# MULTI-SCALE MODELING OF THE BASILICA OF SAN PIETRO IN TUSCANIA (ITALY). FROM 3D DATA TO 2D REPRESENTATION

**Filiberto CHIABRANDO[1], Dario PIATTI[2], Fulvio RINAUDO[2]**

[1]Politecnico di Torino, DINSE
Viale Mattioli 39, 10125 Torino, Italy, filiberto.chiabrando@polito.it

[2] Politecnico di Torino, DITAG
Corso Duca Degli Abruzzi 24 , 10129 Torino, Italy, dario.piatti@polito.it, fulvio.rinaudo@polito.it

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**Abstract**:
*The Basilica of San Pietro is a Romanic architecture located in the municipality of Tuscania in the Lazio Region about 100 km far from Rome. In 1971 the apse dome collapsed during the earthquake and the important fresco of a Christ Pantocrator was destroyed. In 1975 the dome was reconstructed using reinforced concrete. In 2010 an integrated survey of the Church has been performed using LiDAR techniques integrated with photogrammetric and topographic methodologies in order to realize a complete 2D documentation of the Basilica of San Pietro. Thanks to the acquired data a complete multi-scale 3D model of the Church and of the surroundings was realized. The aim of this work is to present different strategies in order to realize correct documentations for Cultural Heritage knowledge, using typical 3D survey methodologies (i. e. LiDAR survey and photogrammetry). After data acquisition and processing, several 2D representations were realized in order to carry out traditional supports for the different actors involved in the conservation plans; moreover, starting from the 2D drawing a simplified 3D modeling methodology has been followed in order to define the fundamental geometry of the Basilica and the surroundings: the achieved model could be useful for a small architectural scale description of the structure and for the documentation of the surroundings. For the aforementioned small architectural scale model, the 3D modeling was realized using the information derived from the 2D drawings with an approach based on the Constructive Solid Geometry. Using this approach the real shape of the object is simplified. This methodology is employed in particular when the shape of the structures is simple or to communicate new project ideas of when, as in our case, the aim is to give an idea of the complexity of an architectural Cultural Heritage. In order to follow this objective, a small architectural scale model was realized: the area of the Civita hill was modeled using the information derived from the 1:5000 scale map contours; afterwards the Basilica was modeled in a CAD software using the information derived from the 2D drawings of the Basilica. Finally, a more detailed 3D model was realized to describe the real shape of the transept. All this products were realized thanks to the data acquired during the performed survey. This research underlines that a complete 3D documentation of a Cultural Heritage during the survey phase allows the final user to derive all the products that could be necessary for a correct knowledge of the artifact.*

## 1. INTRODUCTION

The importance of the Basilica of San Pietro in Tuscania has placed the attention to the issue of the integration of different survey techniques such as LiDAR, photogrammetry, total station and manual measurements with particular interest to the LiDAR technique in order to build up a complete and multi-scale documentation of the site. The already achieved experiences (e. g. [1]) demonstrate that only a suitable integration between the available technologies allows a complete and exhaustive collection of metric information to be achieved. The acquired data can be used to produce a correct documentation such as traditional 2D drawings (plans, sections and façades), 3D models and videos able to transmit the correct shape of the surveyed object to different skilled people. The evolution of LiDAR and digital photogrammetry techniques forces to move the selection of the needed information from the field to the office, after all the measurements have been already done. This fact speeds up the acquisition phases but drastically increases the time needed to extract useful information with the different degrees of detail and accuracy required by the different considered representation scales. Both LiDAR technique and digital photogrammetry allow fast acquisitions of a big amount of metric information which can be used to produce 2D and 3D models at different nominal scales [2,3,4,5]. At the end of the acquisition phase, a metrically coherent archive of information can be realized from which geometric and semantic information can be extracted at different scales up to the maximum scale allowed by the employed acquisition techniques. In the proposed example the 2D drawings and the 3D models were realized at the maximum possible scale for some interesting details of the structure; more general 3D models and videos where also produced, which are useful to explain to visitors the relationship between the land context and the single architectural artifacts. In the proposed approach, both raw LiDAR data and the photogrammetric data are shared besides the final products, in order to allow possible integration and deeper information extraction by other interested users.

## 2. HISTORICAL BACKGROUND

The survey of the site of San Pietro in Tuscania gives the possibility to verify the multi-scale approach used to build up a metric and semantic archive of information acquired by using LiDAR and digital photogrammetry techniques. The San Pietro site is composed by different structures with heterogeneous architectural styles realized over some centuries for historical reasons: the Basilica, two medieval towers and a palace used in the past as Bishop main site. The Basilica is a Romanic style building with three naves: the most ancient nucleus (XI cent. a. C.) is represented by the crypt, which was realized under the actual settlement of the basilica, the apse and the first part of the naves. It is surrounded by the ruins of the ancient Bishop citadel and it is placed on the top of the Civita Hill (Figure 1 left) in a rural area outside the current urban area of Tuscania; the Basilica was the religious center before the gradual abandonment of the area. In the XIII century the Basilica reached the actual shape: the three naves were protracted and the main façade was realized by using a monumental decorative apparatus (Figure 1 right). In 1971 an earthquake caused the collapse of the apse half-dome (Figure 2 center and right) and the damage of a medieval fresco representing a Christ Pantocrator (Figure 2 left).

**Figure 1:** A view of the Civita Hill (left) and the main facade of the Basilica di San Pietro (right).

In 1975 a first restoring intervention fitted a concrete half-dome in order to stop the deterioration of the Basilica. During the earthquake all the other structures were subjected to non-structural damages; therefore, after the restoration, the site was re-opened to the public.

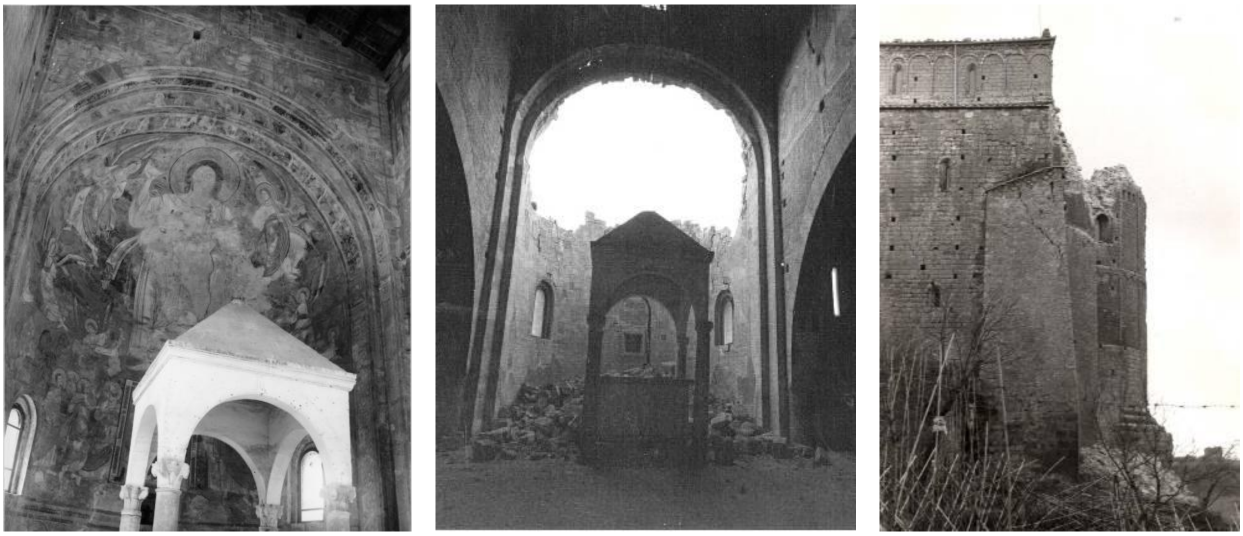

**Figure 2:** The old fresco (left) and the apse after the earthquake in 1971 (center and right).

## 3. THE 3D SURVEY OF THE BASILICA

The data acquisition was planned considering a complete survey of all the structures of the site. The shape and the size of the details to be recorded suggested the authors to plan all the acquisition phases by considering a final accuracy of 2 cm. Therefore, the following aspects were considered:

- a control network was realized by means of total station and rigorously adjusted in order to estimate the final accuracy on the vertexes. All the possible distances and horizontal angles were considered in order to have redundant measurements and a local coordinate system was established;
- the LiDAR acquisition stations were planned in order to reach the minimum number of locations and to realize a complete point cloud acquisition. Also the resolution of each scan was fixed to properly describe the different surfaces of the buildings and structures;
- natural and ad-hoc signalized points were chosen on the surface to guarantee a good registration of the acquired point clouds. That points were surveyed by using the total station to connect all the acquired LiDAR point clouds in the local coordinate system;
- each point cloud was integrated with the radiometric information coming from the digital images in order to have colored point clouds; moreover, some overlapping images were used in order to integrate LiDAR data by using a photogrammetric approach.

### 3.1 The control network

The main role of the control network is to establish a unique and stable coordinate system able to satisfy all the accuracy requirements for a complete architectural 3D survey. In the area of the Basilica of San Pietro a total station survey was realized according to the shape of the object: the vertexes of the network were placed in order to have the maximum visibility of the other vertexes. Each point of the control network was documented by means of witnessing diagrams to allow future use of the same network. The vertexes were materialized and hidden in order to preserve them from natural and men actions. The obtained control network was composed of 12 vertexes: 5 outside and 7 inside the Basilica. The distance and angle measurements were realized by using LEICA total stations (TS02 and TS06) following accurate procedures in order to eliminate systematic errors and gross errors. After the control network adjustment the mean square error (m. s. e.) of all the estimated coordinates is less than 5 mm, therefore suitable for the survey purposes.

### 3.1 Integration surveys

All the points useful to orient the overlapping images and to register the point clouds were materialized by using reflective targets (pasted on the structure) or by using natural points in order to establish a robust connection between LiDAR and photogrammetric data. By using the total stations the coordinates of those points were measured simply by using single collimations from the vertexes of the control network. The surveyed control points were integrated with a set of check points useful to verify the real achieved accuracy after the modeling phase at the end of the work. With the same instrumentation and techniques all the portions of the site without special requirements for modeling (e.g. low level of details) were measured by selecting only the information useful to make a complete 3D model at the selected scale. Also the geometric elements necessary to describe the upper parts of the towers were measured by using the above described methodology in order to integrate the LiDAR survey.

### 3.2 LIDAR acquisition

The LiDAR acquisitions were performed by using the RIEGL LMS-Z420 scanner. In order to carry out a complete survey of the Basilica, fifteen different scan positions were planned and realized: seven outdoor and eight indoor to record all the required details of the building. Each scan was previously verified in terms of overlaps between adjacent scans in order to reach an overlap of at least 30%, which is necessary to guarantee an accurate registration of the scans. Moreover, several reflective targets were positioned in such a way that at least three of them were visible for each scan. Each acquired point cloud was integrated with the digital images acquired by using a calibrated camera placed on the top of the scanner. In this case a CANON EOS 5D camera with a 24 mm focal length optics was used. The overlap between adjacent images acquired by the camera was fixed in order to ensure a correct and complete radiometric mapping of the point clouds. To document the LiDAR acquisition phase, each scan was described by means of a table which contains the needed information to understand the content of the scan.

## 4. 2D DRAWING AND MULTISCALE 3D MODEL PRODUCTION

First of all in order to obtain a suitable product for the realization of the drawings the LiDAR data were processed. The registration of the fifteen recorded point clouds was realized by using the RISCAN PRO software in order to reach an approximate 3D model of all the acquired surfaces. During this phase all the visible reflective targets were employed to give a preliminary solution, than an ICP approach was used to refine the registration. The first comparisons of the achieved accuracies performed by using the check points show discrepancies higher than expected, therefore a complete compensation of the scans considering indoor and outdoor scan as a block was realized.

**Figure 4:** 3D models of the Basilica of San Pietro.

The six registration parameters have been than re-estimated by using a rigorous least squares approach [1]. After that, the discrepancies on the check points showed values lower than 2 cm.

The editing of the complete point cloud was performed by using the GEOMAGIC Studio software. Automatic and manual procedures were employed in order to reduce the number of points in regular surfaces and to extract the break-lines. During this latter part of the procedure also the points acquired during the total station survey were integrated and, in some cases, manual and photogrammetric measurements were used in order to define the missing details [6,7]. Finally the data were separated in two different models: one of the whole site (which has been modelled at 1:200 representation scale, Figure 4 left) and one of the interior and exterior part of the Basilica (which has been modelled at 1:50 representation scale, Figure 4 right). Both sets of data points and break-lines were used to produce the TIN (Triangulated Irregular Network) surfaces with different resolution.

### 4.1 Realization of plans, sections and facades

The obtained 3D models delivered an accurate description of the surveyed object and where therefore used to extract different kind of representations. 2D drawings are the most required final products and their production by using 3D models always needs a huge cost in term of time and competencies. The first problem to be faced, especially when architectonic scale (e.g. 1:100 or 1:50) have to be used, is the integration of the information in order to build up a correct description of the object. Figure 5 shows the well-known problem between sections extracted from point cloud models and the correct geometry which has to be realized.

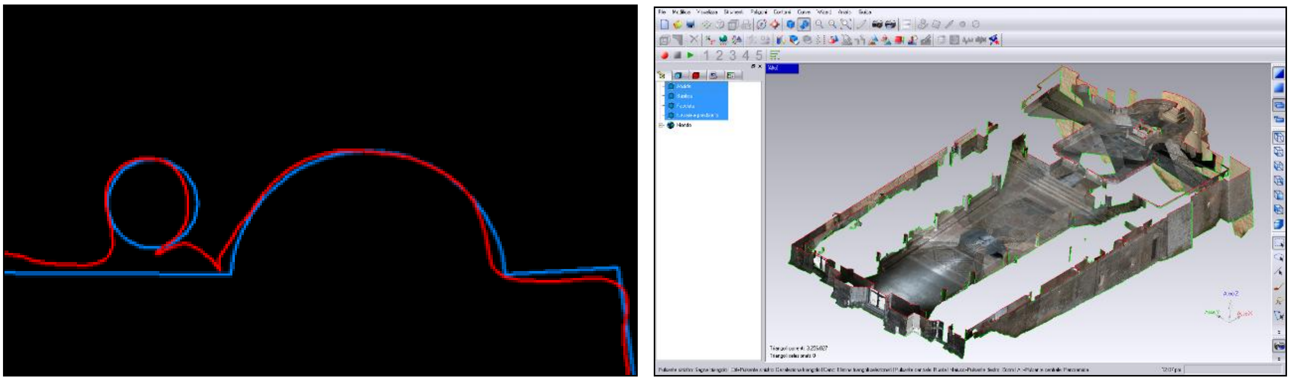

**Figure 5:** Section extracted from the 3D model (red line) and needed model (blue line) (left), horizontal sections generated on the 3D model with the GEOMAGIC Studio software (right).

In order to minimize the number of scans the surveyor has to integrate the foreseen lack of information of LiDAR scans by using other techniques (e.g. manual measurements, total station survey or photogrammetric technique). Obviously a good knowledge of the fundamental of architecture is required to give a satisfactory result. Therefore, the survey team has to be composed of both architecture experts and survey experts, since it is not easy to find all these competencies merged in a unique person. When the interpreted integrations are realized on the 3D model, the generation of 2D drawings can be speeded up and the final results show the advantage of using an integrated approach instead of a traditional one.The user can choose the needed position of the intersecting planes and can produce coherent drawings by actually extracting 2D information from a unique 3D reality (Figure 5 right). When drawings at lower representation scales have to be generated, the operator has to clearly understand which are the details that have to be simplified and to adopt the correct symbols and graphical conventions [8]. In the case of the Basilica of San Pietro an accurate integration between LiDAR data, total station data, photogrammetric data and manual measurements were used in order to produce the final 2D drawings of the building. All the phases, from the measurements to the 2D representation, were conducted by a multidisciplinary team (Engineers, Architects and Historical experts) in order to represent the correct information and to achieve the proper drawings. Two examples of the achieved 2D products are reported in Figure 6: a plan carried out using the section extracted from the LiDAR survey integrated with some manual measurements (Figure 6 left) and a façade realized using the information derived by the LiDAR data integrated with the photogrammetric and total station measurements (Figure 6 right).

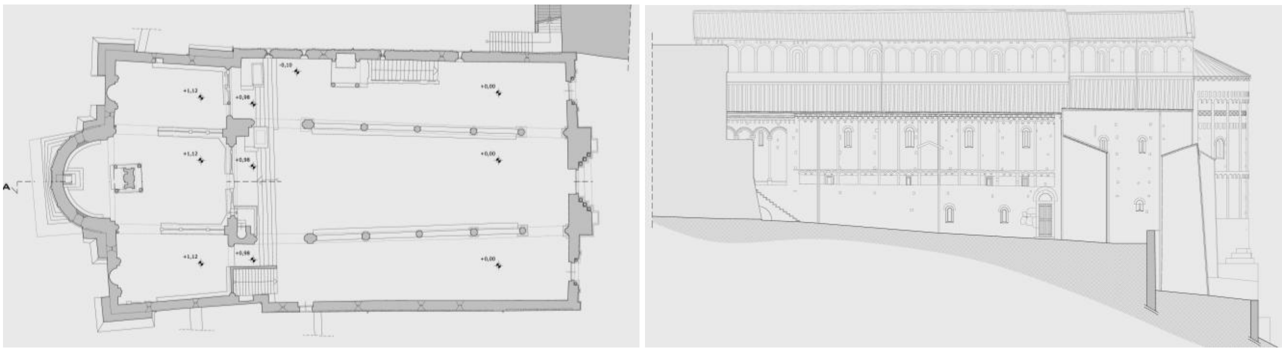

**Figure 6:** Plan of the Basilica (left) and north façade of the Basilica (right).

## 4.2 The urban scale 3D model of the San Pietro site

3D models are not yet a way to produce 2D drawings but are more and more used in order to increase the knowledge of an architecture and to diffuse the achieved results to people which are not used or able to understand 3D reality by means of 2D drawings. The main advantage of a 3D model is the possibility to better describe the spatial intersections and relationships between the architectural elements. Actually, 2D drawings are not able to give a complete idea of the 3D shape of the surveyed object. 3D models allow a direct inspection of the surveyed space to be performed thanks to 3D videos and 3D navigation tools; moreover, the radiometric information gives the user the possibility to simulate a real visit up to all the details as interpreted by the surveyor. The possibility to see also 3D realistic models generated by using photogrammetry allows also the user to integrate or correct 3D models. In the case of the Basilica of San Pietro a multi-scale approach was employed: first of all in order to give an overview of the hill where the Baslilica is located and a first idea of the shape of the architecture, a simplified 3D model at urban scale was realized using the data derived from the 2D drawings and the information of the surroundings derived from the Regional Carthography at 1:5000 scale. This first model was achieved using the 3D Studio Max software (Figure 6 left). Afterwards the realized 2D representations were employed to carry out a simplified model of the Basilica: all the parts of the Basilica were modeled using CAD software [9,10] (Figure 6 right).

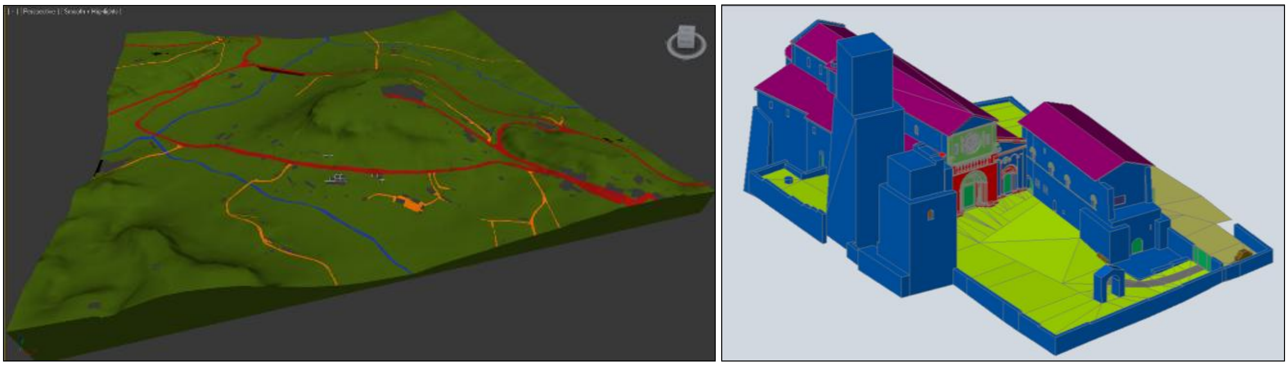

**Figure 6:** 3D model of Civita hill and surroundings (left) and 3D model of the Basilica at 1:200 scale (right).

The buildings were modeled at 1:200 scale considering the conventional contents of this scale: all the 3D information outside and inside the buildings were reduced to simple geometric shapes in order to allow a good comprehension of the space and of the relationships between the different structures of the site. Finally, the 3D model of the Basilica site was inserted into the cartographic coordinate system by using homologous points between the available cartography and the 3D model; in this way, a complete overview of the area was realized (Figure 7 left). Special attention was paid to the use of lights and shadows in order to give a clear view of the different locations of the structural elements inside (Figure 7 right) and outside the Basilica. Also the selection of the correct illumination parameters is a topic which needs experts able to understand the fundamental elements to be underlined for a correct and complete transmission of the achieved knowledge of the surveyed structure [11,12,13,14].

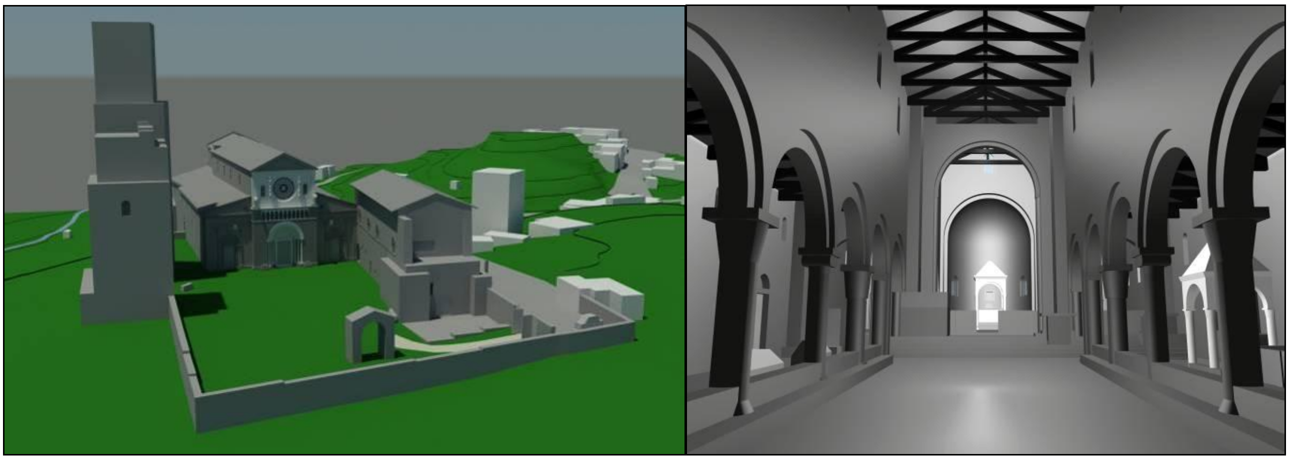

**Figure 7:** 3D urban model (left) and rendering of the Basilica principal nave (right).

### 4.3 The 3D model of the transept of the Basilica

After the realization of the urban scale 3D model, in order to describe with an higher level of detail the shape of the interior of the Basilica, an high resolution 3D model was achieved using the integration between LiDAR data, photogrammetric data and topographic data. The modeling phase was focused on the transept of the Basilica. For this purpose, all the high resolution data were used and several integrations were realized using the data extracted from stereoscopic photogrammetric models in order to recover the hidden parts in LiDAR scans. In this detailed description (Figure 8 left) the light and shadows are of strategic importance to show the results of the survey to the final user. The 3D model phase was conducted using different software: the GEOMAGIC Studio software for the LiDAR data processing and editing on the mesh; the Rhinocerous software for data integration and merging and finally the 3D Studio Max software for the rendering phases. In order to speed up the navigation inside the model the amount of data was actually reduced by only mapping the relevant surfaces with the high resolution RGB images (Figure 8 right).

**Figure 8:** Rendering of the transept (left) and textured rendering of a painted wall (right).

## 4.CONCLUSIONS

3D models are today the best answer to the complete knowledge of architectural artifacts. The possibility to build up 3D models and videos with a selected level of information is one of the main advantages of this kind of approach. One important aspect to be pointed out is the time needed to produce this kind of 3D models. In our case, after a week necessary for data acquisition, more than three months of two skilled operators were spent in order to reach the presented results. The above described experience was developed by using a rigorous approach: first, all the data were documented in order to allow a possible re-use and/or integration by other surveyors; then, several survey techniques were used in order to take the best advantages from each of them; moreover, a check of the final accuracy was realized in order to verify the suitability of the 3D geometric model; finally, the data interpretation and the final products were realized by people with special skills on metric survey and architecture. It is worth remembering that the needed data for a correct modeling phase are related to the level of detail of the final model to be obtained. Therefore, the survey operations have to be designed accordingly to the level of detail of the requested 3D model. For the creation of a simplified 3D model a complete LiDAR survey is not necessary, since a traditional topographic survey with some photogrammetric integrations could be enough. On the contrary, if an high resolution model is requested, a complete survey of the object using suitable survey techniques is necessary in order to accurately describe the shape of the object. Finally, in order to create photorealistic rendering and real videos of the investigated area, it is necessary to plan and realize a complete image acquisition campaign.

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