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FROM SURVEY TO MODEL: A ROUND-UP OF THE MODELLING TECHNIQUES

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2.3.1. Overview of the employment of reality-based 3D models in the Cultural Heritage field

In the Cultural Heritage field, three-dimensional digital models, based on geomatic surveys, are increasingly regarded as special tools for documentary recording and sharing, visual analysis approaches and communication/educational applications. The factors behind this are, on one hand, that computers have increased their computing power and graphical display quality, and that the Internet and high-speed connections are widely accessible. On the other hand, the technologies needed to acquire and process relevant data are becoming more affordable and the tested procedures and resources have been simplified and shared.

However, there is still a lot to do before reality-based 3D is widely adopted, especially by the institutions in charge of the management, interpretation and presentation of the Cultural Heritage. The obstacles are, on one hand, that the acquisition devices and processing softwares required to obtain good models are still expensive and require specific expertise; and on the other, that complex 3D models are difficult to manage and interact with in a low-cost, fast and user-friendly environment.

Besides that, another open challenge for its advancement is that 3D needs to become a working resource for Cultural Heritage professionals, such as administrators, art historians, conservators and restorers: but in thinking this we are probably still ahead of our time, because of the costs, training and change of mentality implied in taking up new schemes. However, the main reason that it has not been adopted is probably still a lack of awareness of its potentialities for the stakeholders' own purposes; and, directly related to this, the fact that the technicians are not really conscious of the Cultural Heritage practitioners' specific needs, therefore they do not know which tools should undergo more development.

In the research field there are attempts to overcome these open issues concerning the clients and commissioning bodies, with work on automation of the acquisition and processing phases [Cignoni & Scopigno, 2008], and, from another point of view, on collecting and sharing good practices and guidelines with the aim of showing the impacts and benefits of 3D digitization, eliminating the doubts that had arisen due to previous misuse of the technology, and, therefore, broadening access to it.

High-level Cultural Heritage institutions have become progressively more aware of the potentialities of 3D digitization in the last decade: this can be perceived if we are to look at the projects and coordination initiatives that have sprung up all over Europe, anticipated by similar experiences in North America (Canada, with the National Research Council, and the USA, with Stanford University, UCLA University of California-Los Angeles, and the Institute for Advanced Technology in the Humanities at the University of Virginia)[1]. A

[1] Internationally, at the theoretical level it is worth mentioning the Charter that the International Council on Monuments and Sites (ICOMOS) prepared and then ratified in 2008 on the *Interpretation and Presentation of Cultural Heritage Sites* (see The ICOMOS Charter, 2008; Silberman, 2006), considering all the activities and information implemented for those purposes, as well as the London Charter (see The London Charter, 2009; Denard, 2012) on the principles that should inform the best practice in computer-based heritage visualization. An important test project was *RecorDIM – Recording, Documentation and Information Management* (2002-2007), a partnership fostered by ICOMOS, the Getty Conservation Institute (GCI) and the International Committee CIPA Heritage documentation, with the purpose of bridging the gaps between the information users (conservation experts) and providers (heritage recorders).

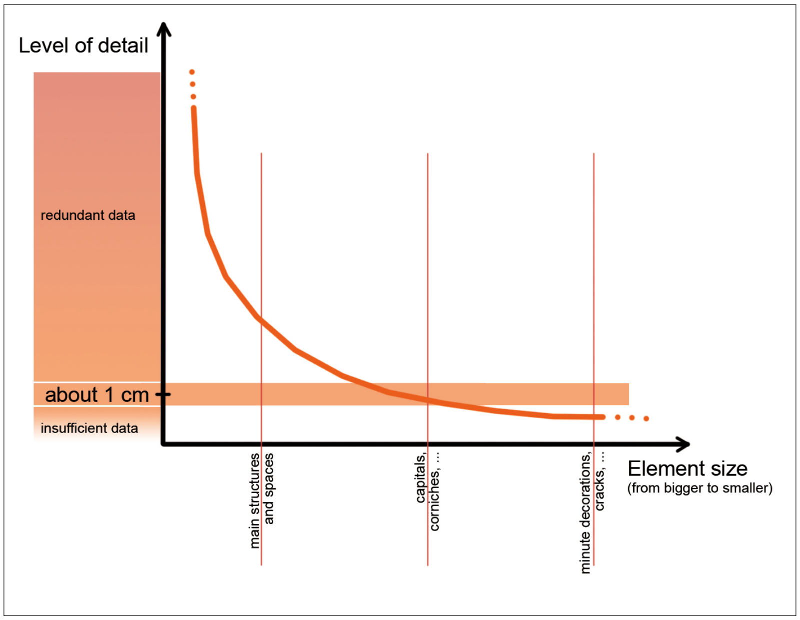


FIGURE 2 The graph illustrates the relationship between the size of the elements to be modelled (on the x-axis) and the appropriate degree of detail needed to represent them (on the y-axis). The resolution of the laser scanning survey can be quantified in centimetres: therefore it appears excessive for modelling the main structures and spaces, but suitable for the capitals, cornices, etc.. Yet it is not sufficient for details of less than one centimetre, such as structural damage or minute decorations.

few European Union initiatives have been directly related to the task of using 3D and other information technology in the protection of cultural assets. The aims of these projects have been to establish 3D documentation as an affordable, practical and effective mechanism for the long-term documentation of tangible cultural heritage and to provide access to a network of relevant organizations, tools and guidance references[2].

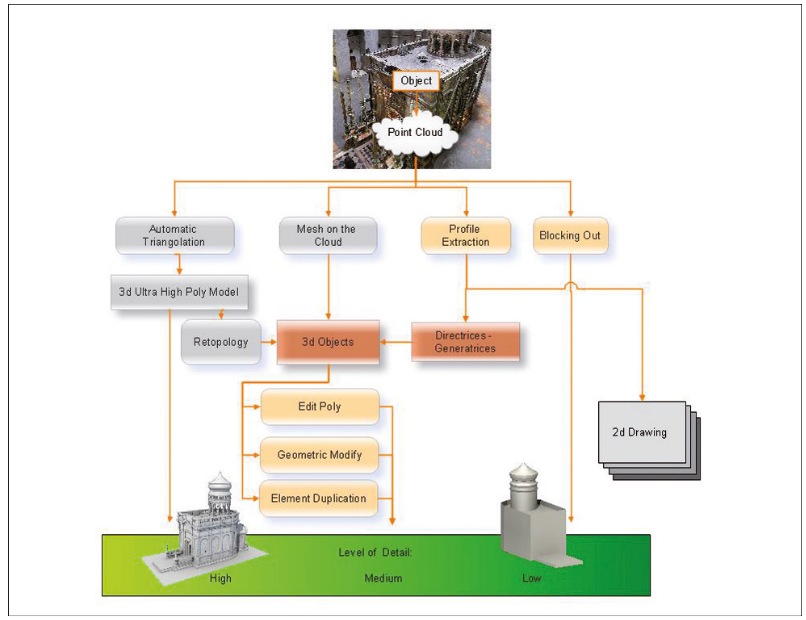


FIGURE 3 Summary of the different modelling approaches followed.

2.3.2. 3D modelling of the Holy Sepulchre monumental complex

Thanks to the 3D survey of the Church of the Holy Sepulchre, an important project is currently underway to model the actual state of the whole monumental complex. The project goals are to prepare a tool to aid the knowledge and exploration of a very intricate space both in terms of conformation and historical layers. The tools to visualize and explore the building can be pinpointed from among the numerous possibilities offered by the most modern technologies and optimized on the basis of the types of end user that we want to reach each time (pilgrims, tourists, scholars, etc.). During this first phase, we chose to visualize the model that we were creating by rendering static views. One of the ways in which we intend to use it is to create a solid model starting from the complete numerical model, as described in Figure 2.

As was the case for the survey, we also started the modelling from the most important symbolic element in the Holy Sepulchre monumental complex: the *Aedicula*. Then we extended the modelling to the *Rotunda*, the *Katholicon* and the naves known as the "Arches of the Virgin". In order to identify the best IT tools and operating procedures we performed a series of tests beforehand. Nevertheless, we were not able to choose a single approach for the modelling. Owing to the variety of environments, the diverse structural importance of the various parts and the different detail of the decorative elements we used different approaches, which we optimized each time on the basis of the geometric complexity of the part to be modelled and its significance within the whole model. These last two parameters can be summed up in the concept of the 'level of detail' needed for every element of the model. Even though it is very dif-

[2] Among the promoters is the English Heritage, which encourages professional guidance and training development through the *Heritage3D* project and website, led by the School of Civil Engineering and Geosciences at Newcastle University, as well as a series of useful handbooks (e.g. English Heritage, 2011). Another project was *Virtual Heritage: High-Quality 3D Acquisition and Presentation (ViHAP3D)* conducted in 2002-2005, aimed at the protection, presentation, sharing and promotion of cultural heritage, using high spatial quality interactive graphics. One more important framework from the same period was the *European Research Network of Excellence in Processing Open Cultural Heritage (EPOCH)*, conducted in 2004-2008, which focused on the efforts of about 100 European cultural institutions to exchange their expertise, and improve the quality and effectiveness of information and communication technologies adapted to cultural heritage. Together, academic departments, research centres, cultural institutions such as museums and government heritage agencies, and commercial enterprises have also attempted to overcome fragmentation in this field and share a clear common pattern with the more recent *3D-COFORM* consortium, which was a sort of continuation, from 2008 to 2012, of the *EPOCH* partnership.
The European Union' initiative "EUROPEANA" brings together cultural heritage and technology professionals to make cultural heritage content available to a global audience. The main aim of the project is to share collections that have been digitised by museums, galleries, libraries and archives and thus to let 3D models available for research, learning, and creative purposes.

ficult to make an objective quantification, we must consider that in architectural-scale representations, the typical level of accuracy is centimetres and all the scanners that are used in this field obtain similar degrees of precision and resolution. As a consequence, in order to model the various architectural elements, depending on the case in question, where required owing to the high level of detail we used the data available at maximum resolution, or at a much lower resolution where there were no rich decorative elements.

The flow chart in Figure 3 sums up the different approaches followed. Each one was tested on significant architectural elements: the more detailed decorations require triangulation or modelling based on retopology systems, while vaults, walls and other elements with simple geometries can be modelled using a geometric approach. Regardless of the procedures with which they have been made, all the models will be integrated into a single final model. The following paragraphs illustrate the different approaches adopted for the modelling.

2.3.2.1. Triangulation

Triangulation is an automatic process in which a surface is defined with triangular mesh starting from a point model. Of course in the areas where the points have not been surveyed – because they are hidden from the scanner by other elements at the moment of acquisition – some gaps appear on the surface. Therefore, although the calculation is automatic, this is counterbalanced by the laborious elaborations needed to reconstruct and to fill in the missing parts. These operations require careful manual intervention by the operator and therefore have a significant impact on the time taken for the modelling.

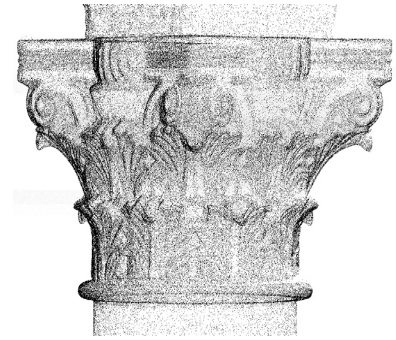
The data used as the initial set is called 'non-structured', that is, it is arranged irregularly in space. The only restriction is that it belongs to the surface under survey. In the same way, the triangular mesh of the calculated surface responds to the requirement to 'stick' to the points that generated it, with tolerance intervals that can be adjusted by the operator. The number of triangles of the mesh surface should be adjusted to describe the object effectively, considering that more complex surfaces require smaller triangles to approximate the object shape better. On the contrary, when considering simple surfaces, as planar walls or regular vaults, a much lower number of polygons should be sufficient to describe the object. This is why a triangle mesh is not optimal for describing a simple object in the most efficient way.

In depth: number of points / triangles

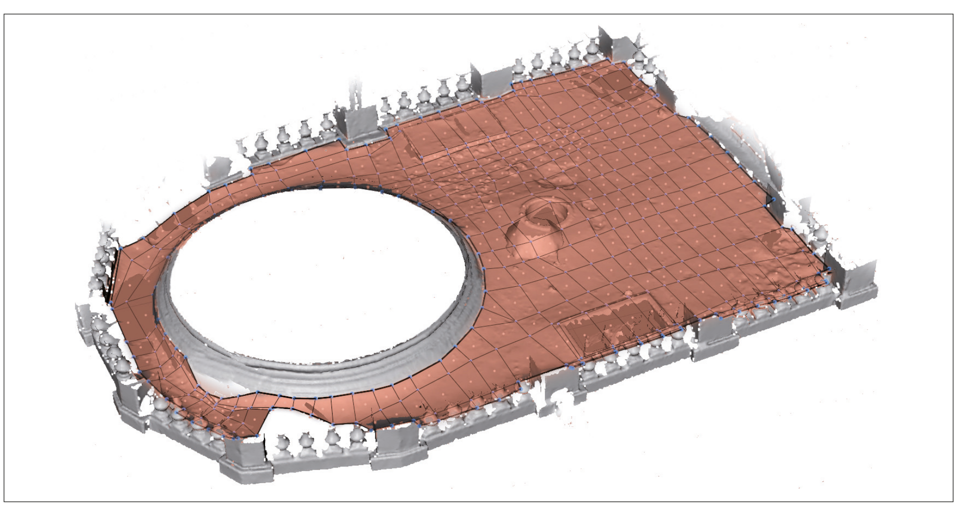
The large number of triangles in a mesh created by triangulation makes it demanding to manage even small models with regard to the hardware resources needed. This is why triangulation is reserved for the elements with the highest level of detail, or is only carried out after the surveyed points have been decimated. We followed this second method to obtain a 'base' model, which we then elaborated as described further on.

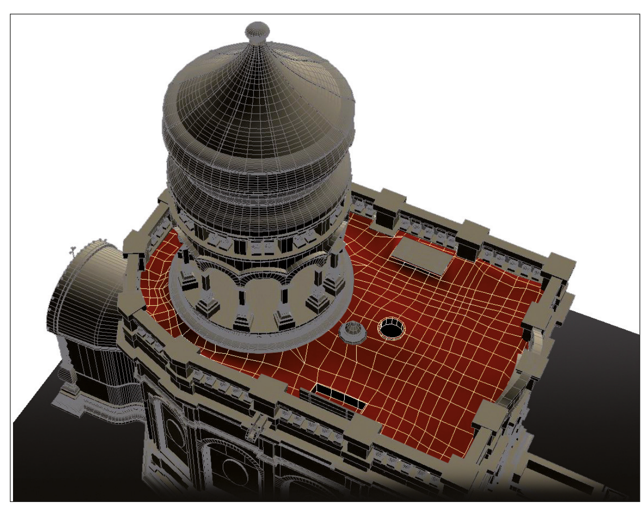
The possibility of producing effective triangulated models depends on the noise of the data surveyed and on their completeness. Consequently, we can state that the level of detail of triangulated models should be defined during the acquisition phase (data triangulation aims at keeping the description as accurate as possible), while the level of detail of a surface rebuilt through mesh can be 'designed' during modelling.

The solution identified to maintain a high level of correspondence with the original form, while at the same time significantly reducing the number of polygons, is 'retopology'. Given a high-resolution triangulated model – therefore with a small mesh – it consists of hooking up to the original surface to 'redesign' a new surface made up of a much larger mesh. The new surface is therefore projected onto the original one to minimize the differences.

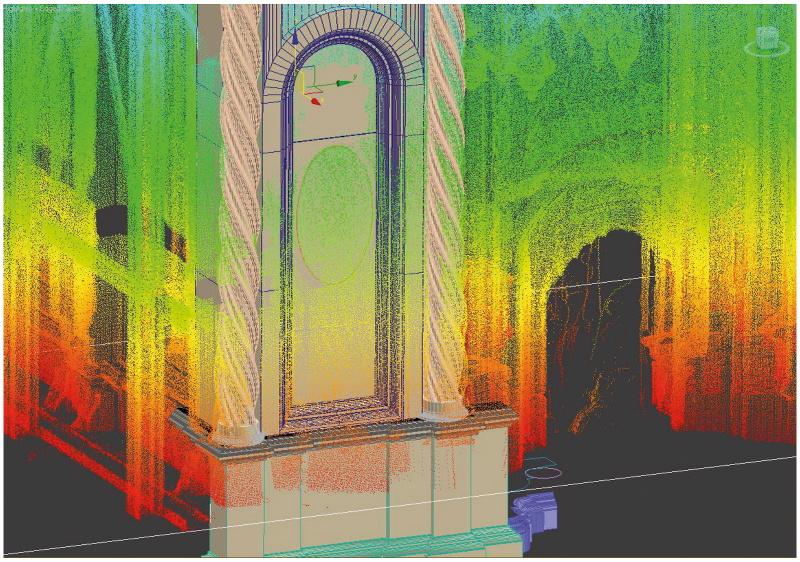


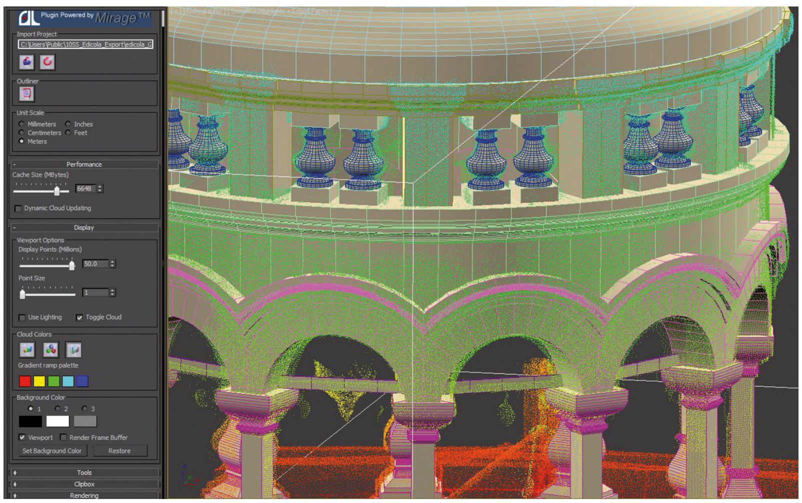
FIGURES 4 AND 5 Here is an example of the highest resolution model of the column in the *Rotunda* (by Michele Russo). This element has very dense mesh details. At the time we worked on the project, available hardware and software technologies could not manage such a huge amount of data for every architectural element of the monumental complex.





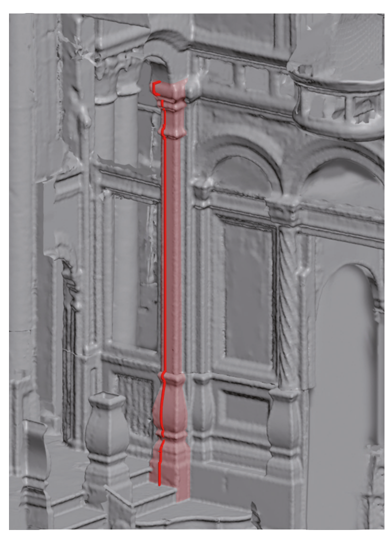
FIGURES 6 AND 7 Some retopology systems were tested to model elements with 'organic' (or 'non-Euclidean') geometry or with a trend that cannot be described through discontinuity, as was the case for the surface covering the *Aedicula*.

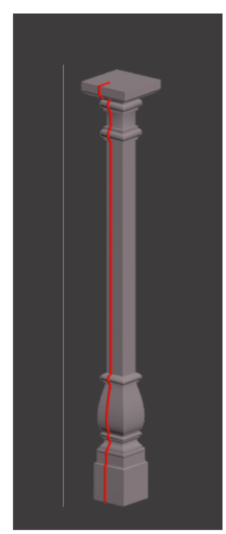




FIGURES 8 AND 9 The 3D modelling of the *Aedicula* of the Holy Sepulchre was carried out with 3ds Max (Autodesk) software, with a plug-in, which easily manages the display of point model portions (small volumes or slices) and allows the definition of vector profiles and mesh surfaces. Moreover, it is possible to perform modelling using all the 3ds Max tools.

In this case too, the presence of gaps creates a problem as it forces the mesh to deform in order to snap onto the nearest point of the original surface.
Retopology systems are very effective in the presence of consistent models or if there are no clear discontinuities. Indeed, the lack of characteristic CAD modelling tools makes it almost impossible to define alignments, check conditions of orthogonality, etc...





FIGURES 10 AND 11 Some profile have beene extracted from the raw surface model and used as guidelines in a translation-based modelling approach.

2.3.2.2. Mesh on the cloud

In an architectural survey made with 3D scans, models consisting of millions of points are acquired in a short time. These are extremely difficult to manage in software environments that are not specifically designed. However, recently various plug-ins have become available that enable even large point models to be visualized in 'traditional' modelling environments. The operations that can be done on the point models are limited, and yet fundamental because they allow the original data and the deriving models to be visualized in the same software, and therefore to check at every step the congruency and accuracy of the model under construction and the point model. We have defined this approach "mesh on the cloud". The main advantage is given by the fact that triangulation – which is a time-consuming process – is not necessary and the surface modelling is based directly on the point cloud. In addition, it can be done using the most common tools. On the other hand, in some cases it has proven problematic to correctly single out the snapping points for the modelling. The "mesh on the cloud" modelling approach is indeed particularly advantageous for large surfaces with scant decoration.

2.3.2.3. Modelling using profiles

Every surface can be considered as being generated by the translation or rotation of a director curve with respect to a generator curve. (Brevi, 2004) This is the most classic approach adopted in 3D modelling which, in the architectural sphere, derives its initial information from two-dimensional representations (plans, sections, elevations): to give a simple example of this, the outline of a cornice is defined by translating one of its (generator) sections along the (director) line of the wall. The generator curve usually derives from a vertical section of the room, and the director curve from the plan (horizontal section). It is evident that in order to be able to model the cornice in question, it is indispensible to have a vertical section of the location that crosses it. The laser scanning survey potentially enables us to know all the necessary curves which can be vectorized each time by suitably sectioning the point model or the deriving triangulated surface [Vaughan, 2012; De Luca & Al., 2007].
More complex surfaces can be generated by translating long polygonal, curved or mixtilinear profiles.

In depth: 'in' and 'end' profiles

Some surfaces can also be considered to be generated by translating an 'initial profile' that transforms into an 'end profile', following a pair of guidelines that define it in the orthogonal direction to that of translation. For example, the vaults in the zone of the "Arches of the Virgin" and the *Katholicon* have been modelled in this way. A Coons surface is indeed a bicubic surface interpolated between four edge curves, which can be general space curves; it passes through the vertices and each side, ensuring the correspondence of the whole outline of the generated surface. The number of subdivisions of the edge curves is defined by the operator and it can be changed later to verify the degree of detail. The interpolation performed by the Coons algorithm, nevertheless, does not guarantee that the new mesh is most faithful to the surveyed data. Hence, it proved indispensible to make a careful visual check and adapt the remodelled surface to the triangulated surface by projecting the first onto the second. This operation was initially realized by manually moving the single vertices and then performed in a more efficient manner with an automatic system.

2.3.2.4. Blocking out

In order to model a large and intricate space like the monumental complex of the Holy Sepulchre it was fundamental to pre-analyse the forms so we could organize the successive workflow. Therefore, the first approach to modelling the various portions consisted of studying the main volumes so as to obtain extremely simplified models.

At higher degrees of detail, in particular for models of considerable size, difficulties inevitably arise linked to the visualization and exploration. A solution to the problem can be obtained by differentiating the degree of detail for the elements observed closer up and described in a more realistic way, and for those further away, which are more diagrammatic.

FIGURE 12 A mesh model, made by triangular surfaces obtained by a triangulation process of the point cloud (left) and a NURBS model after a re-modelling process: in spite of some loss of small details, a more complex topological relationship can be defined.

FIGURE 13 View of the data acquired all around the *Basilica*.

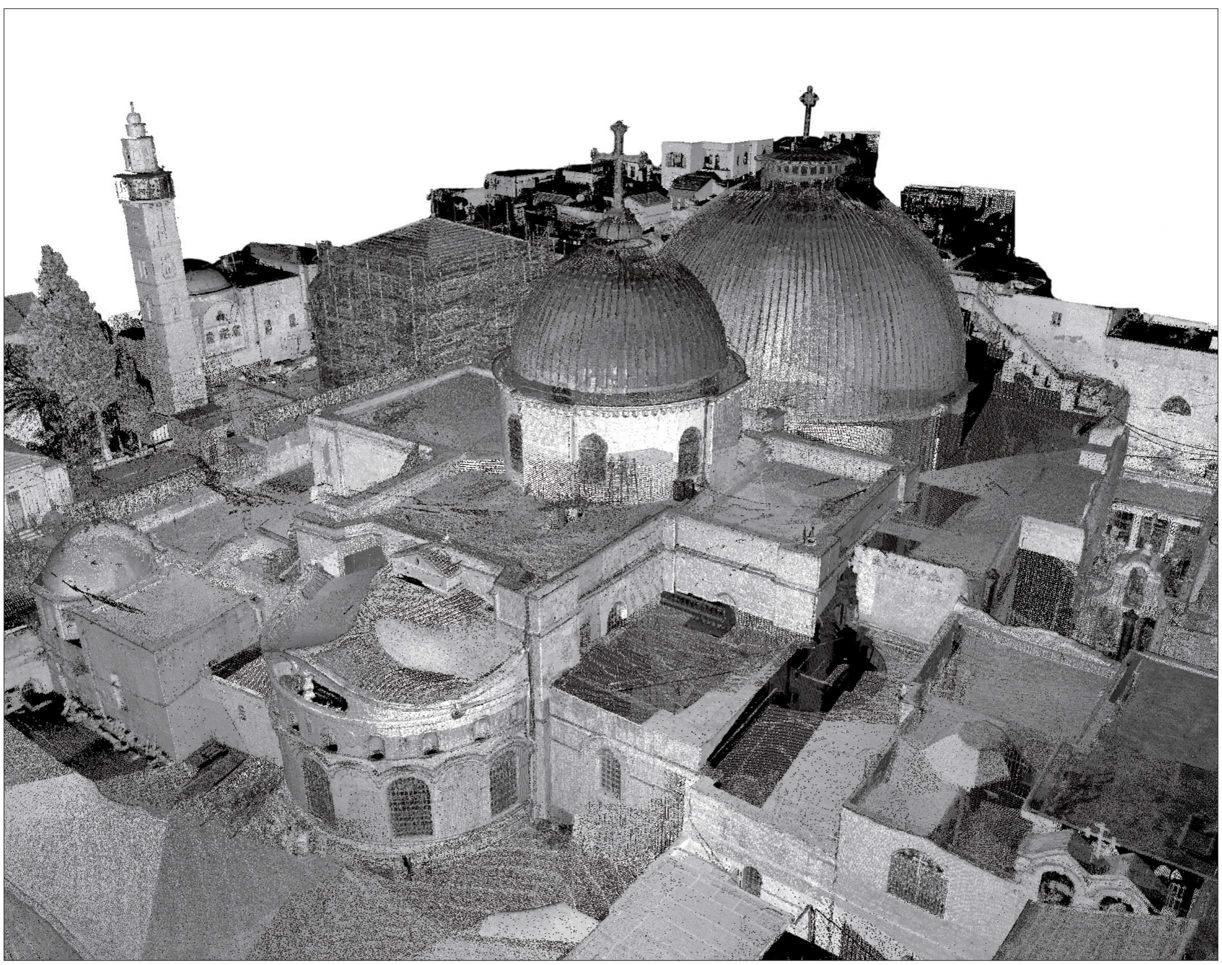


FIGURE 14 A blocking out approach in modelling the *Aedicula*: starting from a very simplified model, small details are progressively added.

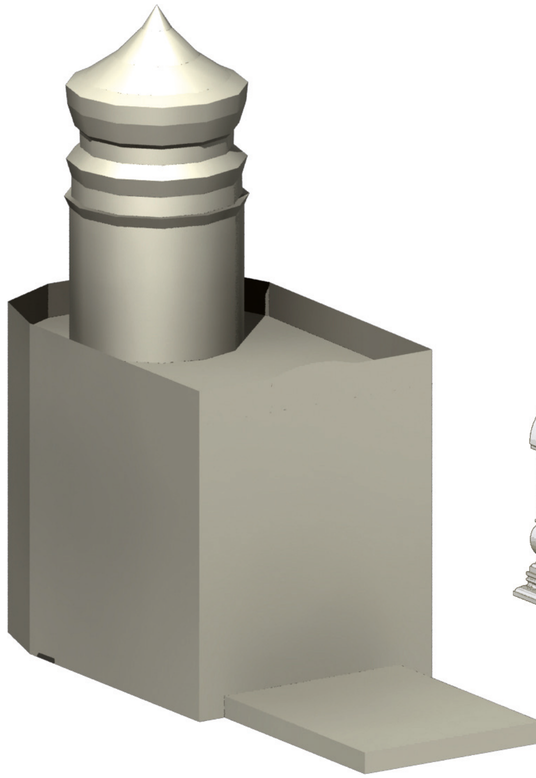
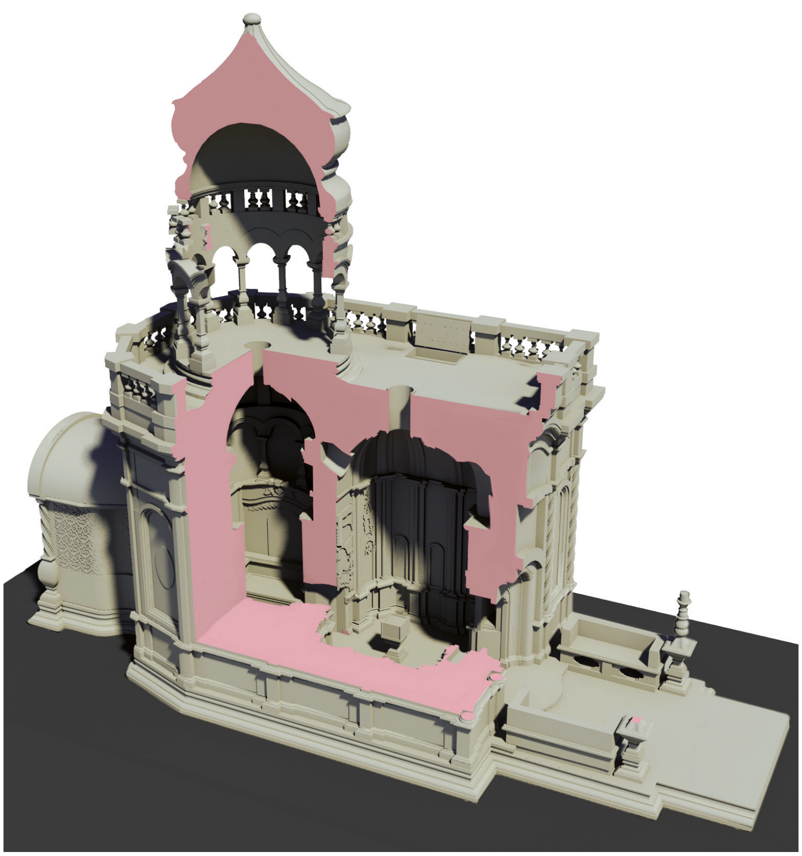


FIGURE 15 *(below)* View of the inside and outside of the 3D model of the *Aedicula*.



2.3.3. State of progress in modelling and future prospects

Over the three survey campaigns, the three-dimensional data acquisition extended to the whole of the Holy Sepulchre complex. Thanks to the technical characteristics of the tools used, at the same time we were able to survey buildings and structures not directly concerned by the studies underway. Thus we were able, for example, to survey the whole width of the street marking the western edge of the complex, the surrounding buildings and the roofs in a large area around the church, up to the minaret on the Omar mosque. Hence, we acquired an enormous database, which at first was just used for the structures analysis considered in the seismic risk vulnerability analysis (see the Survey Chapter).

In a subsequent phase, we pinpointed 3D modelling as a tool that could be the basis for a complex communication project aimed at the variegated target of visitors to the monumental complex. The high resolution and accuracy of the data available has led us to try out different modelling approaches, test new software that has become available during the research, and, after various attempts, define the level of detail with which it seemed correct to represent the building.

In this connection, it is important to underline our choice to model the *Aedicula* in a different manner to the rest of the monumental complex. We concentrated the first tests on the small sacellum, which is interesting owing to its rich decoration and the significant deformations caused by earthquakes and fires. Therefore, we decided to ignore the deformations of the stone cladding and render the geometry of the *Aedicula* with the 3D model after calculating a triangulated model from the surveyed points. The first illustrates the original building, at least in its last configuration, while the second documents its present state, with the numerous oil

lamps that adorn it and the metal support structures surrounding it.

For the rest of the building, the non-negligible limits of managing the hardware for a high-resolution model meant we had to set a lower degree of detail, even though no geometrical schematization was introduced: the columns are not cylinders, the irregular layout and outline of the barrels of the cross vaults reflect the real configuration of the spaces, and the points of the arches correspond to reality. Instead, for the moment we have not modelled the bases, capitals and cornices which may, nevertheless, thanks to the approach followed, be detailed subsequently, or rendered with texturing techniques.

The model completed to date concerns the *Rotunda*, with the *Aedicula* in the centre, the *Katholicon* and the so-called transept of the Virgins. We hope that the significant experience gained to date may be useful in order to complete a model of the whole complex. This in turn could lead to the creation of new educational/entertainment tools to guide visitors and pilgrims, as well as virtual visitors and scholars, in finding out and understanding spaces that they can observe and explore and intuitively link to the enthralling historical events and religious tradition of the site.

FIGURE 16 A view from the front of the *Aedicula*: the final model represents the architectural structure and the sustaining steel beams as well; only decorations as lamps and candles were disregarded.

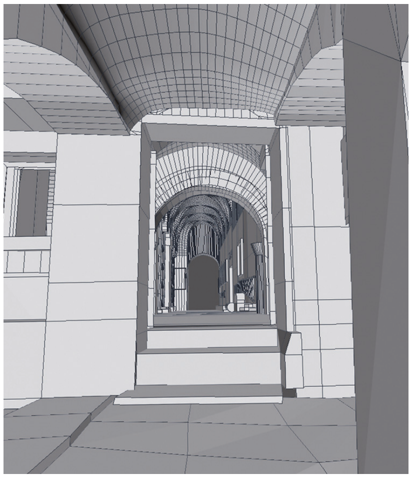
FIGURE 17 View of the *Aedicula* and the *Rotunda*.

Opposite page:

FIGURES 18-24 Wireframe views of the 3D model.

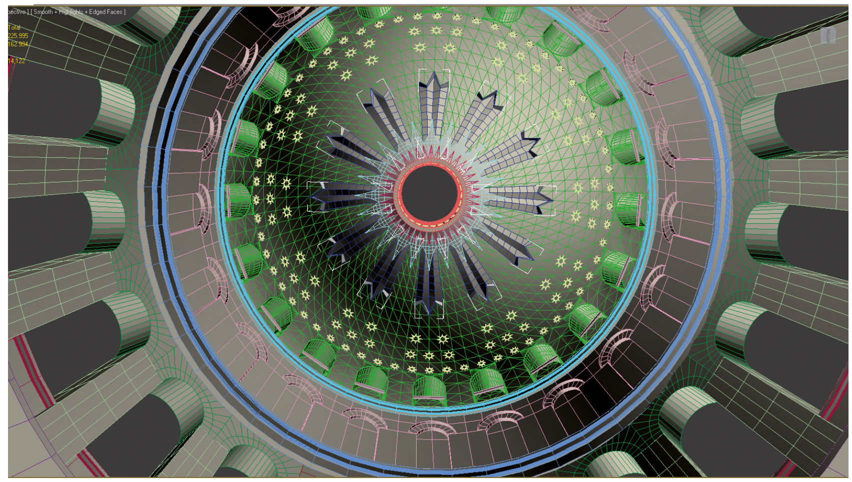
Following pages:

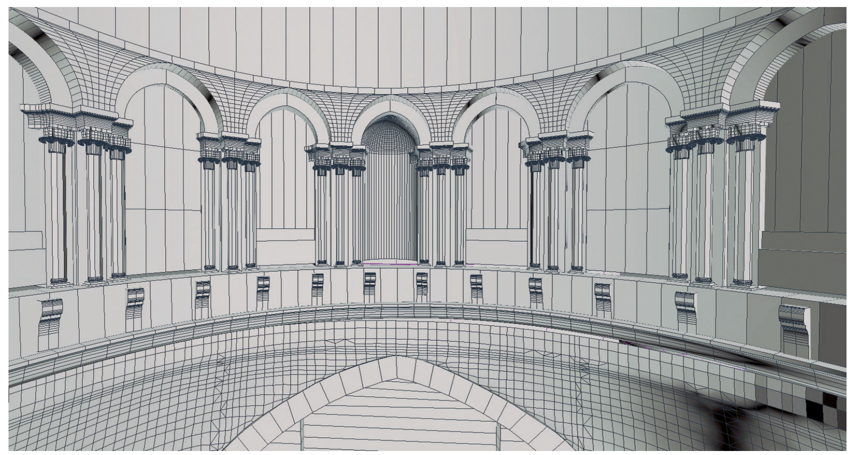
FIGURES 25-28 Renders of the 3D model, showing a not uniform level of detail: in the modelling, the definition of the structural elements was considered a priority and the specific decorations of the individual capitals, frames and bases were neglected. The rendering setting required a lighting study to present the spaces in an effective way.
The images represent the vault of the *Katholicon (upper left)*, the so called Arches of the Virgin area *(low left and right)*.

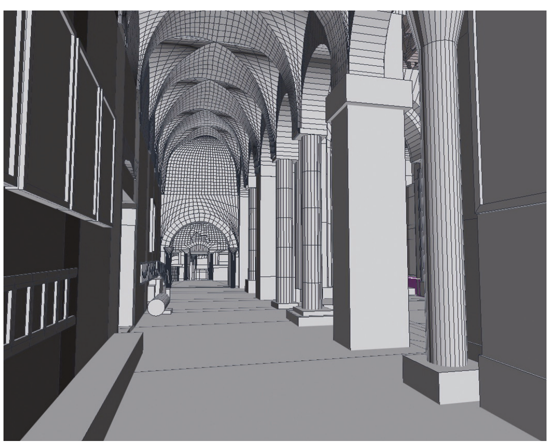


Above: a passage to the *Katholicon*

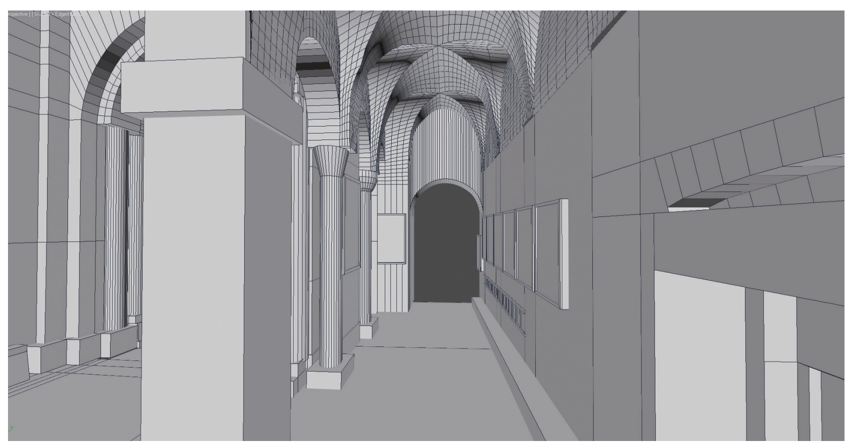
Right: the vault of the *Rotunda*

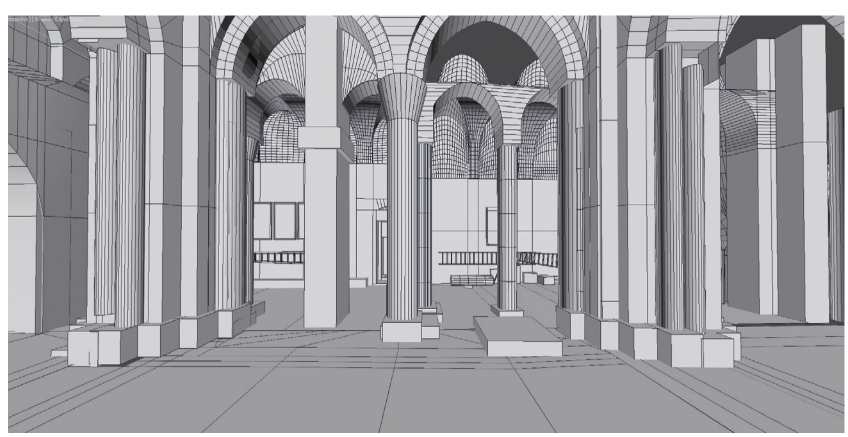






Above and right: the area named "Arches of the Virgin".
Architectural elements are here represented with a low level of detail.





EXAMPLE OF MODELLING WORKFLOW: THE NAVE OF THE *KATHOLICON*

1

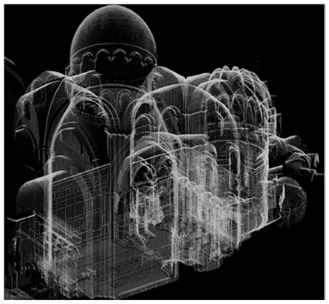


FIGURE A *Point model of the central nave.*

Considering the great quantity of collected data and the consequent difficulties in dealing with it all together, here is an illustration of the procedure followed to model one of the thirty subprojects that the whole monumental complex of the Holy Sepulchre was divided into: the central nave of the *Katholicon.*

The initial data was the point cloud acquired with 3D scans. The oversampling owing to the large number of scans performed to obtain the most complete possible documentation of the spaces was eliminated by decimating the data. Thus the average resolution of the point model was around 1 point/cm (Figure A).

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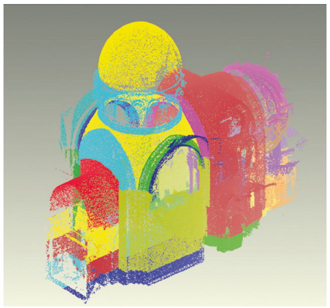

FIGURE B *Segmentation of the point model.*

Prior to the actual modelling itself, two operations were carried out: the data was translated close to the origin of the reference system (the reference adopted previously, as usually is the case in topography, was north-oriented and with a false origin fixed in a vertex of the topographical control network) and the unit of measurement converted from metres (the unit of measurement always used in topography) to centimetres. The aim of both the transformations was to enable the best control of the modelling tools and a suitable level of precision. The whole model was then further segmented manually to pinpoint homogeneous portions from the geometric, architectural or structural point of view. Segmentation makes it easy to manage the data during modelling: hence it was possible to visualize the parts we were working on without any obstructions or having to use too many hardware resources (Figure B).

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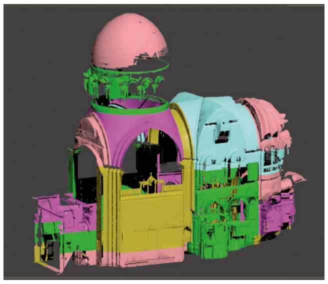

FIGURE C *Triangulated surface model.*

The whole subproject relating to the *Katholicon* was then triangulated; the various parts were saved in single files, and renamed using brief descriptive features (Figure C).

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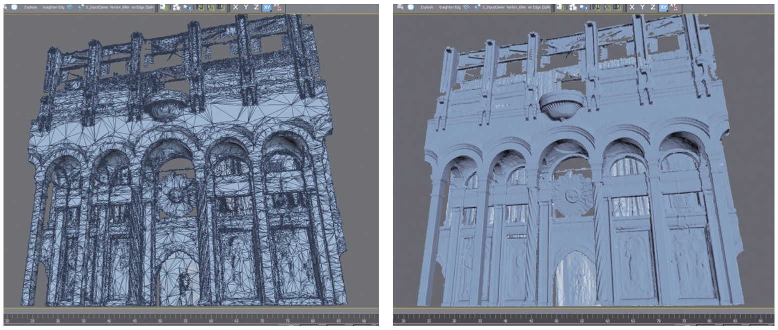

FIGURES D AND E *Above: example of a surface model at the original resolution. Below: simplified surface to optimize visualization during the elaborations.*

The subsequent modelling phases were performed using 3ds Max. Thanks to this software the mesh can be optimized in a non-destructive manner by adjusting the level of detail. By reducing the number of triangles used to describe the surface, the level of detail diminishes; nevertheless, the algorithm used optimizes the reduction and dimension of the new triangles while keeping the forms as legible as possible. In any case, the original level of detail is not lost and it is always possible to go back to the maximum resolution visualization (Figures D and E).

An additional module in the software means that section planes can be translated according to various positions and lies, thus enabling to explore the hidden elements of the model and extract its characteristic sections. (Figure F).

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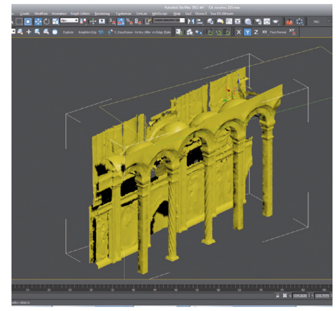

FIGURE F *Visualization of a portion of the model, outlined by moving cut planes.*

Then we performed the 'blocking out' phase: this is an intermediate phase between the high-resolution mesh and the final model. It enables the creation of the medium-resolution mesh to be planned as best possible and can be used directly should a very low level of detail be needed. In this modelling phase, all the non-structural elements were left out, and we only considered the masonry surfaces. (Figure G).

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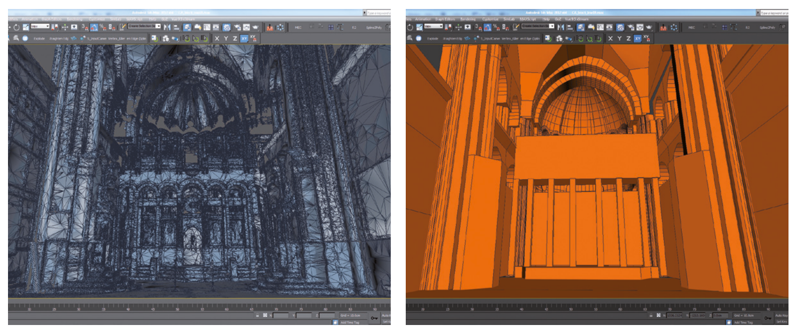

FIGURES G *Above: model triangulated automatically (reduced level of detail as described above). Below: blocking out the same area.*

Last, we performed the modelling with the highest level of detail, using the different techniques illustrated in the chapter on modelling. (Figure H).

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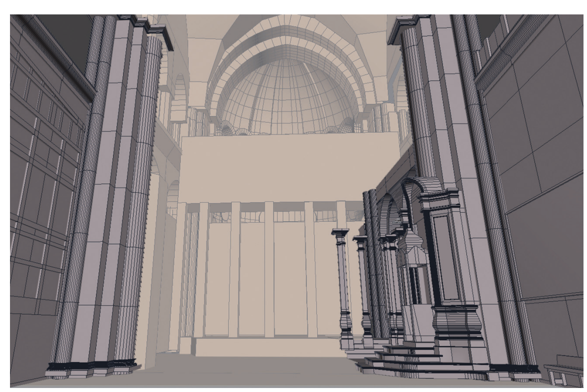

FIGURE H *View of the final model partially superimposed onto the low-resolution model.*

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FIGURE 29 Small crosses carved by medieval pilgrims on the wall of St. Helena Chapel.

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FIGURE 30 Detail of a console on the wall of the Ethiopian convent, above the roof of St. Helena Chapel.

Part two

Chapter IV

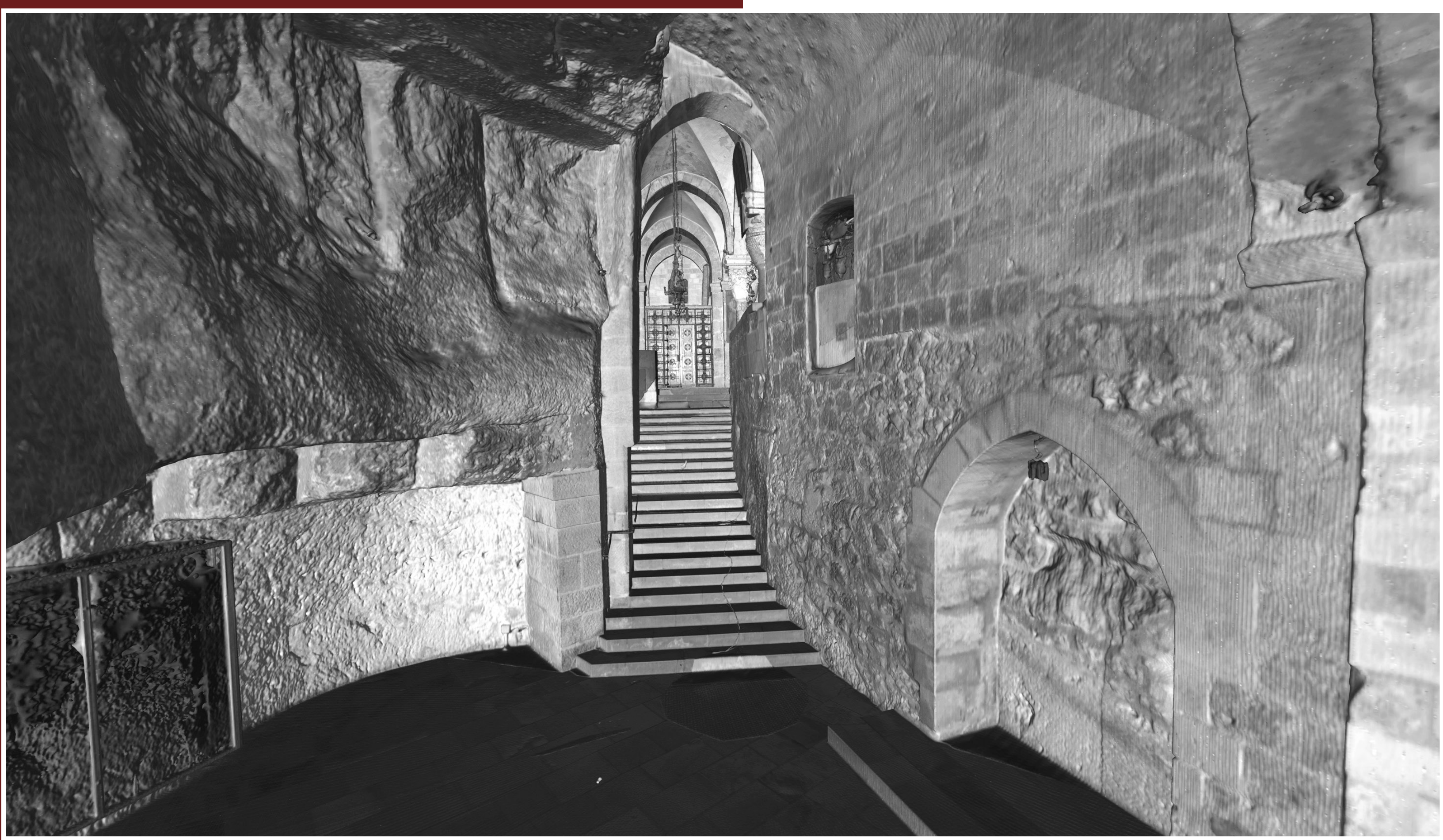

FIGURE 1 3D mesh of the stairs leading to the Chapel of the Invention of the Cross. The high level of detail highlights the different textures of the wall surfaces (L. Fiorini, from point cloud surveyed by Tucci-Bonora).