



CIPA's Perspectives on Cultural Heritage

Andreas Georgopoulos^(✉)

Laboratory of Photogrammetry, NTUA, Athens, Greece
drag@central.ntua.gr

Abstract. Taking care of mankind's cultural heritage is a well-established obligation to us and to our future generations. To that end numerous experts are contributing. Contemporary technological advances, i.e. digital achievements, have helped a lot to this end. In this paper these technological advances are briefly presented and explained. It is attempted to show how these advances may help Cultural heritage if applied correctly and wisely. The argument is not how they will replace traditional documentation or conservation methods, but how they will support, enhance and supplement them for achieving the desired result with sensitivity and knowledge. The available digital documentation techniques are described along with the contemporary non-destructive techniques for cultural heritage pathology diagnosis and conservation. Their advantages are investigated along with their implementation actions. These techniques include image based methodologies for producing three dimensional models of which traditional two-dimensional products may be extracted, laser scanning techniques to acquire directly three-dimensional information from the object, Nondestructive techniques in order to diagnose pathology problems etc. In order to highlight these techniques, several examples are presented. The alternative uses of the contemporary digital techniques are highlighted through these examples. Among others the following applications will be presented: The virtual restoration of a collapsed stone bridge, the virtual restoration of a monument exposed to the weather conditions and the development of a virtual museum are presented. Finally, a future outlook is attempted, in order to envisage the path that the implementation of these technological advances will lead the worldwide effort to document and preserve our cultural heritage.

Keywords: Cultural heritage · Geometric documentation · Digitization

1 Introduction

Cultural Heritage, tangible or intangible is recognized by all civilized countries of the world as the most important carrier of historic memory for mankind. However, it is not respected and protected as it should be in all cases. Hence, Cultural heritage is in great danger as it may be destroyed, lost, altered, forgotten for a number of reasons. The main sources of danger are natural hazards, violent actions, such as wars, terrorism etc., looting, illicit trafficking, vandalism, modern construction activities, globalization, modern way of life and indifference, urban population growth and many more. In Fig. 1 some examples of such destructions are depicted.



Fig. 1. Destruction of Cultural Heritage (Natural Hazards, looting and violent actions) (Image copyrights: <http://www.topontiki.gr> (top left), Author (top right), UNITAR-CNES (bottom left), <http://www.independent.co.uk> (bottom right))

The ideal way to protect Cultural Heritage is to constantly take care of it through certain protective actions. Such actions, as dictated by the numerous International Conventions adopted by UNESCO, ICOMOS (International Council of Monuments and Sites) and other bodies are:

- **Documentation** (Geometric, Architectural, Historic etc.), involving 2D and/or 3D for archiving, for studies, for planning protective interventions etc.
- **Accurate measurements**, suitable for restoration actions, reconstructions, structural studies, protection etc.
- **Monitoring** of its state, involving recording deformations, state of materials, assessing pathology etc.
- Proper **Management** of its data for sustainability, risk management etc.
- **Preservation** possibilities specially suited for fragile objects (e.g. libraries etc.)
- **Public Outreach**, which involves visualization, dissemination, raising awareness of the public and many more

Consequently, their thorough study, preservation and protection is an obligation of our era to mankind's past and future. Respect towards cultural heritage has its roots already in the era of the Renaissance. During the 19th century archaeological excavations became common practice, while they matured in the 20th century. 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 Chart of Venice (1964) and the

Granada Agreement (1985) are some of these resolutions in which the need for the full documentation of the monuments is also stressed, as part of their protection, study and conservation. Nowadays, all countries of the civilized world are using all their scientific and technological efforts towards protecting and conserving the monuments within or even outside their borders assisting other countries. These general tasks include geometric recording, risk assessment, monitoring, restoring, reconstructing and managing Cultural Heritage. Indeed, it was in the Venice Charter (1964) that the necessity of the Geometric Documentation of Cultural Heritage was firstly set as a prerequisite. In Article 16 it is stated “... *In all works of preservation, restoration or excavation, there should always be precise documentation in the form of analytical and critical reports, illustrated with drawings and photographs...*”.

1.1 Interdisciplinary Cooperation

The geometric documentation has been the responsibility of experts concerned with the care of the Cultural Heritage. Traditionally these mainly belonged to the field of archaeology and architecture. However, over the past thirty or forty years more and different specialists developed an interest for the monuments, as they were definitely able to contribute to their study, maintenance and care. Among them are surveyors, photogrammetrists and geomatics engineers in general, as the technological advances have enabled them to produce interesting, alternative and accurate geometric documentation products. Until the end of the 19th century, architectural heritage had been a matter of national concern only and most of the laws regarding the protection of historic buildings, in Europe at least, date back to that period. Countless associations existed in each country, but their scope never went beyond national borders. Cultural internationalism, as we know it today, was an outcome of the First World War, with the creation of the League of Nations, and most of all of the Second World War, with the creation of the United Nations Organisation and the establishment of the UNESCO. The Athens Conference (1931) on restoration of historic buildings was organised by the International Museums Office, and the Athens Charter, drafted by Le Corbusier at the fourth Assembly of the International congresses on Modern Architecture (1933) was published anonymously in Paris in 1941 both represent a major step in the evolution of ideas because they reflect a growing consciousness among specialists all over the world, introducing for the first time in history the concept of international heritage.

Today the mentality is gradually changing and traditionally involved experts, like Archaeologists and architects, tend to accept and recognize the contribution of other disciplines to the agenda of Cultural Heritage. Hence it is rapidly becoming an interdisciplinary and intercultural issue (Fig. 2).

UNESCO (1946) and the Council of Europe have formed specialized organizations for taking care of mankind's cultural heritage. ICOMOS (International Council for Monuments and Sites) is the most important one, but also CIPA-Heritage Documentation (International Committee for Architectural Photogrammetry, initially: Comité International de Photogrammétrie Architecturale), ISPRS (International Society for Photogrammetry & Remote Sensing), ICOM (International Council for Museums),

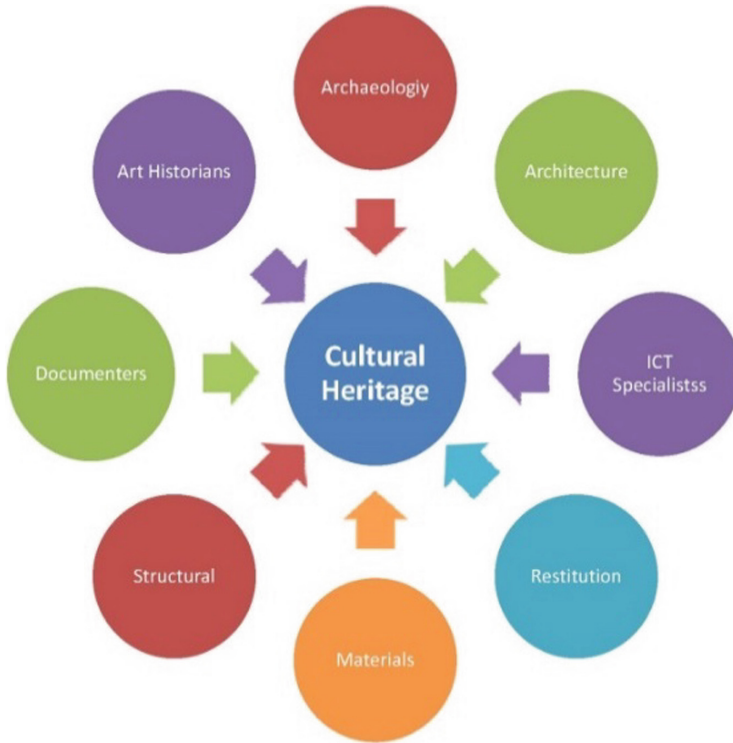


Fig. 2. The interdisciplinary contribution to Cultural Heritage (© Author)

ICCROM (International Centre for the Conservation and Restoration of Monuments) and UIA (International Union of Architects) are all involved in this task (Fig. 3). The Venice Charter was born from the need to create an association of specialists of conservation and restoration independent of the already existing associations of museologists, ICOM. In 1957, in Paris, the First Congress of Architects and Specialists of Historic Buildings recommended that the countries which still lack a central organization for the protection of historic buildings provide for the establishment of such an authority and, in the name of UNESCO, that all member states of UNESCO join the International Centre for the Study of the Preservation and Restoration of Cultural Property (ICCROM) based in Rome.

ICCROM is an intergovernmental organization dedicated to the conservation of cultural heritage. Its members are individual states which have declared their adhesion to it. It exists to serve the international community as represented by its Member States, which currently number 133. It is the only institution of its kind with a worldwide mandate to promote the conservation of all types of cultural heritage, both movable and immovable. The decision to establish the International Centre for the Study of the Preservation and Restoration of Cultural Property was made at the 9th UNESCO

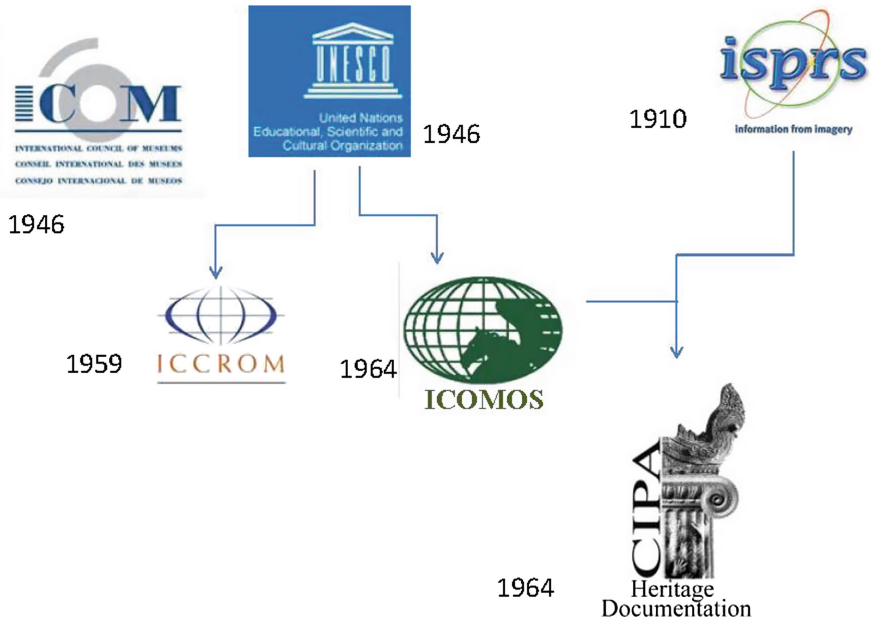


Fig. 3. International organizations involved in Cultural Heritage (© Author)

General Conference in New Delhi in 1956, at a time of mounting interest in the protection and preservation of cultural heritage. It was subsequently established in Rome in 1959 at the invitation of the Government of Italy. ICCROM aims at improving the quality of conservation practice as well as raising awareness about the importance of preserving cultural heritage. The Second Congress of Architects and Specialists of Historic Buildings, in Venice in 1964, adopted 13 resolutions, the first one being the International Restoration Charter, better known as Venice Charter, and the second one, put forward by UNESCO, provided for the creation of the International Council on Monuments and Sites (ICOMOS).

1.2 CIPA Heritage Documentation

CIPA Heritage Documentation was founded in 1964 as an International Scientific Committee (ISC) of ICOMOS and ISPRS (International Society for Photogrammetry and Remote Sensing) and hence is a dynamic international organization that has twin responsibilities: keeping up with technology and ensuring its usefulness for cultural heritage conservation, education and dissemination. These two sometimes conflicting goals are accomplished in a variety of ways, through (cipa.icomos.org):

- Encouraging and promoting the development of principles and good practices for recording, documentation and information management of cultural heritage;

- Leading and participating in international training programs for conservation and informatics professionals, students and site personnel;
- Advising government bodies, regional authorities, non-profit groups and institutions on tools, technology and methods for using technology;
- Sponsoring an international network of professionals in both the fields of technology and cultural heritage for scientific research but also applied practical experience;
- Providing a platform with the bi-annual International Conference for the exchange of ideas, best practices as well as scientific research papers.

In the recent past CIPA undertook the RECORDIM initiative, recognizing that there are critical gaps in the fields of heritage Recording, Documentation and Information Management between those who provide information for conservation and those who use it, i.e. providers and users of contemporary documentation information. In response, the International Council on Monuments and Sites (ICOMOS), the Getty Conservation Institute (GCI) and CIPA together created the RecorDIM (for Heritage Recording, Documentation and Information Management) Initiative partnership. The purpose of the initiative (started in 2002 and closed on 2007) was to bring information users and providers together to identify the nature of the gaps between them, to develop strategies to close the gaps and to recommend a framework for action. 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 CIPA's RecorDIM (<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. This interdisciplinary approach to the issue of Cultural heritage has opened vast new possibilities and led to new alternative products for the benefit of monuments. These new possibilities include, among others, the production of 3D models, virtual reconstructions, virtual restorations, monitoring of constructions and the applications of serious games for educational and dissemination purposes.

Digital surveying and geometric documentation of cultural heritage requires the cooperation of several disciplines and expertise in order to produce results that sufficiently satisfy the high demanding environment of conservation, restoration, research and dissemination. It should not escape our attention that resources are frequently inadequate while the infrastructure used (equipment, hardware and software) is expected achieve the maximum possible benefit.

2 Digitization of Cultural Heritage

Nowadays, the rapid advances of Digital Technology (DT) also referred to as Information Communication Technologies (ICT), have provided scientists with new powerful tools. We are now able to acquire, store, process, manage and present any kind of information in digital form. This may be done faster, more completely and it may ensure that this information may be easily available for a larger base of interested individuals. Those digital tools include instrumentation for data acquisition, such as scanners, digital cameras, digital total stations etc., software for processing and managing the collected data and -of course- computer hardware, for running the software, storing the data and presenting them in various forms.

The introduction of digital technologies has already altered the way we perceive fundamental notions like *indigenous*, *artifact*, *heritage*, *3D space*, *ecology* etc. At the same time, they tend to transform the traditional work of archaeologists and museums as they are so far known. In other words, DT redefines the relationship to CH, as they enable universal access to it and they also connect cultural institutions to new “audiences”. Finally, they appeal to new generations, as the latter are, by default, computer literate. In this way we experience a “democratization” of cultural information across geographic, religious, cultural and scientific borders. Cultural Heritage is nowadays, an international, interdisciplinary and intercultural responsibility.

The introduction of Digital Technologies may contribute to all traditional steps of Archaeological practice. It goes without saying that the degree of contribution of Information and Communication Technologies (ICT) is different in the various stages and in the various cases. Modern technologies of remote sensing and archaeological prospection assist the touch less and rapid detection of objects of interest. Spectroradiometers or ground penetrating radars or even the simple processing of multispectral satellite images may easily lead to the rapid location of underground or submerged objects of interest. Contemporary non-contact survey technologies, such as photogrammetry, terrestrial laser scanning and digital imaging, may be used to produce accurate base maps for further study, or 3D virtual renderings and visualizations. The collected data may be stored in interactive databases, georeferenced or not, and be managed according to the needs of the experts. Finally, ICT may assist in the presentation stage, by producing virtual models, which may be displayed in museums or be included in an educational gamification, or serve purposes of enabling handicapped persons to admire the treasures of the World's cultural heritage.

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* [32] 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 artifacts or even intangible articles of the world's legacy.

The impact of digital technologies to the domain of Cultural Heritage has increased 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. 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, games, museums, medicine etc.). All in all, the digitization of the world's Cultural Heritage whether it is tangible or intangible is now possible.

3 ICT at the Service of Cultural Heritage

The integrated documentation of monuments includes the acquisition of all possible data concerning the monument and which may contribute to its safeguarding in the future. Such data may include historic, archaeological, architectural information, but also administrative data, past drawings, sketches, photos etc. Moreover, these data also include metric information which defines the size, the form and the location of the monument in 3D space and which document the monument geometrically. The geometric documentation of a monument, which should be considered as an integral part of the greater action, the integrated documentation of Cultural Heritage may be defined as [31]:

- 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 records the present of the monuments, as this has been shaped in the course of time and is the necessary background for the studies of their past, as well as the care of their future.

The geometric documentation of monuments actually is the orthogonal projection of a carefully selected set of points on -usually- horizontal or vertical planes (Fig. 4), in order to record all geometric properties of the monument in the best possible way. The action of selecting those points implies deep knowledge of the monument and its structure, as well as mastering of the traditional and contemporary techniques for determining the position of these points in 3D space. This implies that all determined points lie in a common reference system in 3D space, which is a great advantage for further studies. In this process notions as scale of the final documentation product and accuracy of positioning the points are of utmost importance and are directly related to the data collection method.

For the geometric recording, several recording methods may be applied, ranging from the conventional simple topometric methods, for partially or totally uncontrolled surveys, to the 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 may allow it, 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.

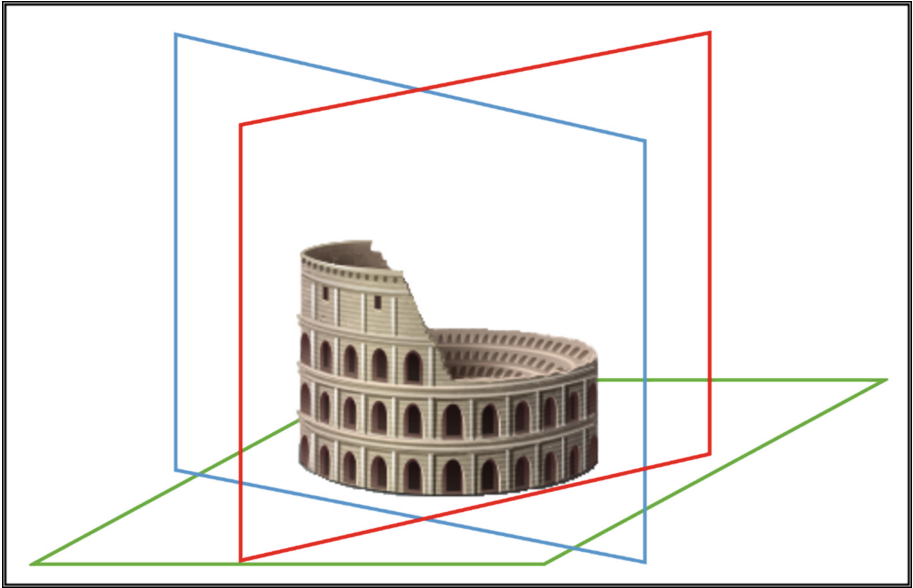


Fig. 4. Vertical and horizontal planes of geometric documentation (© author)

They indirectly 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 may surely meet any requirements with the least possible total cost and the biggest total profit. To this measurement group belong complicated surveying methods with total stations, 3D image based photogrammetric surveys and terrestrial laser scanners (TLS). All these methods manage to collect a huge number of points in 3D space, usually called point cloud, in a very limited time frame [28].

All these techniques can be categorized in different ways. The experience shows that the most efficient method is to characterize them by the scale at which they can be used as well as by the number of measurements they can be used during data acquisition. Practically, this means that they are related to the object size as well as to the complexity of the object. Boehler and Heinz proposed and developed a system to summarize all existing techniques in terms of scale and object complexity. This is adapted to include modern technologies and is shown in Fig. 5 [4].

According to this figure, the metric surveying techniques are organized considering the scale of the outcome which is a function of the object size and the representation based on the required details. The complexity of the survey can be conveyed by the number of recorded points. In practice, this ranges from one single point describing the geographic location of a single cultural heritage object, to some thousands of points

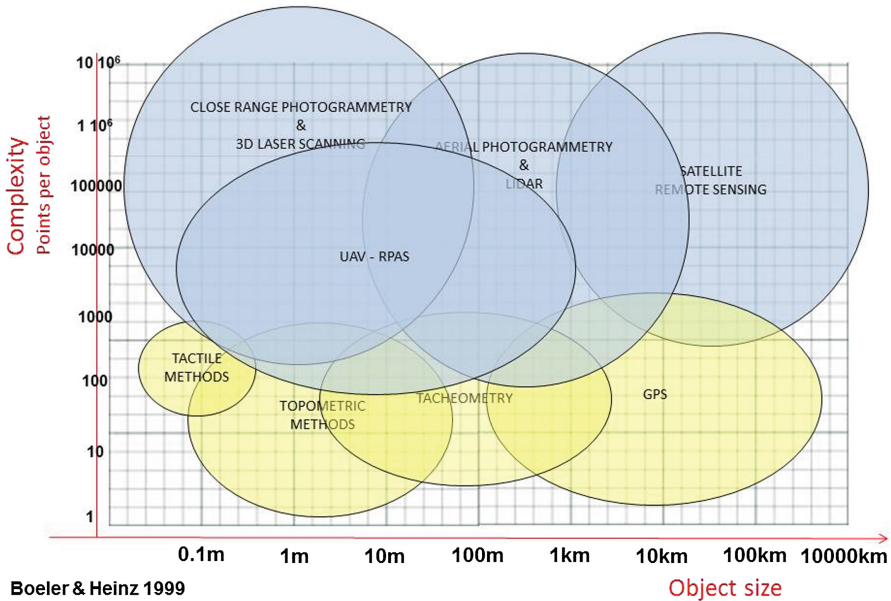


Fig. 5. Three-dimensional survey techniques characterized by scale and object size and complexity (adapted from [4]) (Color figure online)

(e.g. a single CAD drawing of a simple monument) or to a few millions of points (e.g. a point cloud) for the detailed representation of a cultural heritage site. In Fig. 5 the methods depicted in blue use images, while the yellow ones do not.

Recording techniques are based on devices and sensors which perform the necessary measurements either directly on the object, or indirectly by recording energy reflected from the object. In the latter category one may broadly distinguish between active and passive sensors. Active sensors send their own radiation to the object and record the reflectance, while passive ones rely on the radiation sent to the object from some other source. Usually, the latter are image-based sensors, which record the visible light reflected from the objects of interest.

Terrestrial image-based survey comprises all those methods, techniques and technologies that are using images in order to extract metric and thematic information from the object imaged. Within this section the most important image-based digital technologies supporting the digital surveying and documentation of cultural heritage will be discussed and presented. The main concern will be given to digital cameras and sensors, especially the new entries, the contribution of the Unmanned Air Vehicle (UAV) or Remotely Piloted Aircraft Systems (RPAS) or Unmanned Aerial Systems (UAS), but also the useful role that Image Assisted Total Station (IATS) technologies are playing in the recording, monitoring and documentation of cultural heritage.

Nowadays, contemporary technologies have integrated traditional and modern measuring and data acquisition techniques with advanced management and georeference software. This software is also known as Geographic Information Systems and enables the storing, managing and correlation of information collected, always referring it to its geographic location. This combination has led to what today is known as Geoinformatics or Geomatics (Fig. 6).

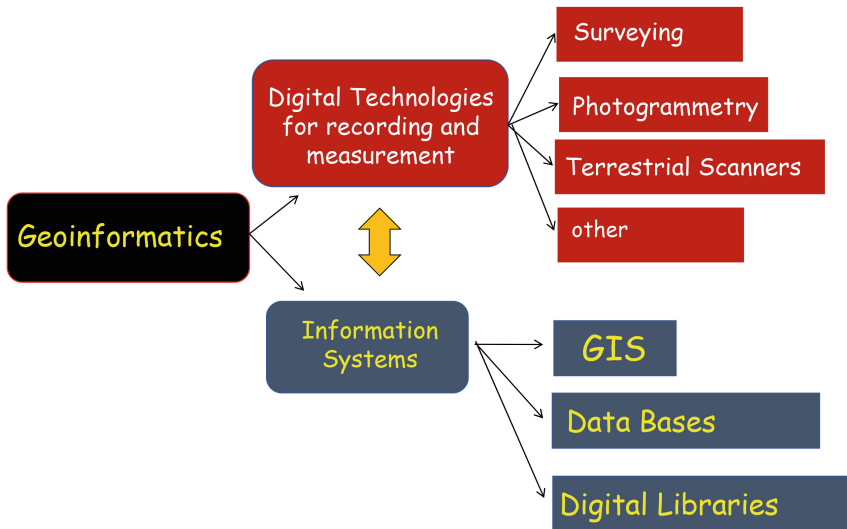


Fig. 6. Geoinformatics as a link between data acquisition and cultural heritage management (© author)

4 Selected Examples

In order to illustrate the above, some representative examples of Cultural Heritage Digitization will be presented. They include (1) the successful attempt to digitize a collapsed traditional stone bridge for assisting the restoration study, (2) the complete geometric documentation of a prominent Athens monument based entirely on image based techniques and (3) the implementation of an HBIM (Historic Building Information Modelling) system for cultural Heritage.

4.1 The Restoration of a Collapsed Bridge¹

A variety of arched stone bridges exist in the Balkan area, built mainly in the 18th and 19th centuries or even earlier. Just in the Epirus region in north western Greece there are more than 250 magnificent examples of such historic structures spanning over the

¹ Adapted from [27].

rivers and streams and bridging them with one to four arches. Such structures were built for pedestrian and animal passage, as the rivers did not allow easy crossing, especially during winter [18].

The stone bridge of Plaka over river Arachthos (Fig. 7) was a representative example of the aforementioned monuments. It was built in 1866 by local Greek stonemasons in order to facilitate transportation and trade needs (<http://www.petrinagefiria.uoi.gr/>). It was the widest stone bridge in the area of Epirus with 40 m span and the biggest single-arch bridge in the Balkans with a height of 20 m (Fig. 7). Next to the main arch, there were two smaller ones 6 meters wide, the so-called relief arches.



Fig. 7. The Plaka stone bridge Image copyrights: Google Earth (above) and ntua.gr (below)

Apart from its significant size and age, the stone bridge of Plaka was a renowned stone bridge in Greece because of its emblematic historic meaning. Firstly, it was the border between free Greece and the occupied part of Greece by the Ottoman Empire between 1881 and 1912. During World War II the bridge was bombed by the German

army with partial damages. At the same period, representatives of the various armed groups of Greek Resistance signed the Treaty of Plaka on this very bridge. Unfortunately, in February 2015 the emblematic stone bridge collapsed after severe flooding and fierce water volumes coming from the mountains (Fig. 8).

Before the implementation of any actions, a thorough geometric documentation is necessary, as clearly dictated by the Venice Charter (1964). For that purpose, the Laboratory of Photogrammetry undertook two tasks (a) to produce digital three-dimensional drawings from a documentation study conducted in 1984 using traditional surveying techniques [14] and (b) to produce a textured three dimensional model of the Plaka Stone Bridge in order to geometrically document its shape and size before the collapse. This 3D model would be produced from existing images taken by visitors of the bridge over the years. These documentation products will form the basis for any eventual reconstruction study.



Fig. 8. The remains of the bridge after destruction (http://epirusgate.blogspot.gr/2015/02/blog-post_32.html)

Common image-based 3D modelling of the current state of a monument requires data acquisition in the field. Surveying, photogrammetry and laser scanning techniques can be combined to produce a full and accurate 3D model of the object. Such approaches cannot be applied in cases of sudden loss of cultural heritage objects due to a number of reasons such as fire, earthquakes, floods, looting, armed conflict, terrorism, attacks etc.

Modern photogrammetry and computer vision techniques manage to create useful and accurate 3D models of objects of almost any size and shape, by combining robust algorithms and powerful computers. Multiple images depicting the object from different viewpoints are needed and the so-called SfM and MVS procedures are implemented. These images do not necessarily need to have been captured by calibrated cameras, though. Compact or even mobile phone cameras can also be used. Moreover, capturing

geometry is nowadays flexible, in contrast with the traditional strict stereo-normal case of the past. A variety of recent studies are examining the creation of 3D models of cultural heritage objects and sites with the use of SfM algorithms [2, 15, 24, 25]. The lack of images or other surveying data in lost cultural heritage objects has led to the use of random, unordered images acquired from the web. However, few projects, many of them EU funded, make use of data available in the web for such a purpose. Some recent studies are dealing with the 4D (space-time) virtual reconstruction of Cultural Heritage objects using web-retrieved images [16, 20, 26]. An approach for diachronic virtual reconstruction of lost heritage based on historical information integrated with real metric data of the remains was proposed by Guidi and Russo [12].

For image-based virtual reconstruction many images from different points of view are required. As already implemented in similar cases in the past, the contribution of people that have visited the area for tourism or other reasons and have taken pictures was sought. Crowdsourcing has already been used for applications in the cultural heritage domain [23]. However, none of the similar actions produced a metric product like the present one.

The key aspects of a project like the present one, concerning crowdsourcing information can be summarized as follows:

- The project has a time limit.
- The contribution of the users is of one type of content, i.e. images or video sequences.
- Special information (metadata) about the viewpoint of the images, the equipment used or the time taken could be useful.

To provide a suitable framework for the above, a website has been developed using the Drupal CMS (Fig. 9). Drupal is a Content Management System (CMS) with proper functions for community websites and has been used for educational and research crowdsourcing purposes [13, 22]. More specifically, the website developed includes five sections: (a) a news and announcements page, (b) a general info page, (c) a submit content (images) page, (d) a submit page for volunteers and (e) a blog page. To collect the images, the “submit images” page is the only section utilized, since it also provides the required information to the contributors.

Within the first month of its operation the website has been visited around 2800 times. More than 470 images were uploaded to the platform during these sessions by more than 130 contributors. Apart from the uploaded content, approximately 200 images and 15 videos were collected through other means, mainly by ordinary mail delivery, by contacting the contributors.

The majority of the collected images were of high resolution, correctly focused and without significant perspective or optical distortions. However, we had to cope with some special challenges in order to exploit as much as possible the rest of the images, which had many different problems. In addition, the majority of the collected photos were taken facing upstream and mainly from the east riverside due to landscape inaccessibility. This causes gaps and difficulties for the algorithm to converge to a stable geometry. After a thorough and careful sorting, it was established that less than 60 images fulfil the needs of the project in terms of viewpoint, image resolution, lighting conditions, occlusions etc., which corresponds to 10% of the total contributions.

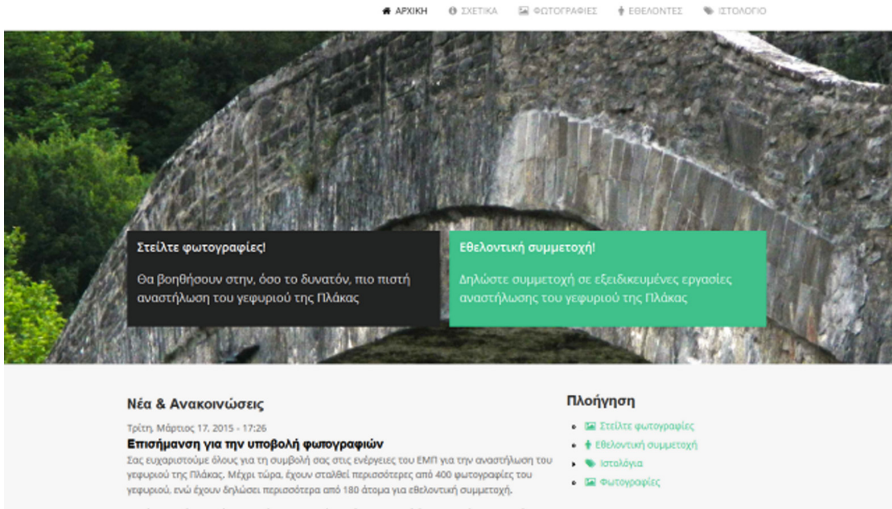
Να "βάλουμε πλάτη" να σηκώσουμε ξανά το Τεφύρι της Πλάκας!

Fig. 9. Home page of the crowdsourcing webpage (© author)

The selected data have been processed using commercial as well as free software. VisualSfM is a free GUI application for 3D reconstruction that implements SfM and PMVS along with other tools [6, 7, 33–35]. In this case study, a dense point cloud was produced by 51 images (Fig. 10).

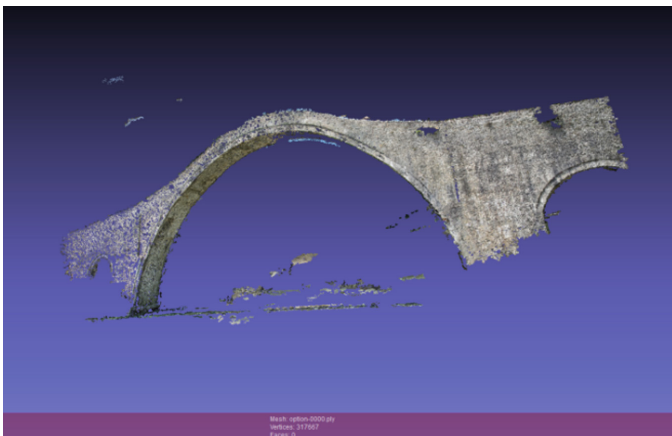


Fig. 10. Dense point cloud after PMVS software (VisualSfM) – 51 images (© author)



Fig. 11. Dense point cloud produced in Agisoft PhotoScan – 56 images (© author)



Fig. 12. A view of the textured mesh created in Agisoft PhotoScan (© author)

In order to improve the results, a masking procedure was applied on the images while processed in Agisoft PhotoScan. Therefore, background elements that are subjected to temporal changes and obstacles (people, trees, mountains etc.) have been excluded during photo alignment. This results to less noisy dense point clouds (Fig. 11). A mesh has also been created, followed by the texturing procedure (Fig. 12).

The experts working for the restoration proposal needed also the documentation of the current situation. Hence during a campaign some months ago, data was collected for the creation of the 3D models of the remaining pedestals. They were imaged with a high resolution DSLR and some Ground Control Points (GCP) were measured. Using again SfM/MVS software the three-dimensional models were produced (Fig. 13) and served as a detailed geometric basis for the restoration proposal.



Fig. 13. 3D models of the remaining parts of the bridge (© author)

It should be stressed that the wide promotion of the 3×3 Rules proposed by CIPA [32] and revised in 2013, available at the relevant webpage (www.cipa.icomos.org) would ensure the existence of more useful images and related metadata for the Plaka Stone Bridge, as the public would be more aware of the eventual future significance of their souvenir images. This may be useful in the future for other monuments in similar situations.

4.2 Geometric Documentation of the Holy Aedicule²

The Church of the Anastassis (Resurrection) or of the Holy Sepulchre, as it is mostly known to western visitors, lies majestically in the heart of the Old City of Jerusalem, and has a very long history spanning over seventeen centuries (Fig. 14). The first church in this site was erected by Saint Helen, the mother of Emperor Constantine the Great, when she discovered the Holy Cross at the beginning of the fourth century A.D. Since then, a lot of constructions, modifications, additions, renovations and alterations took place, the major one being that imposed by the crusaders in the 12th century A.D. when they conquered the Holy Land. The Church of the Holy Sepulchre in Jerusalem comprises within its walls, among others, the main large Greek Orthodox church, the Catholicon, the Holy Rock of Golgotha, the Tomb of Christ and the place where the Holy Cross was discovered. Adjacent to these main places of worship and pilgrimage are numerous little chapels, monk cells, store rooms, corridors and staircases, extending to approximately 8000 m^2 in plan area and to about 35 m of height difference. The main building complex has common borders with the Greek Orthodox Patriarchate, the Syrian Patriarchate, the Roman Catholic Monastery, the Ethiopian Monastery and a series of little souvenir stores.

² Adapted from [10].



Fig. 14. The Church of the Holy Sepulchre (© author)



Fig. 15. The south façade of the Holy Aedicule in 2015 (© author)

Today the Church complex is a living monument and it is visited every year by thousands of pilgrims. All different Christian Communities are represented and active within its walls. Greek Orthodox, Roman Catholic Franciscan, Armenian and Coptic priests and monks and others are coexisting in harmony worshipping the same God.

The monument is divided into sections each one “belonging” to a Community. There are, of course, sections of it common to everybody. All Christian Communities respect this unique state of ownerships while it is hardly sensed by the visitors. It constitutes the Status Quo of the Church of the Holy Sepulchre, which has its origins in historical tradition.

The Tomb of Christ is in the Church of the Holy Sepulchre in Jerusalem. The original Holy Rock is covered by the Holy Aedicule, a majestic little structure situated within the large complex of the Church of the Holy Sepulchre in the centre of the Rotunda, a 25 m tall cylindrical building. The Holy Aedicule is the latest in a series of constructions and additions to the initial Crusader Aedicule which had occupied the same site for centuries [3]. Responsible for the design and reconstruction of this latter one was the architect Komnenos in the early 19th century. The present form of the Holy Aedicule, which exists without significant alterations since 1810, is a result of repair and restoration of the earlier building after the catastrophic fire of 1808. It has approximately a length of 8.3 m, a width of 5.5 m, and a height of 6.7 m plus a dome of 6.0 m on its roof.

In 1927, this construction was badly damaged by an earthquake which also weakened the dome over the Rotunda and other parts of the complex. Marble slabs cover the outside surface of the Aedicule, while it is also surrounded by a metallic construction (Fig. 15) erected by the British in 1947 which provides support and stops the collapse of the Holy Aedicule. Timber wedges were inserted between the steel girders and the load-bearing stone walls of the Holy Aedicule. It appears that this steel girdle is no longer functional, as lately deformations were observed especially as far as the Komnenos' marble slabs are concerned. The inside the Holy Aedicule is a complex structure with two very confined, highly ornamented rooms.

However, the state of preservation of the Holy Aedicule continued to deteriorate due to the water and humidity transfer phenomena within, around and below the Aedicule structure, due to incompatible past interventions and due to the successive earthquake activity, to the extent that proper conservation, reinforcement and repair interventions were needed to rehabilitate the Holy Aedicule. The first task of the interdisciplinary team of NTUA was to perform the geometric documentation of the Holy Aedicule, as foreseen in the Venice Charter (article 16). This documentation was, of course, part of a wider range of technical studies of the interdisciplinary team of NTUA engineering experts.

In the past, several efforts for the geometric documentation of the Church of the Holy Sepulchre and the Holy Aedicule in it took place. Already since the 60's the Franciscan monk Corbo, documented, mainly as an archaeologist, a large part of the Church using of course the then available technological means [5]. Later [3] a team of British experts documented in high detail the Holy Aedicule. In the years 1993–1999, the Laboratories of General Geodesy and of Photogrammetry of NTUA undertook and executed (Fig. 16) the complete geometric documentation at a scale of 1:50 of the Church of the Holy Sepulchre for the Greek Orthodox Patriarchate [1, 8, 17]. Finally, in the years 2007–2009 a team of Italian experts embarked on terrestrial laser scanning for the complete 3D documentation of the Church [30].

For the current geometric documentation of the Holy Aedicule before the restoration works, several campaigns were necessary. The first one took place in May 2015 [21] and the second one in January 2016. Data acquisition included geodetic measurements, digital image acquisition and terrestrial laser scanning around and inside the Holy Aedicule.



Fig. 16. Sample of the geometric documentation 1993–1999 (© author)

This present geometric documentation aims at the production of the necessary base material on which the structural and material prospection studies will be based. For the needs of this documentation it was decided to produce a high resolution three-dimensional model and to perform specialized high accurate geodetic measurements for the production of conventional 2D base material on one hand and for the documentation of the deformations and deviations of the construction today on the other. Due to the peculiarities of the object of interest, the crowds of pilgrims always present inside and around the Aedicule, most of the works for the data acquisition took place after the closure of the Church. The methodology implemented for the production of the above described products applied the most contemporary geomatics techniques and specialized instrumentation. Briefly, an automated 3D imaging methodology based on high resolution digital images, terrestrial laser scanning and high accuracy geodetic measurements were implemented. These data were georeferenced to an already existing local plane projection reference system from previous work of NTUA [1].

Specifically, the geometric documentation produced an accurate three-dimensional (3D) model with the use of photogrammetric and geodetic methods, both for the interior and the exterior of the Holy Aedicule through images and scanned data collection for the reconstruction of the model in actual scale. This was realized via data processing (sorting of images, orientation, export 3D cloud points, dense point cloud processing, creation of surfaces and grouping them), for reconstructing 3D scenes of increased reliability and high accuracy. From this 3D model, the production of sections at specific positions was also possible, supported by suitable geodetic measurements.

For the image based approach, digital image sequences from varying distances were collected using a calibrated professional Canon EOS-1Ds Mark III full frame CMOS digital camera with 21MP resolution (5616×3744 pixels) and $6.4 \mu\text{m}$ pixel size, aiming to reconstruct the 3D scene of the Holy Aedicule through structure from motion (SfM) and Dense Image Matching (DIM) techniques. These techniques are the state of the art in reconstructing 3D scenes and offer high reliability and high accuracy as a cost and time effective alternative to the use of scanners. For this purpose, different lenses with a varying focal length (16 mm, 50 mm, 135 mm and 300 mm) were used. The image acquisition took place under low natural lighting conditions and during the night, exploiting the existing artificial lighting. No additional light sources were used (flash, studio flash, etc.). Therefore, the use of a photographic tripod was necessary since in some cases, the exposure time was up to 30 s. 3.757 images in total were captured requiring up to 59.3 GB of hard drive space. Image acquisition was carefully planned so that all details of the object were imaged on at least three consecutive images. Control points were not measured, but were extracted from the drawings of previous documentation effort [1] However, a selection process was applied in order to ensure a highly accurate result according to the requirements of the study and the significance of the object. Finally, distances were accurately measured on the Holy Aedicule in order to scale the final 3D model. Problems in the acquisition processes such as lighting conditions and camera-to-object relative positioning as well as difficulties in the alignment step and mesh optimization are also encountered without reducing the accuracy of the final results. These problems included, among others, the large distances between the object and the camera, the poor or inadequate lighting, the continuous population of the area by pilgrims, the smoke from the candles, which create faded areas on the images or unpredictable optical deformations due to the refraction effect caused by the temperature difference of the air.

In addition, laser scanning was also employed, in order to cover the areas where image acquisition was impossible, like e.g. the dark and smoked interiors of the two domes of the Holy Aedicule and the two staircases leading to the construction's roof. The two techniques act complementarily to each other. For this procedure, the terrestrial laser scanner FARO 3D X 330 was chosen as it is a lightweight third generation scanner, which uses the phase shift method for measuring the distance. It has the ability of collecting one million points per second with an accuracy of 2–3 mm in its space position. It can record points 360° around the vertical axis and 300° around the horizontal axis. For the complete coverage of the Holy Aedicule special scanning strategy was designed, in order to avoid gaps in the point clouds on one hand and to record all necessary details on the other. For that purpose, it was necessary to acquire overlapping scans from different scan positions. In total 58 scans were needed, of which 13 around the Holy Aedicule, 8 on top of its roof, 8 in the two staircases, 10 from the Rotunda Gallery and 19 in the inside. The total number of points collected was 65 million for the outside and 42 million for the inside. The density of the scans was selected to 1 point every 5 mm, in order to record all fine details, even those necessary at a later stage. The time required for each scan varied depending on the distance of the scanner to the object, a fact which differentiates the total number of points necessary. In any case the time for each scan was not more than a few minutes.

The creation of the final accurate three-dimensional model from the digital images is a complicated procedure requiring large computation cost and human effort. It includes the already mentioned collection of geometric data in limited space and time, the selection of the images, the 3D point cloud extraction, the creation of the surface, the noise filtering and the merging of individual surfaces. It is important to note that in such cases, the detail of the surface is very important, thus the noise filtering must be a carefully implemented procedure. The initial data were processed using various software packages in order to produce the final accurate 3D model of the Holy Aedicule. In the diagram of Fig. 17 the flowchart designed and adopted for the initial data processing procedure (images and measurements) is presented. After the careful selection of the necessary images and the creation of thematic folders, the radiometric correction of the imagery took place aiming at their quality improvement by minimizing the effects of the shadows and dark areas. Then, the images are imported into the software that implements SfM and DIM techniques. Subsequently, the dense point cloud is exported and imported to another software package in order to be subjected to a time-consuming process for removing outliers.

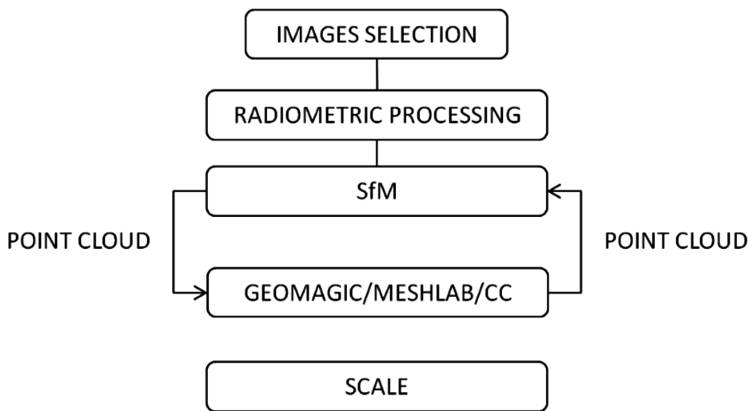


Fig. 17. Data processing workflow

Finally, the processed point clouds are merged and exported again in order to be scaled. The SfM technique for the orientation of the images and the 3D point cloud extraction procedure were realized through the use of Agisoft's PhotoScan® software, which has been extensively evaluated for increased accuracy in prior research internationally but also of the Laboratory of Photogrammetry. For the full coverage of the Holy Aedicule and the creation of a complete 3D model, images were captured from many different locations. It is important to note that for every part of the 3D model, the sparse point clouds consist of 10.000 to 60.000 points. After an inspection of the alignment results, the generation of the dense point cloud model took place. At this stage, the Agisoft PhotoScan® algorithms, based on the estimated camera positions calculate depth information for each camera to be combined into a single dense point cloud. It is noted that the dense point cloud of each part of the 3D model of the Holy

Aedicule consists of about 35.000.000 points and the entire model of about 280.000.000 points (Fig. 18). At this stage, colour is attributed to each point based on the images where it appears. In the outside coloured point cloud of the Holy Aedicule is presented.



Fig. 18. The coloured point cloud of the Holy Aedicule (© author). (Color figure online)



Fig. 19. The 3D model of the dome textured (left) and non-textured (right) (© author)

The processing of the Holy Aedicule point cloud was realized within the Geomagic Studio®, Meshlab® and Cloud Compare® software. Also, to sort out the outliers, several filtering algorithms are applied using the above mentioned software packages. In addition, algorithms were applied in order to make the point cloud uniform in terms of point spacing and reduce its density. Finally, the processed dense point clouds are wrapped into meshes. Figure 19 presents the part of the 3D model of the dome, which is one of the more complex parts of the Holy Aedicule. Through the created 3D model, it is possible to identify vulnerable and destroyed areas of the Holy Aedicule with not physical access on them.

The laser scanner data were thoroughly examined for their completeness in situ, i.e. before the departure of the team from Jerusalem. For that purpose, test registrations of the point clouds were performed in order to establish this possibility on one hand and their completeness on the other. After these tests, additional scans were required sometimes from very unconventional scan positions. The final point cloud registration was performed in the Laboratory of Photogrammetry of NTUA. As the volume of data was huge it was decided to perform the registration separately for the inside and outside parts of the Holy Aedicule. For the point cloud registration, at least three points are required. This role was undertaken by the special targets, whose coordinates in the common reference system were carefully determined, as ICP (Iterative Closest Point) algorithm does not provide reliable results in such cases. Hence after registration the point clouds were also referenced to the common system. The accuracy achieved for the registrations was of the order of 2–3 mm. In Fig. 20 a sample of the registered point clouds is shown.

For registering and georeferencing the three-dimensional models of the Holy Aedicule which were produced with the methods described to the common reference system, specially targeted points were put in suitable positions on inside and outside of the Holy Aedicule but also in the surrounding area. In total 38 control points were used.



Fig. 20. Part of the registered point clouds inside the Holy Aedicule (© author)

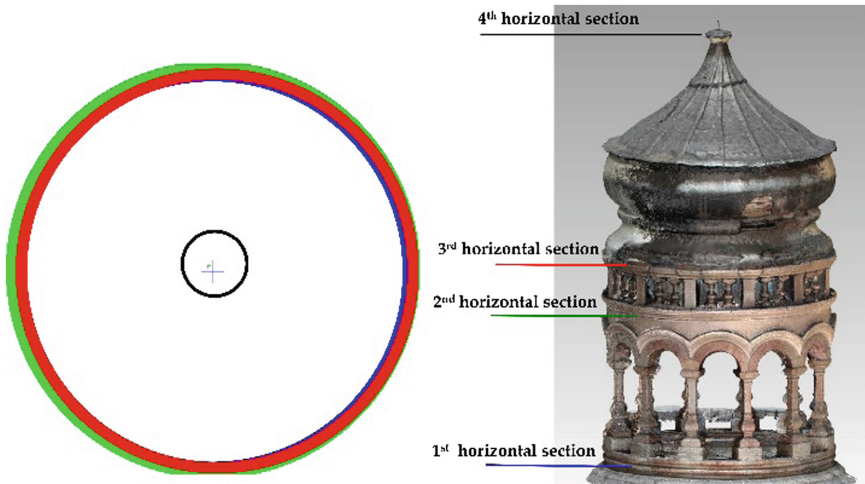


Fig. 21. The horizontal sections of the upper dome of the Holy Aedicule (© author)

Accurate geodetic measurements were performed in order to assess the verticality of structural elements, like the iron girder set up by the British in 1947 and some of the pillars of the monument. For that purpose, a local 3D network was established at the site around of the Holy Aedicule in order to support the creation of the 3D model of the Holy Aedicule and to determine probable deformations and displacements of the monument. The above mentioned geodetic network connected with the old geodetic network which had been established the period 1993–1999, in the framework of the Geometric and Architectural Documentation of the Church of the Holy Sepulchre in Jerusalem [1].

For checking the eventual deviations and deformations of the structural elements several measurements were performed. A longitudinal section of the upper dome of the structure, four horizontal sections of the same dome at 6.0 m, 8.0 m, 8.8 m and 12.0 m from the floor, two horizontal sections of the pillars and the marble supports of the Aedicule at 0.7 m and 4.4 m from the floor. In addition, special accurate measurements were conducted in order to establish the deviation from the vertical of the steel pillars of the cage built by the British.

Moreover, the change of the position of each the five basic columns at the north façade and the counterpart columns at the south façade of the Holy Aedicule, was determined from the corresponding position that the British as registered in 1947. These measurements led to the important conclusion that the upper dome of the structure does not present any significant deformations, as all sections were concentric circles within 7 mm (Fig. 21). This was also established by examining the longitudinal section of dome. The horizontal sections of the pillars revealed deviations between 40 and 90 mm. These results were also verified from the 3D model produced.

4.3 Developing Virtual Museums

Developing and displaying a museum in a virtual environment has some advantages especially concerning the preservation and promotion of cultural heritage but also the development of tourism and the promotion of the touristic product. Virtual museums are important to both the visitors and the museums themselves and their curators. The majority of the museums only exhibit a small part of their collection due to the lack of space and of course due to the fact that some objects are extremely valuable or fragile [19]. In a virtual and interactive environment the visitor is able to interact with the digitised exhibits and learn all the essential, historical information about them. Moreover, in a virtual environment the visitor can view a virtual reconstruction of important objects, buildings and archaeological sites that may no longer exist are damaged or access to them is not permitted. Moreover collections may also be displayed made of objects that are spread in various museums around the world.

The digitisation of cultural heritage helps to preserve, store, renew, retrieve and make it accessible for a wider audience in a more appealing and contemporary way, especially to people with special abilities or people that may never have the chance to visit the real museum [29]. The wide use of internet, social media and websites can make the digitised content of a museum more accessible and transport it to everyone all around the world. It is important to mention the result of the Colorado's University research according to which 70% of a total of 223 million people who visit a museum website would subsequently be more likely to go and also visit the real museum [11]. This means that the virtual museum functions in a complementary manner to the real museum. Finally, in virtual museum exhibitions the visitor is able to fully control the navigation as well as to freely explore, move around, manipulate the exhibits and create his/her own, unique virtual experience or collection of 3D digital exhibits even from different museums. It is obvious that every effort and innovation that concerns the digitisation of cultural heritage and the development of virtual museums and applications is a complicated, difficult, controversial task with many advantages and can only benefit and offer both the museums and the visitors. Especially in Greece, 65% of the tourists make an online search of their destination and 45% of them are interested in cultural heritage, monuments, museums and archaeological sites.

The Virtual Museum of the Stoa of Attalos is an application where the visitor is able to make a tour in the museum on his own, explore it, interact with the exhibits, rotate them and learn all the necessary information about them. The development of this application took into consideration various aspects such as the requirements' analysis, the architectural design, the planning of the exhibits' presentation, the user interaction, the programming process and the evaluation of the final product [19].

As far as the Virtual Museum of the Stoa of Attalos is concerned, the virtual environment hosts some of the exhibits which can be found on the ground floor of the Stoa of Attalos, in the Ancient Agora of Athens. For this project, 16 of the exhibits were chosen from the south part of the colonnade of the museum and the most important concern was to produce accurate, realistic and appealing 3D models that can be used in virtual applications, especially in a short period of time. That is why photogrammetric methods and 3D surveys were used for the mass production of the exhibits' 3D models and the development of the virtual museum. In order to process

the data and build the accurate, textured 3D models of the exhibits PhotoScan Professional® v.1.1 software by Agisoft was used.

The application is available in Greek and English. In the beginning of the virtual tour the visitor has the chance to read the instructions that are available in order to freely navigate in the environment and understand the options and opportunities he/she has in the virtual museum (Fig. 22). The parameters that concern the movement, speed, rotation, height vision and behaviour of the visitor were extremely important in order to make the navigation friendly and easy for the visitor, as the majority of them may not have any previous experience with this kind of applications or even with the use of computers.

Moreover, the ambience and the depth of field were properly adjusted in order to have a more clear and realistic view of the exhibits, which is also important to the visitor and his/her virtual experience in the museum. The visitor has the chance to learn and find out more information about the exhibits that attract and interest him/her simply by clicking on them (Fig. 23). Moreover, the visitor is able to rotate the exhibits while the panel with the information appears on the right part of the screen. In that way the visitor is able to manipulate, closely examine and observe the details of every exhibit and at the same time learn not only the available information of the small panel that exists in the real museum, but also further information about it. The curator of the museum has the opportunity to choose the information that will be available to visitor and this is one of the advantages of this kind of applications. Finally, the last element that was added in the virtual environment was a mini-map to help the visitor move around and navigate in the environment without feeling disorientated, simply by offering him/her a view of the virtual museum from the top [9].



Fig. 22. The environment of the virtual museum (© author)



Fig. 23. The virtual museum with all included elements (© author)

5 Concluding Remarks

With the presentation of a few characteristic implementation examples, it has been shown that digital contemporary technologies can contribute decisively to the conservation of Cultural Heritage. The final products are 3D models and virtual restorations or reconstructions of monuments that either do not exist today or are at risk. Consequently, digital technologies and interdisciplinary synergies are of utmost importance. Equally important are the discussions and suggestions of scientists who have studied the monuments from an historical and archaeological point of view, proving once again that such interventions are a multi-disciplinary process.

Virtual reconstructions, virtual restorations, monitoring and 3D models on the other hand support many other disciplines involved in cultural heritage. They help architects and structural engineers 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.).

References

1. Balodimos, D., Lavvas G., Georgopoulos, A.: Wholly documenting holy monuments. In: CIPA XIX International Symposium, Antalya (2003)
2. Barsanti, S.G., Guidi, G.: 3D digitization of museum content within the 3D-ICONS project. ISPRS Ann. Photogramm. Remote Sens. Spatial Inf. Sci. **II-5/W1**, 151–156 (2013)

3. Biddle, M.: *The Tomb of Christ*. Sutton Publishing Ltd., Stroud (1999). 173 p. ISBN 0-7509-1926-4
4. Boehler, W., Heinz, G.: Documentation, surveying, photogrammetry. Paper presented at the XVII CIPA International Symposium, Olinda, Brazil (1999)
5. Corbo, V.C.: *Il Santo Sepolchro di Gerusalemme*. 3 vols. Publication of the Studium Biblicum Franciscanum, Jerusalem (1981)
6. Furukawa, Y., Ponce, J.: Accurate, dense, and robust multiview stereopsis. *IEEE Trans. Pattern Anal. Mach. Intell.* **32**(8), 1362–1376 (2010)
7. Furukawa, Y., Curless, B., Seitz, S.M., Szeliski, R.: Towards internet-scale multi-view stereo. In: 2010 IEEE Conference on Computer Vision and Pattern Recognition (CVPR), pp. 1434–1441. IEEE (2010)
8. Georgopoulos, A., Modatsos, M.: Non-metric bird's eye view. *Int. Arch. Photogramm. Remote Sens.* **34**(5), 359–362 (2002)
9. Georgopoulos, A., Kontogianni, G., Koutsaftis, C., Skamantzari, M.: Serious games at the service of cultural heritage and tourism. In: Katsoni, V., Upadhya, A., Stratigea, A. (eds.) *Tourism, Culture and Heritage in a Smart Economy*. SPBE, pp. 3–17. Springer, Cham (2017). https://doi.org/10.1007/978-3-319-47732-9_1
10. Georgopoulos, A., Lambrou, E., Pantazis, G., Agrafiotis, P., Papadaki, A., Kotoula, L., Lampropoulos, K., Delegou, E., Apostolopoulou, M., Alexakis, M., Moropoulou, A.: Merging geometric documentation with materials characterization and analysis of the history of the Holy Aedicule in the church of the Holy Sepulchre in Jerusalem. *Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci.* **XLII-5-W1**, 487–494 (2017). <https://doi.org/10.5194/isprs-archives-XLII-5-W1-487-2017>
11. Griffiths, J.-M., King, D.W.: Physical spaces and virtual visitors: the methodologies of comprehensive study of users and uses of museums. In: Trant, J., Bearman, D. (eds.) *Proceedings of International Cultural Heritage Informatics Meeting (ICHIM 2007)*, Archives & Museum Informatics, Toronto, 24 October 2007. <http://www.archimuse.com/ichim07/papers/griffiths/griffiths.html>
12. Guidi, G., Russo, M.: Diachronic 3D reconstruction for lost Cultural Heritage. *ISPRS-Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci.* **3816**, 371–376 (2011)
13. Kaliampakos, D., Benardos, A., Mavrikos, A., Panagiotopoulos, G.: The underground atlas project. *Tunn. Undergr. Space Technol.* **55**, 229–235 (2015)
14. Karakosta, E., Papanagioutou, B., Tragaris, N., Chatzigeorgiou, Th., Arampatzi, O., Doggouris, S., Mpalodimos, D.-D.: *Plaka Bridge: Survey-Check for vertical deformations*, Diploma thesis, National Technical University of Athens (1984)
15. Kersten, T.P., Lindstaedt, M.: Image-based low-cost systems for automatic 3D recording and modelling of archaeological finds and objects. In: Ioannides, M., Fritsch, D., Leissner, J., Davies, R., Remondino, F., Caffo, R. (eds.) *EuroMed 2012*. LNCS, vol. 7616, pp. 1–10. Springer, Heidelberg (2012). https://doi.org/10.1007/978-3-642-34234-9_1
16. Kyriakaki, G., Doulamis, A., Doulamis, N., Ioannides, M., Makantasis, K., Protopapadakis, E., Hadjiprocopis, A., Wenzel, K., Fritsch, D., Klein, M., Weinlinger, G.: 4D reconstruction of tangible cultural heritage objects from web-retrieved images. *Int. J. Heritage Digit. Era* **3**(2), 431–452 (2014)
17. Lavvas, G.: *The Church of the Holy Sepulchre in Jerusalem*, Academy of Athens (2009). 192 p. (in Greek). ISBN 978-960-404-139-8
18. Leftheris, B.P., Stavroulaki, M.E., Sapounaki, A.C., Stavroulakis, G.E.: *Computational Mechanics for Heritage Structures*. WIT Press, Southampton (2006)
19. Lepouras, G., Katifori, A., Vassilakis, C., Haritos, D.: Real exhibitions in a virtual museum. *Arch. J. Virtual Reality* **7**(2), 120–128 (2004)

20. Makantasis, K., Doulamis, A., Doulamis, N., Ioannides, M., Matsatsinis, N.: Content-based filtering for fast 3D reconstruction from unstructured web-based image data. In: Ioannides, M., Magnenat-Thalmann, N., Fink, E., Žarnić, R., Yen, A.-Y., Quak, E. (eds.) *EuroMed 2014*. LNCS, vol. 8740, pp. 91–101. Springer, Cham (2014). https://doi.org/10.1007/978-3-319-13695-0_9
21. Moropoulou, A.I., Labropoulos, K.C.: Non-destructive testing for assessing structural damage and interventions effectiveness for built cultural heritage protection. In: Asteris, P. G., Plevris, V. (eds.) *Handbook of Research on Seismic Assessment and Rehabilitation of Historic Structures*, pp. 448–499. IGI-Global, Hershey (2015)
22. Munoz-Torres, M.C., Reese, J.T., Childers, C.P., Bennett, A.K., Sundaram, J.P., Childs, K. L., Anzola, J.M., Milshina, N., Elsik, C.G.: Hymenoptera genome database: integrated community resources for insect species of the order hymenoptera. *Nucleic Acids Res.* **39**, D658–D662 (2011)
23. Oomen, J., Aroyo, L.: Crowdsourcing in the cultural heritage domain: opportunities and challenges. In: *Proceedings of the 5th International Conference on Communities and Technologies*, 19 June–2 July, Brisbane, Australia (2011)
24. Remondino, F., Del Pizzo, S., Kersten, T.P., Troisi, S.: Low-cost and open-source solutions for automated image orientation – a critical overview. In: Ioannides, M., Fritsch, D., Leissner, J., Davies, R., Remondino, F., Caffo, R. (eds.) *EuroMed 2012*. LNCS, vol. 7616, pp. 40–54. Springer, Heidelberg (2012). https://doi.org/10.1007/978-3-642-34234-9_5
25. Santagati, C., Inzerillo, L., Di Paola, F.: Image-based modeling techniques for architectural heritage 3D digitalization: limits and potentialities. *Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci.* **5**(w2), 555–560 (2013)
26. Santos, P., Serna, S.P., Stork, A., Fellner, D.: The potential of 3D internet in the cultural heritage domain. In: Ioannides, M., Quak, E. (eds.) *3D Research Challenges in Cultural Heritage*. LNCS, vol. 8355, pp. 1–17. Springer, Heidelberg (2014). https://doi.org/10.1007/978-3-662-44630-0_1
27. Stathopoulou, E.K., Georgopoulos, A., Panagiotopoulos, G., Kaliampakos, D.: 3D visualisation of lost cultural heritage objects using crowdsourcing. *Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci.* **XL-5/W7** (2015). 2015 25th International CIPA Symposium 2015, 31 August–04 September 2015, Taipei, Taiwan (2015)
28. Stylianidis, E., Georgopoulos, A.: Digital surveying in cultural heritage: the image-based recording and documentation approaches. In: Ippolito, A., Cigola, M. (eds.) *Handbook of Research on Emerging Technologies for Digital Preservation and Information Modeling*. IGI Global Publishing, Hershey (2016)
29. Sylaiou, S., Liarokapis, F., Kotsakis, K., Patias, P.: Virtual museums, a survey and some issues for consideration. *Arch. J. Cult. Heritage* **10**, 520–528 (2009). ISSN 1296-2074
30. Tucci, G., Bonora, V.: Geomatic techniques and 3D modeling for the survey of the Church of the Holy Sepulchre in Jerusalem. In: *Proceedings XXIII CIPA Symposium, Prague, Czech Republic, 12–16 September 2011*
31. UNESCO: *Guidelines for the Preservation of Digital Heritage*, CI-2003/WS/3 (2003)
32. Waldhäusl, P., Ogleby, C.L.: 3 × 3 rules for simple photogrammetric documentation of architecture. *Int. Arch. Photogramm. Remote Sens.* **30**, 426–429 (1994)
33. Wu, C.: SiftGPU: A GPU Implementation of Scale Invariant Feature Transform (SIFT) (2007). <http://cs.unc.edu/~ccwu/siftgpu>

34. Wu, C., Agarwal, S., Curless, B., Seitz, S.M.: Multicore bundle adjustment. In: 2011 IEEE Conference on Computer Vision and Pattern Recognition (CVPR), pp. 3057–3064. IEEE, June 2011
35. Wu, C.: Towards linear-time incremental structure from motion. In: 2013 International Conference on 3D Vision-3DV 2013, pp. 127–134. IEEE, June 2013