2.4

DIGITAL MODELS FOR DOCUMENTATION AND COMMUNICATION: NEW OUTLOOKS FOR USING THE 3D DATABASE

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Premise

The concept of cultural heritage is rapidly evolving, bringing together intrinsic and extrinsic value that includes several economic, territorial, environmental, academic and social aspects.
The terrible natural disasters (cyclones, cloudbursts, floods, landslides, volcanic eruptions and earthquakes) that periodically occur weaken our fragile cultural heritage, which is constantly exposed to risk factors. Failing to protect it has negative effects on the sectors mentioned above, as we know that for some of these phenomena man's action (i.e. pollution, improper use) actively contributes to their occurrence. In compliance with this wider view, scientific and technological research is being carried on in different fields: from chemical, physical and biological sciences to nanosciences, spatial positioning methods and information sciences.

2.4.1. Facing the risk with maintenance management

A correct intervention strategy in a conservation project has to start from knowledge: documentation is the first step in understanding. This highlights the primary role of documentation and the interdependence between knowledge and conservation strategy: you should know the object surveyed as well as the risk factors to which it is exposed in order to plan the conservation works and the maintenance programmes that can be useful to prevent risks and to avoid facing emergency situations.
The only possible way to hand over 'heritage documentation' to future generations in modern times is through digital records that are as permanent as possible.
Digital tools and media offer new opportunities for collecting, analysing and disseminating information about heritage sites. For the approach presented here, careful attention has been paid to the role that geomatics should play to implement a thorough prevention policy, in compliance with the recent scientific approach adopted against heritage obsolescence, which aims at optimizing preventive (rather than corrective) maintenance on buildings. This method has apparently higher investment costs, but they are amortized over the long term. This is briefly the logic at the basis of the strategy and methods of 'building maintenance management' [Lee, 1993]. This revolution in the philosophy and tasks of restoration, which has always been limited to repairing or renovating existing damage, emphasizes the strategic impor-

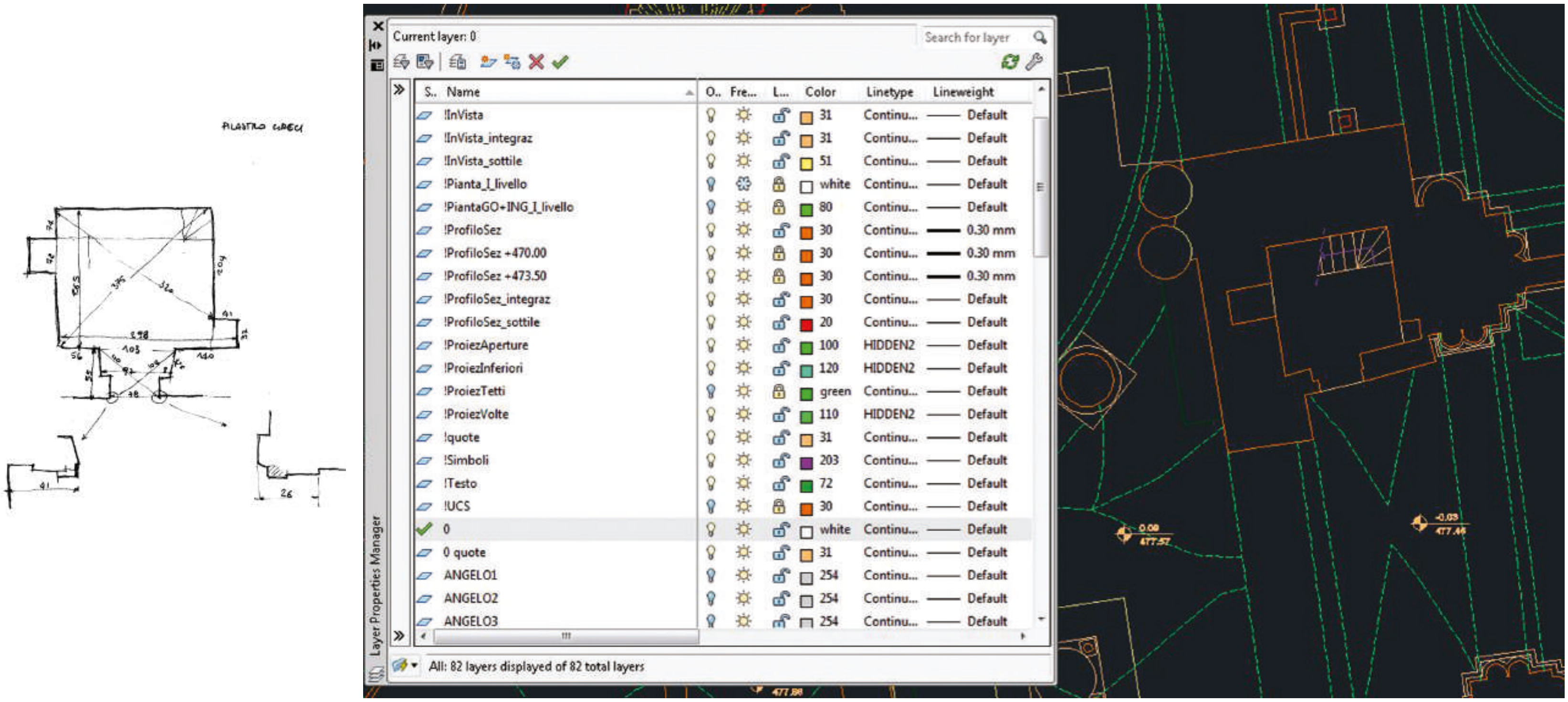
FIGURES 2A AND 2B Documentation of the Aedicula requires a high level of detail in order to record the decay and deformations of the stone.

tance of adopting suitable survey tools and methods to support the prevention of 'expected damage'. This kind of activity is based on timely detection of deterioration phenomena (as well as their mechanisms and possible causes) in order to limit their development and assess their incidence on the artefact's life cycle.

The decay curve of the artefact's 'performance quality', from the very beginning up to the minimum threshold allowed for the function carried out, allows us to assess its 'useful life' and plan maintenance works, leaving any unexpected failures aside. Without preventive maintenance, small problems with monuments and buildings can quickly grow into critical issues. While in the building industry these works normally include modifying and replacing damaged parts, in the cultural heritage sector they should not undermine the values (authenticity, artistic value, historical interest, etc.) of every artefact. The information model required to inform conservation action was established in the Venice Charter (Article 16) [ICOMOS, 1964] and expanded in the ICOMOS Sophia Principles [ICOMOS, 1996]. Conservation of the built heritage follows a series of work phases, involving analysis to establish value and significance, give priority to action and allocate resources; diagnosis to identify the causes of damage and decay; therapy to choose the remedial measures; and controls or monitoring to review and assess the efficiency of the intervention or conservation regime [Santana Quintero & al., 2007]. The contribution of geomatics is fundamental in all the four phases described above, which should not be considered as part of a linear process with a beginning and an end, but rather as a cycle: each phase requires thorough, correct and up-to-date metric knowledge of the object surveyed, also according to different levels of detail and accuracy (Figure 3).

2.4.2. Digital records for Heritage documentation

Metric surveys are the base for all types of documents required during analysis, diagnosis, intervention and monitoring. According to the English Heritage, this type of survey is 'the measurement and pictorial presentation of land and buildings to a specified standard, supplying reliable and repeatable base data without specific thematic input' [English Heritage, 2003]. The output of the contemporary metric survey is an information system in which data can be structured according to geom-



etry, materials, pathology and so on, and linked to a database, which will be used when necessary to extract important output for the assessment of the 'useful life' of artefacts or elements, evaluating their vulnerability in the event of natural or man-made risks.

It is thus possible to provide graphic representations responding to a different specific query each time. That is why metric surveying should become an element aggregating multidisciplinary contributions, a common platform hosting every kind of knowledge and not just a simple 'service' activity.

Good conservation of our cultural heritage is based on informed decisions. The first and effective step towards prevention is up-to-date documentation of what needs to be pre-emptively defended: the heritage itself and not documentation for documentation's sake. Documentation is expensive, but contributing towards a better knowledge of the building and its problems reduces conservation costs to a minimum.

FIGURE 3 Traditional sketch and CAD drawing; irrespective of the technique adopted for recording data, nowadays metric surveys are always represented with digital tools.

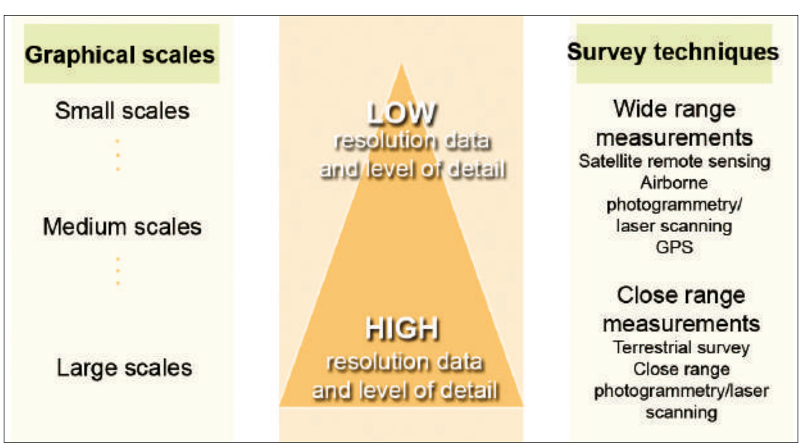


FIGURE 4 LEVEL OF DETAIL DIAGRAM

The surveying should be planned and carried out to reach a level of detail that can provide helpful information while optimizing the invested resources. The frequent need to have data with different scales underlines the importance of integrating various levels of detail into a single documentation project. On top of the pyramid scheme (Figure 2) there are catalogues and inventories, which are the most basic form of knowledge, as they only require the 'identification' and recording of data. Therefore, each element belonging to the cultural heritage must first be identified, then geo-referenced and finally stored, and its position associated with other basic information, if necessary. At the base of the pyramid there are high-resolution 3D models, whose level of detail allows the materials and conservation status to be described by means of a texture. In the middle there are all other types of 2D or 3D representations, made with metric data.

FIGURES 5A AND 5B A wide range of digital sensors are available for documenting the cultural heritage: a UAV equipped with a digital camera, and a laser scanner on a special-built track.

2.4.3. Digital tools for Heritage documentation

Currently, a wide range of digital sensors are available for documenting cultural heritage. In the last decade, we have seen the final digital transposition of photography and photogrammetry, the development of scanning systems based on different technologies, electronic total stations and satellite receivers. We are witnessing the birth of 'hybrid' sensors, such as total stations with GPS antennas or laser scanners with cameras, sometimes placed on supports that can acquire data on the move, such as cameras mounted on drones or UAV, mobile mapping systems, digital cameras on rotating heads, and range cameras, which integrate distance measurements and imaging aspects.

After the development of sensors that can acquire high quality data, we are now seeing a process that aims to optimize productivity. Only a few years ago, in 2007, we spent entire nights surveying the monumental complex of the Holy Sepulchre in Jerusalem, which required approximately three hours for each scan. With the scanner we use now in our laboratory, one scan takes only ten minutes. We are presently working on a system mounted on a motor vehicle integrating a laser scanner, GNSS, IMU and digital camera.

2.4.4. The Appeal and Risks of Virtual Worlds

The higher and higher resolution of data and its more and more rapid acquisition risk leading to a separation between the surveyor and the object surveyed. The time spent in the past observing and drawing an object before writing down its measurements down was the first step of a knowledge process in which measurement was often the element confirming or denying a hypothesis (concerning shape, construction, structure and so on) put forward by the surveyor 'while' observing the object. Nowadays, the shorter time spent on site postpones interpretation. Therefore, the acquisition of very high resolution data is often linked to the possibility of considering the digital reference sufficient to represent the real object rather than to the need to describe tiny variations during the representation phase of the surveyed object.

Even though the situation has changed,

the problem of measurement still remains a central element in the issue of scientific knowledge applied to real life. It is an uninterrupted alternation of analysis and synthesis of the detected object, where size measurement is the analysis and modelling is the synthesis and they can hardly be separated because they are always present at the same time. The survey tools and methods available today mean we can, pass from the monument to a realistic model, where geometries are real within the uncertainty of measurement and 'shapes' are not interpreted according to historical and stylistic experience, but according to the positioning of several points belonging to architectural elements within a suitable reference system. (Achille et al. 2004) In any case, it is clear that the transposition of analyses from the real world to the virtual one is both fascinating and potentially dangerous.

Roberto Pane's remark stating that «in short, we need to understand that the only real and complete representation of a monument is [...] the monument itself» (Pane, 1948) seems to be called into question by the unstoppable progress of technology. But if we consider a documentation project as a series of investigations looking for a series of answers, the only thing we can do is acknowledge the fact that the choice of questions is fundamental and confirm the leading role of the person operating the tool. Even though we use objective tools to quantify information, its recording is still a selection and interpretation operation influenced by the experience, cultural context and time in which the surveyor works.

The degree of 'automation' reached by some tools should be considered as the possibility of managing repetitive and complex processes and operations requiring limited human intervention, but we should not confuse it with 'autonomy', which is the capacity of choosing among different alternatives without the direct intervention of the user. According to this definition, therefore, an 'autonomous' system would be able to work without any specific parameter, which could be inferred from past knowledge.

2.4.5. Management, Communication, Dissemination

Thanks to the union of range maps and digital images it is now possible to «follow three different and complementary directions: the first pushes architectural analysis to the limits of materials and the transformation processes involving them; the second provides us with powerful means of calculation and orientation to make design choices and the third opens the doors of virtual reality, allowing us to forecast the outcomes of our design choices and the consequences that they will have on future transformations».

In fact, surveying is not only an effective means to describe the built-up space, but it also «imposes some forms of transcription and communication [...] Indeed, the ability of turning the critical or scientific acquisitions of the survey into a message is the guarantee that surveying will not become a mere descriptive act with the sole aim of generating useless graphic representations». [Torsello, 2005]

At the same time, digital information and communication technologies (ICT) have produced a wide range of applications for collecting and processing historical data, documenting and monitoring the physical conservation of objects and monuments, visualizing historic structures and environments, and creating interactive information networks that can link professionals and scholars with students, museum-goers, and interested amateurs. However, it is important to understand that ICT is a complex field whose contribution to cultural heritage can only be accomplished if it is utilized in effective, sustainable ways. It cannot be considered an immediate or magical cure-all. Cultural heritage professionals must understand what ICT can do, and in which situations or contexts it is most effective. With the rapid development of digital applications for historical research and presentation of the public heritage, the integration of digital technologies in the field of cultural heritage must be undertaken with the full awareness of their potential uses and effects. [Brizard & al., 2007].

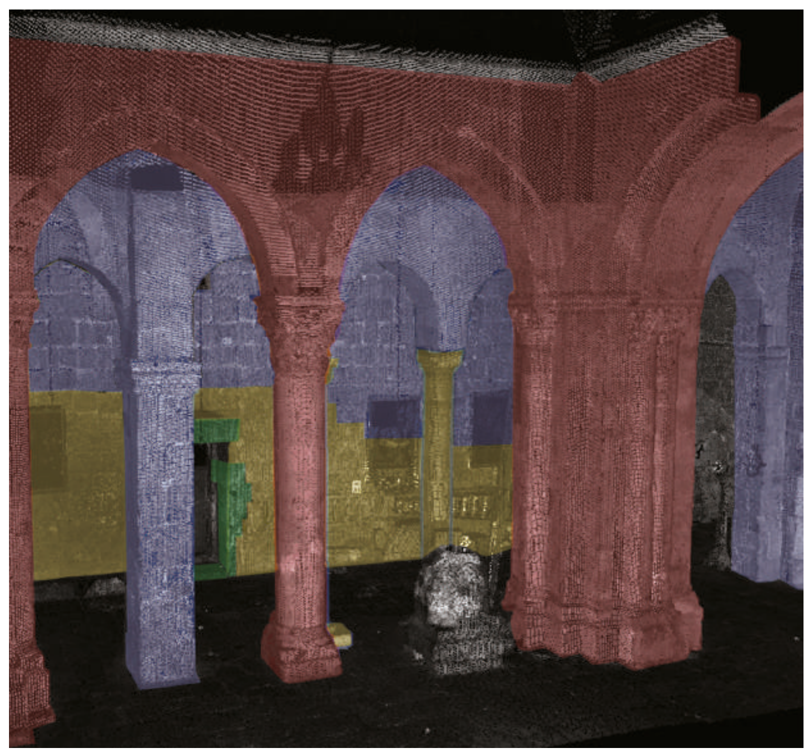


FIGURE 6 Stratigraphic analysis of the masonry, identifying the main construction phases on the 3D model (graphics processing A. Angeloni, see Table 13 in Part one, Chapter 2 of the present volume).

2.4.5.1. A proposal for a communication project

Having a significant database that documents the whole Holy Sepulchre complex makes it possible to develop various projects aimed at the communication and dissemination of a most important piece of heritage. The collected data, a great deal vaster than that elaborated so far, makes up the most complete database to date on the Church of the Holy Sepulchre in terms of kind (3D) and extent (it covers all the spaces – from the underground quarries to the roofs – of the complex architectural system). If this data were used for communicative ends, as well as putting the work already done to good use, it would also represent a non-common scientific approach to the dissemination of material that normally is so drastically simplified as to make the contents quite banal.

In collaboration with the *Associazione Terra Santa* (the no-profit non-governmental organization of the Franciscan Custody of the Holy Land), we therefore set up a coordinated communication and promotion project to foster and provide a better understanding both of the monumental complex of the Holy Sepulchre and the events that have centred around it. What is more, it is an example of an architectural project on an urban scale that highlights to what extent it is possible for religious, ethnic and cultural diversities to no longer enter into conflict, but instead agree on common goals. The project's strength lies in its seeking to collaborate with and involve all the institutions in question, as well as in its possible upshot of training and employment opportunities.

The proposal is to create a work combining cultural communication and furtherance for pilgrims, tourists and scholars, as well as for the local population, so that they can discover how the building has been transformed by the main historical events, social experiences, occurrences stemming from the Christian presence in the Holy Land and the Custody's experience in carrying out its assignment.

The aim of the project is to make tools for multimedia communication, *in situ* and online, such as a large touch screen station for visitors to view the 3D virtual model of the Holy Sepulchre and its main stages of construction. Including all the topics to provide a critical eye on the complex, it will be linked to the Internet for a dynamic and interactive experience.

2.4.5.2. A first experience: the virtual tour of the Holy Sepulchre

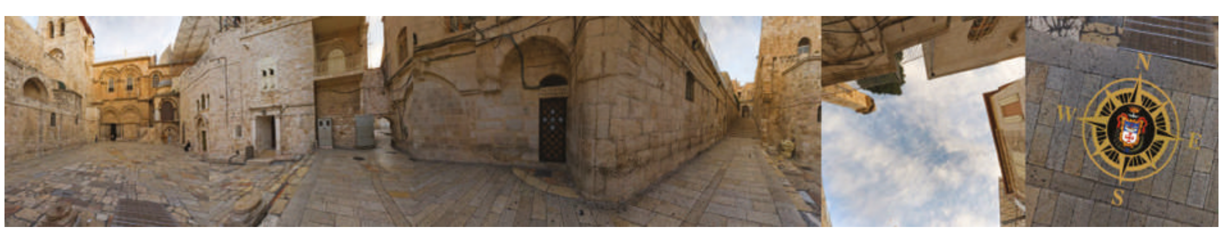
A first training project that involved the researchers from GeCo Laboratory and the Associazione Terra Santa had the goal of transferring the technical skills to make panoramic photographs and a virtual photo tour of the Church of the Holy Sepulchre. The project dealt with the topics of digital photography, HDRI images, and panoramic shots using rotational cameras with ultra-wide angle lenses

Various photographs were taken from each shooting position, with the aid of a camera support enabling rotation around the so-called 'no-parallax point'. In order to limit the number of shots, we preferred to use wide or ultra-wide angle lenses. All the images taken from a spot were then stitched together to create a 'panorama', that is, a photographic image that describes the whole space around the shooting point. This image can be 'developed' on a plane in on-line systems, a particular frame can be observed with the possibility of revolving the point of view at will. Therefore, the experience gives a significant idea of what an observer feels, on site, upon stopping in an interesting point of the building and looking all around. The single panoramas, that is, the single points of observation, were then linked together in a virtual tour: a click of the mouse enables the virtual visitor to instantly move from one significant point to another and from here to have a 360° view of the surrounding space.

This technology, dating from the first half of the 1990s, has undergone a constant expansion, in parallel to the improved features of digital cameras, and still today it is one of the most effective ways of using virtual reality. Indeed, it is both simple to use and the full realism photography very effective: the images can be high resolution, so the user can zoom in to observe even the tiniest details. Furthermore, hot spots can be inserted at the most significant elements to connect multimedia information, such as texts, audio and video, to the tour.

The local workers, technicians and association volunteers who took part in the training then made the virtual tour.

FIGURE 7 A panorama of the Holy Sepulchre square.



2.4.6. 3D solid models

While prototyping systems are usually employed in industrial processes where the prototype is previously planned in a CAD environment, in architecture and archaeology the shape of interest is taken from a real-world object that does not have a pre-existing computer model. In fact, the main role of 3D solid models in architecture and archaeology is to somehow aid communication as a 3D visualization tool. With the cross-migration of techniques to documentation of the Cultural Heritage, sometimes the terminology can be confused. The 'prototype' is no longer the first element in the subsequent production of a series of models. In this field, it is clear that the aim of a rapid prototype project is not to start mass production. Better terms to define this work could be a 'replica' or 'solid model', depending on whether its scale is 1:1 or not. In the early 1990s, CAD had a lasting and far-reaching impact on the work of architects and archaeologists. A similar situation occurred recently with the replacement of manual model-making with rapid prototyping techniques, which are now more and more frequent.

Models are used for several purposes in the Cultural Heritage field: huge differences can be found between models representing the only way of visualizing an architectural or design project before it was built and models documenting the existence of an architectural element, an archaeological site or an antiquity. In both cases, the models can be defined as 'exhibitive': whether they are in full or reduced scale, their main function is to represent the object they reproduce by overcoming the limitations of 2D images.

2.4.6.1. Possible uses of solid models

Solid models can be used in various ways:

- *To illustrate new projects:* in the field of architecture they often replace traditional maquettes built to demonstrate and assess a proposed design project;
- *As demonstration and reconstruction models:* such as in the case of archaeological structures brought to light by trial excavations, but then covered over again due to the need to preserve or use the area;
- *Replicas to replace objects for transfer to a museum:* a poor state of preservation and forms of degradation due to air pollution often make it a good idea to move statues or architectural elements from their original position to a more protected environment, such as an exhibition room or museum warehouse; copies are often made to regain the possibility of admiring these works in their original context;
- *'Tactile' models:* these models can be touched and explored by blind and partially sighted people so that they can perceive and understand objects; indeed, tactile observation is the main means of knowledge for blind people.

2.4.6.2. The solid model of the *Aedicula* of the Holy Sepulchre

Following the long tradition of producing models of the Holy Sepulchre studied by Father Piccirillo [Piccirillo, 2007], we wanted to make a new model of the *Aedicula*. As there is a surface model of a large part of the complex, to this end we were able to adopt one of the Additive Manufacturing techniques illustrated previously. In particular, a three-dimensional printer was used. The dimensions of the model are 9 cm x 23 cm x 19 cm, which correspond to a reproduction in a scale of 1:XXX.

The model is divided into two parts, so it can be opened to observe the Chapel of the Angel and the Sepulchre. Owing to how it is made up, we decided to use a horizontal section plane. The sectioned area of the side walls is highlighted in dark grey, thanks to the possibility given by the printer used to colour the model directly during printing.

Despite the small size of the model, one can appreciate the high level of detail: all the pilaster strips can be seen, the small Solomonic columns, the cornices and the decorations on the tiny door to the chamber of the Sepulchre. In the interior, it was thought better to virtually remove all the oil lamps hanging above the Sepulchre to allow this unusual vision of the vault, which is constantly hidden in the actual *Aedicula*. It was also thought better not to represent the oil lamps on the façade, the bas-relief and the canvas above the entrance to show the structure.

The model is completed by the seats at the sides of the entrance to the *Aedicula* and the adjacent large stone candlesticks as well as the grate that marks off the Copt Chapel.

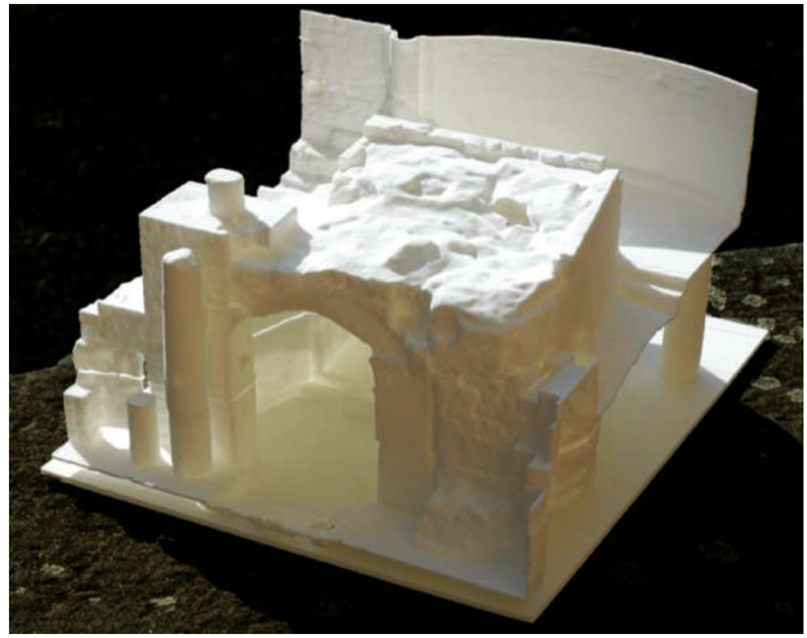


FIGURE 8 Solid model of the Grotto of the Annunciation (Nazareth, Palestine), sintered. The model of the Grotto of the Annunciation in Nazareth was rapid prototyped using a laser sintering machine. After the latest restoration work, pilgrims can no longer access the grotto. The 3D model can be opened in order to show the inner parts.

2.4.7. Future development prospects

At the present time we are witnessing the widespread dissemination of geo-referenced data; notwithstanding the way it is produced, it could prove to give a decisive contribution for the realization of that recurring dream (i.e. comprehensive heritage documentation), which in 1858 led Albrecht Meydenbauer [Albertz & Meydenbauer, 2001], a young German architect, to use photographic images for the first time to document buildings with the aim of creating a Cultural Heritage Archive *(Denkmälerarchiv)*. He knew the risks that cultural heritage was running and he was sure that this kind of documentation would have even allowed reconstruction, if necessary. Between 1885 and 1920, 2,600 buildings were filed through approximately 20,000 photographic images on plates.

We should launch a sharing and networking process for all the output from cultural heritage surveys, as in 'citizen cartography' where the production and sharing of data have been tested for a long time (Google calls its maps 'geospatial applications').

According to Mark Graham [Graham, 2010], the projects carried out by digital neocartographers can be organized into three categories: virtual globes, applications and sites belonging to web giants that allow users to virtually explore any place in the world; wiki-locals, such as Wikitravel and WikiMapia, where users actively participate in the representation of places that can be shown in different scales, and OpenStreetMap, where maps are drawn by volunteers who pick up the GPS signals of our devices, rather than using private or government data.

An idea could be to create a data community for cultural heritage. Images, drawings, models and range maps could be accessible and integrated. After all, if suitably validated, data is a common good with an extremely high value that short-sighted administrators and red tape rarely make available, resulting in additional measurement operations and higher costs.

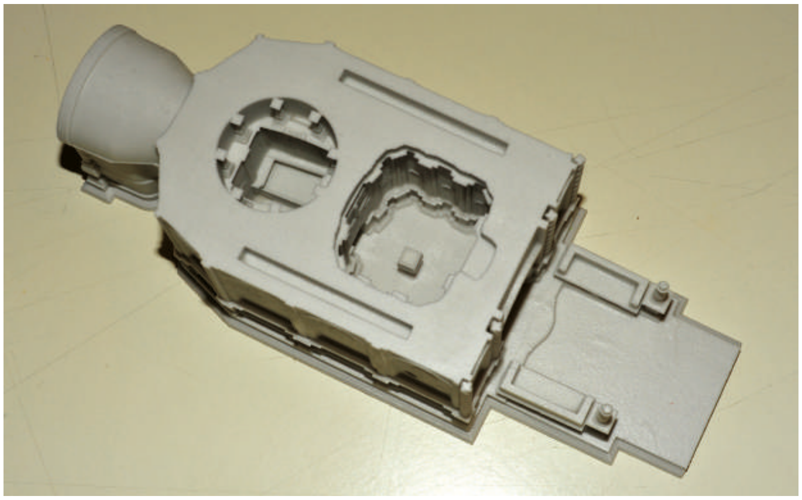
Some projects to make available geographic data concerning the territory have been launched successfully: thanks to the incredible results of the first pilot experiences, 'portability' and 'interoperability' have become watchwords for an ever increasing number of public administrations.

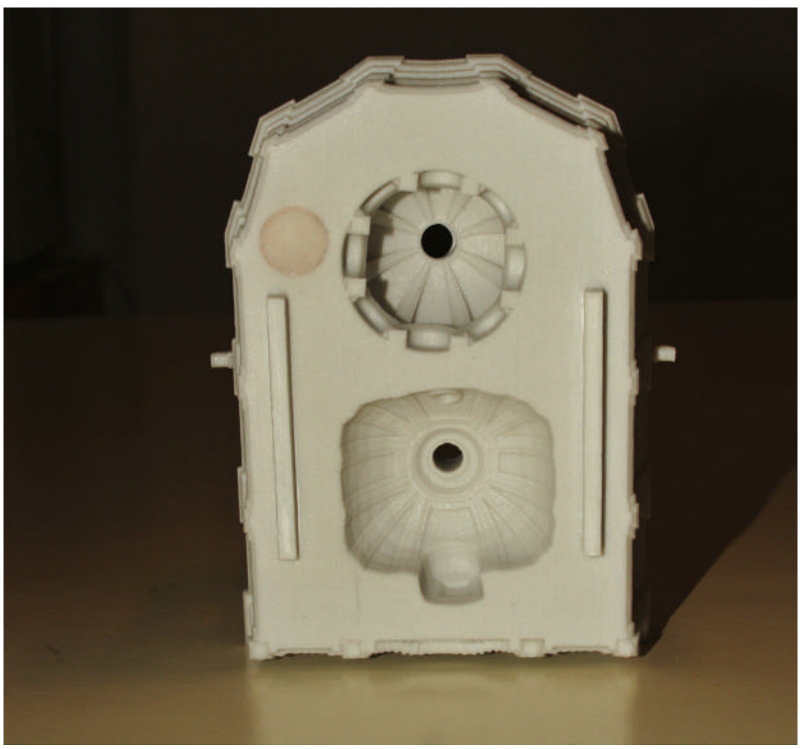
The information regarding cultural heritage is still fragmented and dispersive: similar analyses and surveys are sometimes carried out on the same object by different subjects and within separate research activities, making the work unnecessarily expensive and redundant.

Just as cataloguing represents the lowest level of documentation, which only attests the 'existence' of a good, similarly the first step could be the creation of a digital repository of Cultural Heritage resources (possibly based on open-source software, at least in theory), to prevent the fragmentation and duplication of information.

The already existing «digital repositories are often unable to guarantee affordable features in the management of 3D models and their metadata [...]. The nature of most of the available data formats for 3D encoding seems to be insufficient for the portability across different systems required nowadays by 3D information». [Felicetti & Lorenzini, 2011] The following aspects relating to large-scale documentation have still to be taken into account or remain unsolved:

- Defining a common vocabulary and identifying effective metadata concerning the digitization of cultural heritage.
- Sharing procedural standards, even through the preparation and dissemination of specifications aiming at overcoming the outdated prescriptive approaches and adopting a more contemporary technical approach.





FIGURES 9A AND 9B Solid model of the *Aedicula* of the Holy Sepulchre.

– Defining open-file formats for both raw data filing and subsequent processing operations.
– Outlining validation and test procedures to ensure the quality of data and the resulting information.

Training must become the key element to support this proposal, to update the know-how of qualified professionals, promote the scientific culture linked to 3D technologies (also among public and private customers) and boost the awareness of heritage users in general. Indeed it is only by increasing awareness that we can aid promotion and enhancement of the heritage. New technologies are the right tool to make knowledge 'available', at last. In 1964, article 16 of the Venice Charter [ICOMOS, 1964] was already stressing the importance of documentation and publication, and the concept has been taken up in several subsequent recommendations, including the London Charter and its more recent updates [Denard, 2009].

FIGURE 9C Solid model of the *Aedicula* of the Holy Sepulchre.

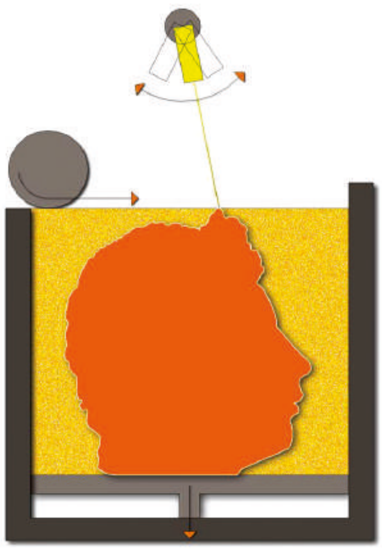


FIGURE 10 Diagram of the laser sintering process.

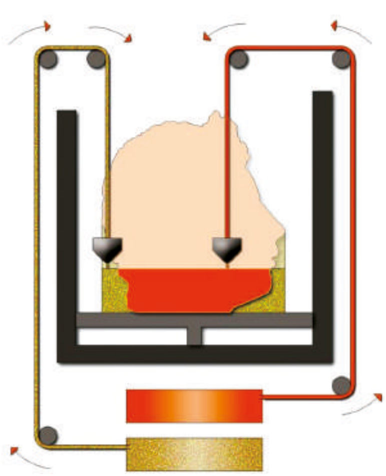


FIGURE 11 Diagram of the fused deposition modelling process.

2.4,8. How additive manufacturing works

According to the purposes of the solid model to build, it is important to evaluate these aspects in advance:

- Working precision, according to the level of detail required;
- Surface aspect: colour, roughness, and so on;
- Mechanical strength, thermal strength, etc., if the model needs to have functional features;
- Possibility of applying finishing;
- Weight of the finished model.

Unlike traditional machining methods, additive manufacturing builds every part by adding material, layer by layer, rather than by subtracting it (as in the case of CNC milling machines). At present there are over 20 different recognized Rapid Prototyping technologies. The majority has been developed and optimized to produce objects with functional capability. We introduce here only the ones that can be used for models whose main aim is display ("exhibitive solid models").

2.4.8.1. Stereolithography (SL)

It was the first generation of machines for rapid prototyping (the first commercial machine dates back to 1987); it builds plastic parts or objects a layer at a time by tracing a laser beam on the surface of a vat of liquid photopolymer. After building, parts are removed from the machine and post-processing in a UV or thermal oven is used to cure any uncured resin. SL has a superior accuracy and definition when compared with other processes. SLA (Stereolithography apparatus) denotes the SL machines from 3D Systems Corporation.

2.4.8.2. Laser Sintering (LS)

It is based on bonding powders: one or more laser selectively fuse or melt, layer by layer, the particles at the surface. A fresh layer of powder is then added to the top and a new profile is traced by the laser bonding it to the layer below. The unfused powder acts as a supporting material which obviates the need for support removal during post-processing. Actually, the word 'sintering' is not correct, as the material is not sintered but partially or fully melted. The first machine was commercialized in 1992.

2.4.8.3. Three dimensional printing

A jetting which deposits a liquid adhesive compound onto the top layer of a bed of powder object material. 3D printing is often used synonymously with *additive manufacturing*, even though according to ASTM standard (F2792-10) it should be reserved for this specific kind of process. In 2001 ZCorp introduced the first commercial colour system: once the layer of powder is spread, the inkjet print heads print the cross-sectional area for bottom slice of the part onto the smooth layer of powder, binding the powder together: the coloured ink also provides the mechanical bond between the powder particles. Resolution suitable for fairly good output is limited by layer thicknesses (0.05-0.1mm): while horizontal resolution is easily achieved, vertical resolution would require to reduce the layer thickness, slowing down the model building.

2.4.8.4. Fused Deposition Modeling (FDM)

It works by extrusion of thermoplastic materials, heated and deposited layer by layer. The term denotes machines built by Stratasys, Inc., which started commercializing it in 1991. Support removal can be manual or, when water soluble supports are employed, they may simply be dissolved.

2.4.8.5. Other manufacturing techniques useful for exhibitive solid models

Laminated Object Manufacturing (LOM):
a laser cutter or a knife cuts profiles of object cross sections from paper or plastic. This method is often applied to large models that require particularly robust properties. Surface finishing by hand is needed to remove layer steps.
Additive/subtractive Solid Freeform Fabrication (A/S SFF):
it combines the advantages of layered manufacturing and material removal processes, such as CNC milling, so it can build parts with complex shapes without compromising precision requirements.

2.4.8.6. Low cost and DIY projects

In the industrial sector the reduction of time to market lead to remarkable cost reduction (that is to say gains). The resulting increase in market shares can justify demanding investments and the revision of a huge part of the production cycle. If we replace the *market value* with the *social value*, the "industry" linked to Built Heritage will have huge potentialities in terms of potential users, improvement of the level of education and training , etc. which very rarely correspond to suitable economic resources. Maybe the offer of "low cost" machines and the availability of "Do It Yourself" systems could contribute to a wider spreading of additive manufacturing systems in this sector. Some examples are available in:
http://reprap.org/wiki/Main_Page;
http://www.evilmadscientist.com/article.php/candyfab;
http://3dprinting.co.nz/?page_id=5.

2.4.9. How conventional prototyping (CNC) works

CNC (Computer Numerical Control) machines make solid models by removing material from a stock shape. They can make different kinds of manufacturing: turning, trimming, drilling, planning, grinding, spark erosion, etc… An important element of a CNC machine is how many axes it has: more axes mean more complexity but also more complex shapes that can be worked. To make simple work, i.e. drilling holes, the motion control along three axes is needed: two of them to position the tool over the hole to be machined and the third to machine it. So working all around a full relief piece needs more complex movements.
The directions of motion can be linear (driven along a straight path) and rotary (driven along a circular path). All movements are related to a "zero point", useful in case of repositioning of the work in following steps to refinish it. The motion type, the axis to move, the amount of motion, and the feed rate are controlled by software. Machines with 5 axes have the highest flexibility: a rotating table can be added to have the 6th movement direction. The main advantage of 5 axis machining is the ability to work complex shapes in a single set-up. Additional benefit comes from allowing the use of shorter cutters that permit more accurate machining. CNC systems can process different materials: polystyrene, wood, stone, and so on.

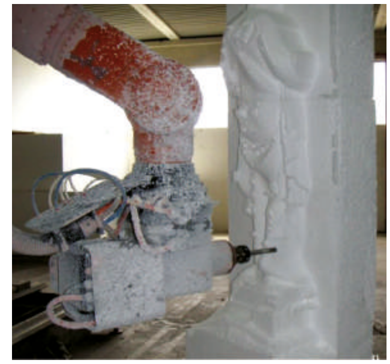


FIGURE 12 A CNC robotic milling machine working on the replica of a statue.

2.4.10. Work-flow

2.4.10.1. Numerical description of the object

CAD model can be created as a solid model (by using primitive instancing or constructive solid geometry) or a surface model (by using Boundary Representation). In order to create good files, all surfaces must be joined so that there are no gaps or overlaps. This stitching or sewing, is a manual and tedious process. If it comes from a survey carried out with 3D scanning, the surface of the model is generally calculated by triangulating the data acquired. Creating a hollow part is a good technique to cut down the weight of the prototype. This is important because volume is one of the main factors that play into the price of the prototype.

2.4.10.2. Data preparation

Data preparation is the manual or automatic control of the closing of all surfaces, which should create a 'waterproof' model. If the size of the mode-ls under consideration exceeded the maximum dimensional capabilities of the machine, it should be split into several different parts, which will be produced separately.

2.4.10.3. Surface tessellation

The inner and outer surface of the numeric model is tesselled with polygons, generally triangular. If the initial model is made of NURBs surfaces, such as for example models of architectural elements or objects during the project stage, approximation with triangular facets will inevitably causes errors, which will be evaluated by using the distance between the centre of gravity of the triangle and the original surface (that is called *chordal error*). It could be necessary to diminish the size of the mesh facets; if their size is too big, facets will show on the solid model. Ideally, the triangle size should be close to the layer thickness used by the rapid prototyping system. The tesselled model is stored in STL format (sometimes STL comes from Stereolitography, other times from 'Solid To Layer'). The STL format stores the 3 coordinates of the vertex of every triangle and the direction cosine of the outward normal of the surface.

2.4.10.4. Orientation and slicing

The layer thickness should be chosen according to the necessary level of detail, and it can vary from some 0.1 to some 0.01 mm. Special care must be take in the orientation of the various parts to ensure best quality and to minimize finishing time of the models: build orientation is important because solid models are usually weaker and less accurate in the vertical direction than in the x-y plane; in addition, placing the shortest dimension in the vertical direction reduces the number of layers, thereby shortening build time.

2.4.10.5. Making the solid model

The technology chosen to build the solid model affects the build time and the operations necessary to finish the model. Deposition of sliced layers leads to staircase effect that cannot be eliminated on a rapid prototyped part completely. Refinement of layers improves the surface finish of the part, but it increases the build time.

2.4.10.6. Final operations

The final steps are removing the part from the machine, detaching support materials, and performing any necessary cleaning or surface finishing. Polishing, sealing, or painting the parts can improve their appearance.

FIGURE 13 Detail of a modern capital with a small cross in high relief on a coloumn in the *Rotunda.*

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