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3D Virtual Reconstructions at the Service of Computer Assisted Archaeological Measurements

Abstract: Technological advances have enabled photogrammetric and surveying methods to produce recording materials surpassing the traditional line drawings in accuracy and completeness. These methodologies may offer products not possible in the past. This paper relates the difficult experience of collecting, archiving, processing, combining, visualizing and exploiting data from a multitude of sources to make accurate geometric records of monuments, implementing the most contemporary, innovative and technologically advanced methods. Issues analysed include collecting and processing field data from a variety of sources and their respective properties, but also the production of different end products, vector and raster, with the main emphasis on complex 3D visualizations. Different approaches are assessed for their usefulness and potential accuracy. Examples covering a variety of Greek and Cypriot monuments are presented, which are acquired from the rich experience of the archaeological surveys of the Laboratory of Photogrammetry of NTUA.

Introduction

We have entered an era where the acquisition of 3D data is ubiquitous, continuous, and massive. In many different areas of application (Medicine, Chemistry, Engineering/Automation, Computer Graphics/Virtual Reality, Geographical Information Systems-GIS, Archaeology, etc), this data comes from multiple sources having high resolution and high quality. Some such sources include:

- Geo-corrected imagery from aerial photography and satellites, ground-based close-up images of buildings and urban features in GIS.
- Medical scanners like Magnetic Resonance Imaging (MRI), X-Ray, Computer Tomography (CT), 2D and 3D-Ultrasound for different parts of the human body for computer diagnosis/simulation and real time computer aided surgery.
- Photogrammetry and laser scanning in close range applications, like archaeology, for the documentation and reproduction of the past in 3D.
- Optical laser scanners, mechanical tactile sensors and stereo cameras in the automotive-, aerospace- and general manufacturing industries for computer aided quality approaches.

To make this scanned data really useful, it should be processed so that it portrays its subject matter as realistically as possible. The digital model should then be available for visualization, interactive exploration, modeling and analysis. Although many different approaches have already been proposed, robust methods are lacking for reconstructing digitized unstructured sets of points (scattered points) within a certain time period in the areas of interest mentioned above. These methods must be applicable to complex geometrical and topological objects, including those which contain holes, branches, and possibly several connected components, even without any prior information.

Monuments are undeniable and valuable documents of world history. Their extensive and integrated study is an obligation of our era to mankind's past and future. Respect towards cultural heritage has its roots in the era of the Renaissance. Over the recent decades, international bodies and agencies have passed resolutions concerning the obligation for protection, conservation and restoration of monuments. The Athens Convention (1931), the Hague Agreement (1954), the Charter of Venice (1964) and the Granada Agreement (1985) are only a few of these resolutions, in which the need for geometric documentation of the monuments is stressed, as part of their protection, study and conservation. All countries of the civilized world are putting their scientific and technological efforts towards protecting and conserving these monuments, either within or outside their borders. These tasks generally include geometric recording and restoring and managing the Cultural Heritage.

The methods of geometric recording of monuments, especially those based on surveying methodologies, have benefited greatly from recent technological advances. The main aim of this paper is to demonstrate the exploitation of the relevant technological advances within the traditional measuring sciences for geometrically documenting, virtually reconstructing and performing 3D measurements of the world's Cultural Heritage.

Geometric Documentation

Digital photogrammetry, laser scanning and mechanical tactile sensors are the most common measurement technologies for the extraction of 2D/3D points or 2D images from different objects in this specific area. The surveyed data is used for the quality inspection of different objects (i.e. the comparison between the virtual Computer Aided Design (CAD) model and the real manufactured object on an assembly line), the automatic generation of CAD drawings from "unknown real objects" (reverse engineering) and replication of real objects (reproduction). Photogrammetry derives all the appropriate measurements from the images (attributes such as color and geometry), rather than measuring the object directly. That is why this technology provides significant advantages over the conventional methods of digitization. The quality and the accuracy of the data and the speed of digitization set the standard for the different applications in these areas.

In the area of Cultural Heritage, the sizes of objects range from microscopic to gigantic, covering monuments, artifacts, mummies, graves, tombs, amphitheatres and archaeological sites. Therefore, a variety of digitizing applications are in use, from satellite and aerial scanning procedures, to close-range photogrammetry, laser scanning, hand-set scanners and specific medical scanners. The accuracy of the data starts at the sub-millimeter level and goes up to centimeters. The speed of digitizing is mostly irrelevant in this area. What is important is that different attributes (color, drawings, engraving, etc.) of the object can be encoded during the digitizing process. The geometric documentation of a monument may be defined as:

- The action of acquiring, processing, presenting and recording the necessary data for the determination of the position and the actual existing form, shape and size of a monument in the three dimensional space at a particular given moment in time.
- The geometric documentation that records the present state of the monuments, as this has been shaped in the course of time and is the necessary background for studies of their past, as well as care for their future (UNESCO 1972).

Geometric documentation should be considered as an integral part of the greater action of the general documentation of the Cultural Heritage. This is comprised of, among other things, historical documentation, architectural and archaeological documentation and bibliographic documentation.

The geometric documentation of a monument consists of a series of necessary measurements, from which visual products such as vector drawings, raster images and 3D visualizations may be produced. These products usually have metric properties, especially those found in suitable orthographic projections. Hence, from the geometric documentation, one could expect a series of drawings which actually present the orthoprojections of the monument on suitably selected horizontal or vertical planes. The scale and accuracy of these products are very important. These should be carefully defined at the outset, before any actions are carried out on the monument (Georgopoulos / Ioannidis 2004).

In this context, "large scale" implies scales larger than 1 : 250. The various alternative scales may be grouped in three main categories. Firstly scales between 1 : 250 and 1 : 100, which serve the purposes of general surveys. Secondly scales between 1 : 50 and 1 : 20, which cover most of the geometric recording cases providing a highly detailed product for practically any sort of serious study. Lastly, scales larger than 1 : 20, which are used for enlarged drawings of special details of interest.

The level of detail is another important issue, and an indication of it should be present in the final product. For an appropriate judgement on this matter, the contribution of the expert-user is indispensable. A survey product, a line drawing or an image always requires a certain level of abstraction or generalization, depending on the scale. Hence, the requirements or the limits of this generalization should be set carefully, always in co-operation with the architect or the relevant conservationist, who already has deep knowledge of the monument (Ioannidis / Potsiou / Badekas 1997).

Geometric documentation is the responsibility of experts concerned with the care of Cultural Heritage. Traditionally these mainly belonged to the field of archaeology and architecture. However, over the past thirty or forty years, more specialists from different fields have developed an interest in monuments, as they have been able to contribute clearly to their maintenance and care. Amongst them are surveyors and photogrammetrists, as technological advances have enabled them to produce interesting alternative and accurate documentation products.

For geometric recording several surveying methods may be applied, ranging from conventional simple topometric methods, for partially or totally uncontrolled surveys, to elaborated contemporary surveying and photogrammetric ones, for completely controlled surveys. The simple topometric methods are applied only when the small dimensions and simplicity of the monument allow for them, when an uncontrolled survey is adequate, or in cases when a small completion of the fully controlled methods is required. Surveying and photogrammetric methods are based on direct measurements of lengths and angles, either on the monument or on images thereof. They determine three-dimensional point coordinates in a common reference system and ensure uniform and specified accuracy. Moreover they provide adaptability, flexibility, speed, security and efficiency. All in all they present undisputed financial merits, in the sense that they are the only methods which will consistently meet any requirements with the least possible total cost and the greatest total profit (Georgopoulos / Ioannidis 2005).

It should, however, be stressed that to date there is no generally acceptable framework for specifying the level of detail and the accuracy requirements for the various kinds of geometric recording of monuments; every single monument is geometrically documented on the basis of its own accuracy and cost specifications. The international scientific community should attend to this matter.

The Impact of IT on Traditional Practices and 3D Reconstructions

The process of turning a set of scattered points (point clouds) or a set of images, contours or slices into a 2D or 3D computer-graphical, geometrical model generally involves several steps: cleanup, simplification, reconstruction of an initial piecewise-linear model, fitting with free-form surface patches such as Bezier, Splines or NURBS and presentation of data in standard exchange formats (IGES, VRML etc).

The emphasis will be given here on the 3D reconstruction step, and in particular on an abstract problem defined in the literature as "Reverse Engineering". Several professionals from different scientific areas worldwide have recognized the problem of 3D reconstruction and have started working in this area since the beginning of the 1980s. A short overview of the most important scientific contributions will be given in order to describe the current state of the applied technology.

An early Delaunay-based algorithm is the "Delaunay sculpting" heuristic, which progressively eliminates tetrahedra from the Delaunay triangulation based on its circumspheres. In two dimensions, there are a number of recent theoretical results on various Delaunay-based approaches to reconstructing smooth curves. Multiple authors have given garuantees for different algorithms (Bernardini / Bajaj 1997; Bernardini et al. 1999; Figueiredo / Gomes 1995; Amenta / Bern / Eppstein 1998; Amenta / Bern / Kamvysselis 1998).

A fundamentally different approach to reconstruction is to use the input points to define a signed distance, and then polygonalize its zero-set to create the output mesh. Such zeroes algorithms produce approximating rather than interpolating meshes. This approach was taken by Curless and Levoy (Curless / Levoy 1996). Their algorithm is tuned for laser range data, from which error and tangent plane information is derived. These authors combine the samples into a continuous volumetric function, computed and stored on a voxel grid. A subsequent hole-filling step also uses problem-specific information. The implementation is especially fast and robust, capable of handling very large data sets. One proposed crust algorithm (Amenta / Bern / Eppstein 1998; Amenta / Bern / Kamvysselis 1998) does not require such parameters; it in effect automatically computes the parameters locally. Allowing the sampling density to vary locally enables detailed reconstruction from much smaller input sets.

Some recently significant specific algorithms for the 3D digitization, reconstruction, visualization and animation in the area of Cultural Heritage are also described elsewhere (Boehler / Patias 2002; Altan 2003).

Innovative Methods and Products

Introducing innovative IT developments into new, sophisticated systems for large volume 3D spatial data recording and storage provided new prod-

Fig. 1 Combination of vector restitution and raster orthoimages: vertical section of Byzantine church of Dafni (Greece), where the internal mosaics are shown.

Fig. 2. Textured 3D model of the external of the Katholikon of Dafni monastery, produced by the combined use of surveying and photogrammetric techniques.

ucts for the geometric recording of monuments in recent years. Moreover, new techniques were developed for the improvement of existing methods and the creation of new procedures for visualization and processing, with an emphasis on automation, accuracy improvement and speed. In terms of instrumentation, new developments are related to:

- Surveying techniques, like robotic total stations, and also the development and broad use of GPS measurements.
- Photogrammetry, in particular the development and use of digital cameras, with large sensor formats and improving resolution, and their integration into geodetic total stations or terrestrial laser scanners for combined data acquisition (Beraldini et al. 2006; Haggren 2005).
- The enrichment of Digital Photogrammetric Workstations (DPWs) with a variety of specified software tools, e.g., for satellite image processing, 3D textured model creation in close range applications using simple and user-friendly operations, to be used by non-photogrammetrists (Ioannidis / Soile / Potsiou 2006).
- Rapid development of airborne and terrestrial laser scanners (time-of-light, phase-based and triangulation scanners), which produce high accuracy, very dense point clouds, appropriate for a broad range of applications, from large archaeo-

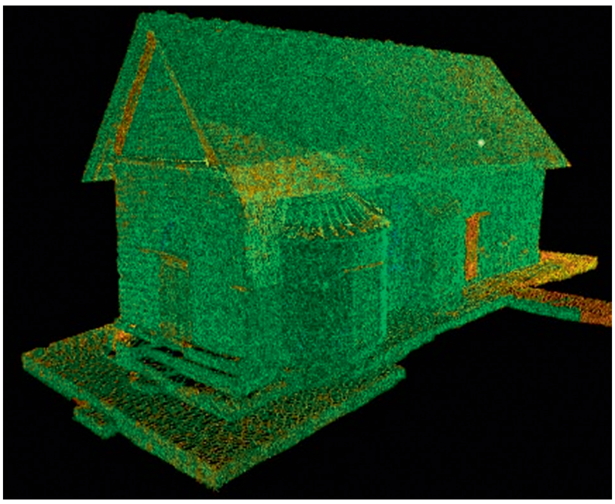

Fig. 3. Registered laser scanning point cloud of Byzantine church of Panagia of Asinou at Troodos mountain (at an altitude of 450 m), Cyprus.

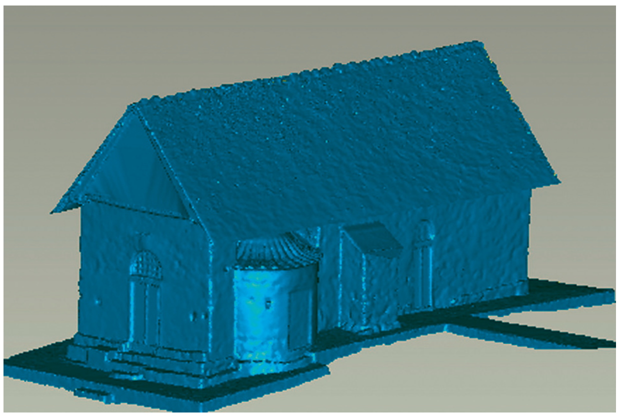

Fig. 4. South-western view of the church's 3D "watertight" model.

Fig. 5. Orthophotomosaic: Northern façade of Asinou church.

logical sites up to complex sculptures or movable artifacts (Cioci et al. 2005; Ruether 2007).

The main result of the abovementioned developments was the combined use of multi-source data for the production of different end products, such as:

- 2D vector plans, using surveying and photogrammetric measurements in combined adjustment.
- Fully automated 2D raster products, like ortho-photo-mosaics, using Digital Surface Models (DSMs) derived from laser scanning point clouds in the digital ortho-image production process *(Fig. 1)* (El-Hakim et al. 2005; Haala / Alshawabkeh 2006; Ortiz et al. 2006). Special software was developed to overcome problems that appeared in the commercial DPWs during orthophoto production in close range applications (mainly for complex surfaces of monuments) or in cases of multiple image coverage, for the creation of developments in the case of documentation of developable surfaces, etc. (Grammaticopoulos et al. 2005; Ioannidis / Skondras / Morfi 2006).
- 3D models and textured 3D models, virtual and augmented reality scenes *(Fig. 2)*. The use of a common reference system for all data, and the implementation of polygonal modeling (through points and lines) for 3D object reconstruction provides the means for a series of operations, such as rendering, 3D visualization, 3D reproduction, and taking 3D measurements in a virtual space (Viti 2003; Georgopoulos et al. 2004; Gruen 2005; Peral / Sagasti / Sillaurren 2005). These measurements are considered to be valuable for the archaeological research or study, and are otherwise extremely difficult or impossible to perform on the physical object (Barcelo et al. 2003; Balzani et al. 2005).

As an example, *Fig. 3* shows the final registered point cloud of a famous Byzantine painted church in Cyprus. This point cloud was derived by merging and georeferencing the fourteen acquired scans, using pre-measured targets and the Cyclone software. The creation of a 3D model of the church *(Fig. 4)* included noise removal and data reduction, the production of a polygon mesh, the filling of holes

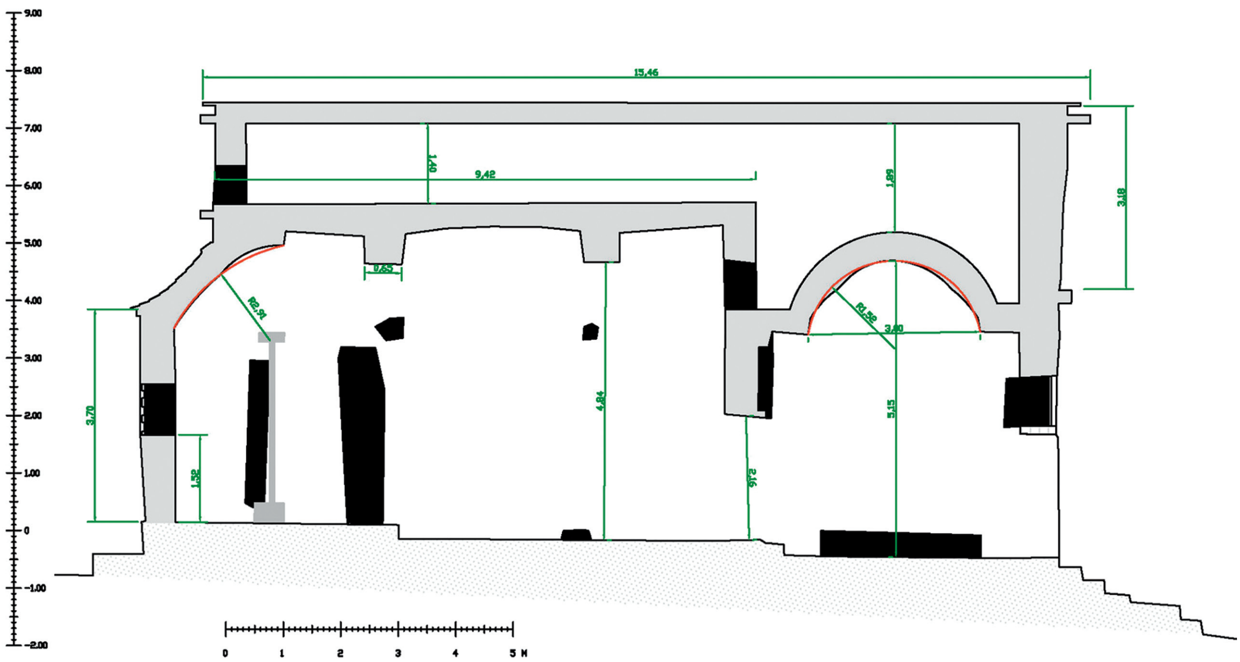

Fig 6. 2D measurements: Measurements on the longitudinal vertical section, “looking” to the south, derived from the 3D model.

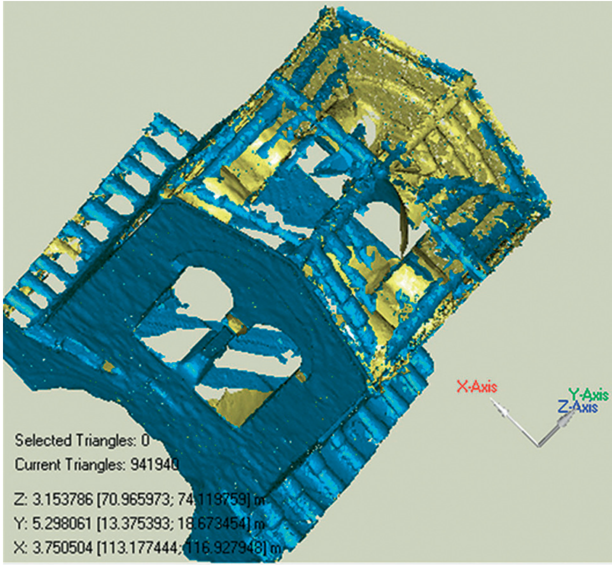

Fig. 7. 3D model of a bell tower as it is derived from laser scanning point clouds modeling. The existence of scan holes is obvious, especially on the roof, due to the difficulty in acquiring data from above.

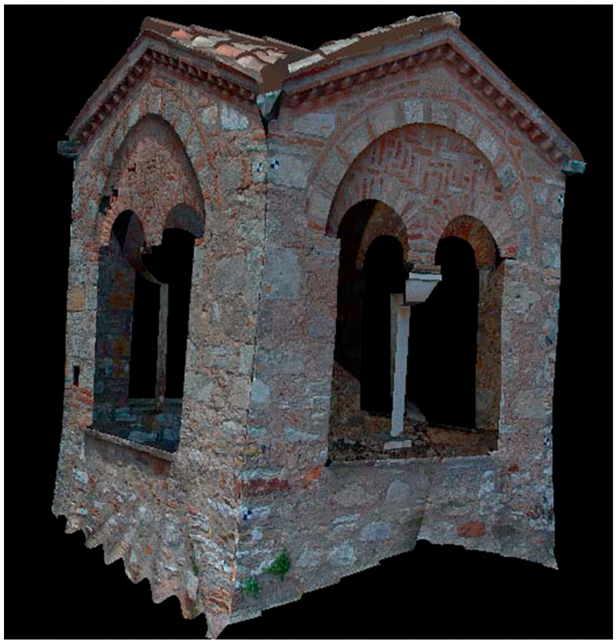

Fig. 8. Textured 3D "watertight" model of the bell tower, after a combined use of laser scanning, photogrammetric processing of digital images and use of software for filling the holes.

and finally the creation of a 3D surface model (Sofocleous et al. 2006). By combining the laser scanner point clouds with the photogrammetric processing of the images taken by a digital camera, a variety of 2D products can be derived, for example orthophotomosaics *(Fig. 5)* or plans appropriate for 2D measurements *(Fig. 6)*, and textured 3D models.

Obviously not all problems have been solved by the use of the abovementioned technologically advanced procedures, even in combination. The topography of archaeological sites and the morphology and the curved surfaces of monuments may increase the difficulties present. For example,

Fig. 9. 3D model of complex monument using laser scanning data and photogrammetric ortho-images production: application on the sculpture of Hermes of Praxiteles.

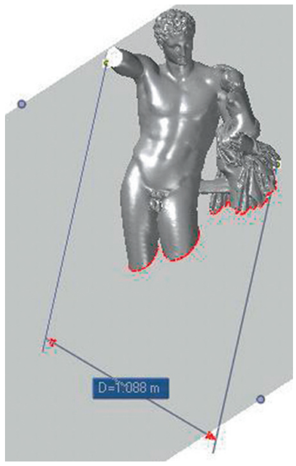

Fig. 10. Measurement capabilities on the 3D model of Hermes.

it is often highly impractical or impossible to create "watertight" models of archaeological sites or individual monuments without scan holes (e.g., *Fig. 7*). In order to solve that problem, the operation of specialized software and often the combined use of various recording techniques, such as the completion of laser scanning data with data derived from photogrammetric stereo-restitution or ortho-images, are necessary *(Fig. 8)*. However, these procedures are time consuming and laborious, since no automated techniques can be applied.

Figures 9 and 10 show the results of application of the methods and techniques described above on more complex and smaller objects, such as sculptures, where higher accuracy and the more detailed recording are necessary. In the left portion of *Fig. 9*, a view of the 3D solid model of the famous sculpture of Hermes of Praxiteles is given, as it was derived from point cloud processing, taken by a triangulated laser scanner (Minolta 9i); in the right portion of *Fig. 9*, an ortho-image of the sculpture's front side is given, derived from photogrammetric processing of digital large scale images, taken by a camera with pixel size of 8 µm (Ioannidis / Tsakiri 2003). *Figure 10* shows a simple example of additional options given to the end user (e.g., 3D measurements) through the existence of the 3D model of the sculpture and the appropriate software for processing and visualization.

Conclusions

Through the contributions of a number of scientific efforts, the digitizing and 3D reconstruction of an object has reached a stage that allows the images, 2D and 3D points and contours to be presented in the form of space-filling, solid, oriented structures. This enables scientists, conservators, students and users in general to virtually interact with the monuments in an unprecedented way. Three-dimensional (3D) reconstructions have undoubtedly shortened the distance between reality and the virtual world.

For those experts who study Cultural Heritage, the interpretation of the geometry of each monument has become more feasible, as they are now able to easily perform 3D measurements, produce arbitrary cross sections and conduct tele-visits in augmented reality animations.

In addition it is possible to enhance 3D reconstructions with as much information as needed, for the benefit of the final output. This, in conjunction with the new uses of conventional digital data and products, has had a beneficial impact on monument documentation, and has made 3D measurements possible and 3D reconstructions feasible.

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