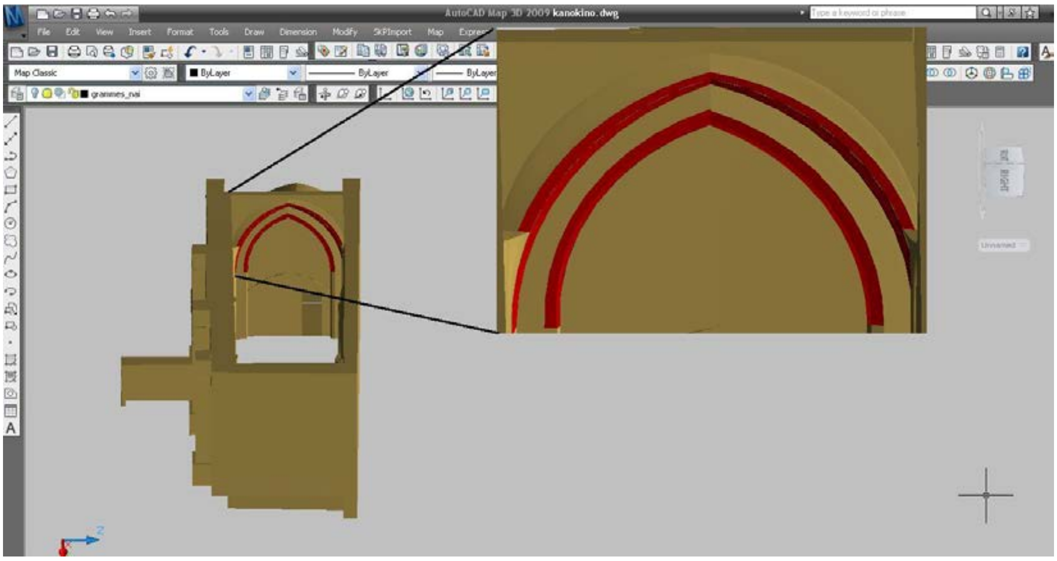

Fig. 18. Differentiation of the arcs of the western wall

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.

In general, one can be more certain for the position, shape and the size of the elements that are part of the current situation and research verifies that they should be part of the reconstruction phase too. The opposite holds for elements that are supposed to have been present, but they do not appear today, such as the roof and the vaults of the church. After the creation of the 3D model it was essential to check it. The parts that do not exist could only be checked by their adaptation to the existing ones. A characteristic example is the vaulting system of the church, which were reconstructed according to other similar church vaults. Their dimensions were based on the traces found on the existing ruined walls. There is uncertainty regarding their exact height and shape. Moreover, we have no data for the existence of some elements of the model like the roof that are only based on the experience of the archaeologists. The exact height and inclination of it cannot be determined with reliability.

In order to give to the final model an estimation of the level of accuracy and likelihood of its elements, it was decided to differentiate on it the elements of different sources. More specifically each element had a different color tone depending on the source it came from. Due to the fact that the sources have different level of accuracy, each source was decided to be presented by a different tone of the same main color, in this case red. The darker the color the more accurate is the position of the element.

A representation of this kind must be followed by a legend which will analyze the correspondence of every color tone. In this case the legend was the following:

- Remains currently available and visible (dark red colour)
- Not visible (hidden underground) but surely existent remains (red)
- Hypothesis based on partial remains that are completed (lighter red - pink colour)
- Hypothesis without remains, but necessary to finish the building (beige)

Fig. 19. Detail of the 3D model – window of the southern wall

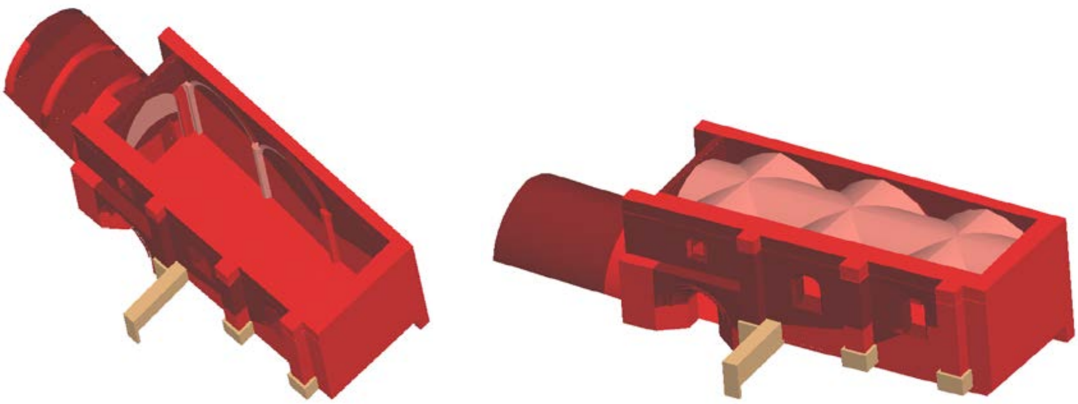

Fig. 20 and 21. Parts of the 3D model

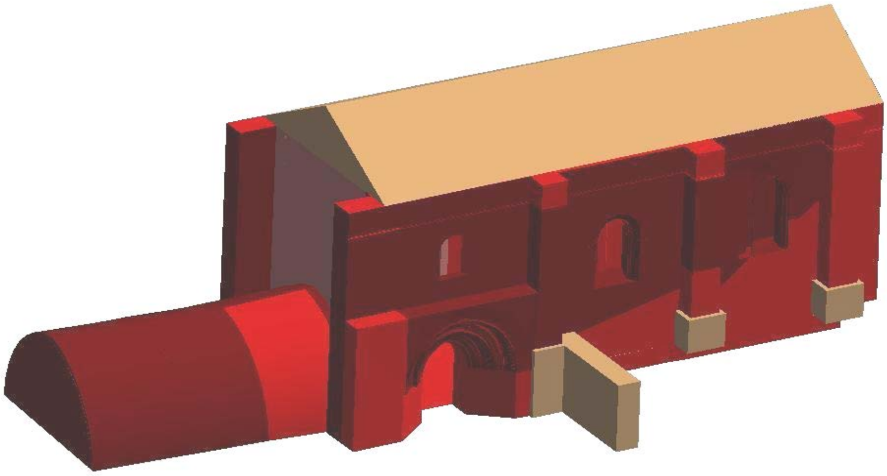

Fig. 22. The entire 3D model

4.3 Oblique Cross-sections

Another product that could be easily obtained after creating the 3D virtual model and provide important information, are the oblique sections that were generated into 3ds Max®.

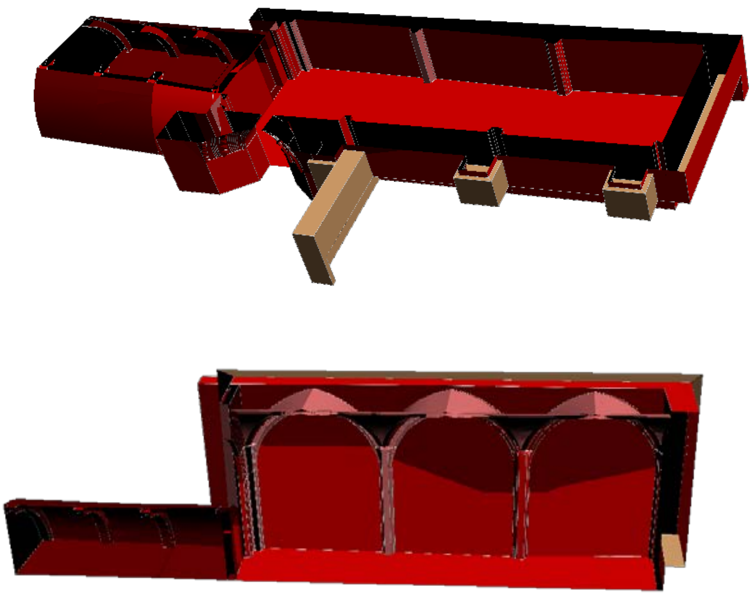

Fig. 23 and 24. Oblique Sections

5 Future Outlook

As far as the management of data is concerned, attention should be paid to careful archiving and the evaluation of the multisource data. Careful archiving is needed because of the collaboration of different scientists and the exchanging of data among them. The evaluation of data is important in order to make the best decisions and create a good result.

Regarding the drawing part, it is proposed:

- There are many pieces of software available for this kind of virtual modeling. It is estimated that the use of AutoCAD® in this case was quite convenient and provided good results. If textures and materials are going to be adjusted, then, the use of other software like 3ds Max is suggested as it is more advanced as far as texturing is concerned.
- In some cases accurate corrections to the drawing would lead to time loss. Hence, it is preferable to leave some small problems on the model or correct them with alternative and not so accurate methods than recreate it from the beginning. It is suggested to think if the corrections should be made, taking into account the criteria of accuracy and time.
- It is suggested that the final virtual model be followed by an explanation regarding the accuracy and likelihood of its elements. Thus, the results will not be overestimated and the viewers will have a fair opinion for them. This explanation could be a text or could be expressed directly through the model as it happens with this project.
- Perhaps the most important conclusion from this work is the fact that accurate geometric documentation provides the opportunity to the engineers to carefully observe the data and study the structural parts, thus discovering secrets of the ruined past.

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Acknowledgements

The 3D Virtual Reconstruction of the San Prudencio Monastery s church is a project that was undertaken by two Universities (National Technical University of Athens and University of the Basque Country) and two laboratories (Laboratory of Photogrammetry and Laboratory of Geometric Documentation of Heritage, respectively). It is the result of the close collaboration of many engineers and archaeologists, students and professors. Except of the professors that are already mentioned it should be mentioned the great help of the architect Roberto Parenti, the archaeologist Chiara Maria D'Anna and the surveyor engineer Miguel Moreno González.

This project is an outcome of the ERASMUS IP activity "TOPCART Geometric documentation of Heritage: European integration of technologies" undertaken during the summer 2010 2009-1-ES1-ERAIP-0013) and 2011 (2010-1-ES1-ERA10-0024).

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