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Architectural analysis and 3D reconstruction: a case study of Leopoli – Cencelle in Italy

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Abstract

This paper focuses on the integration of laser scanning, GPS and orthophotography data in the study of the medieval church of Leopoli – Cencelle. Its main purpose is to present a 3d model and the methodological approaches used in the archaeological analysis. The site of Leopoli – Cencelle is in the area of Tarquinia (province of Viterbo), approximately 70 km to the north of Rome. The town was founded by Pope Leo IV (847 - 855) during his eighth year of pontificate, i.e. on August the 15th 854 AD; the remains of a 740 m long wall with three gates and seven towers are still visible on the top of the hill (at el. 160 m ASL). Since 1994 the Department of Medieval Archaeology and Topography at the University “Sapienza” in Rome has been carrying out archaeological excavations under the directorship of Prof. Letizia Ermini Pani and Prof. Francesca Romana Stasolla. The archaeological excavations brought to light part of the bell tower and the crypt of a church with three naves, which was built in the 12th century, and is one of the most interesting structures at the site. The topographic team of the University surveyed these remains using both laser scanning LEICA HDS 3000 and orthophotography. Laser scanning data have been collected in several scans with a resolution of about 5 mm; orthophotos have been performed with commercial software and digitalized using CAD software. All data were positioned on UTM world standard coordinate system using LEICA GPS and a digital elevation model (DEM) was generated. The 3D model of the building was created according both to these data and to the archaeological information gathered from the excavations; it is presented here along a discussion on the relevance of these methodological approaches in the archaeological analysis.

***Key words**: GPS, 3D reconstruction, laser scanner*

1 Introduction

The archaeological site of Cencelle is located in the northern part of the region Latium approximately 12 Km north-east of the harbor of Civitavecchia (see fig. 1). The town, which was named Leopoli in honor of its founder Leo the fourth (847-855 AD), was built ex novo and was officially inaugurated in the year 854 AD. Main aim of the new foundation, according to the will of the Pope, was to replace the Roman town of Centumcellae, a very important harbor, which was abandoned and considered as being too insecure due to the continuous incursions of the Saracens (see fig. 2). Due to the contribution of a *Magister Militum* to the new urban project, the town gained clear military features: tuff ashlar masonry walls surrounded the flat top of the mound which was provided with natural defences[1].

Since 1994 an archaeological team has been carrying out archaeological excavations at this site on behalf of the department of Medieval Archaeology and Topography at the University “Sapienza” in Rome under the directorship of Prof. Letizia Ermini Pani and Prof. Francesca Romana Stasolla, and it has been organizing several research projects focusing towards the features of the surrounding territory[2]. During these years archaeologists brought to light large and relevant sectors of the urban area, they were able to point out several late medieval structures and to prove the existence of a political and a religious centre at Cencelle.

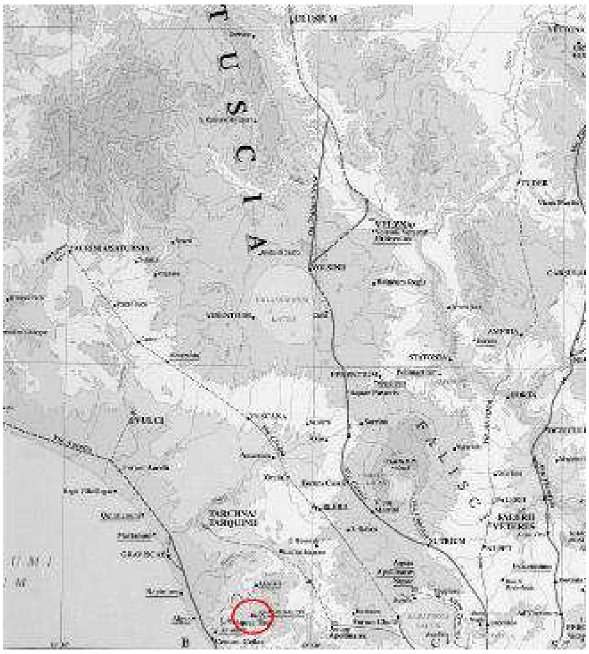

Figure 1. Plan of northern Latium.

[1] Large parts of these walls are still visible as they were inserted in the later late medieval trachyte walls.

[2] This research is carried in cooperation with the University at Chieti (Department of Medieval Archaeology) and with the French School in Rome.

During the last campaigns a large church was brought to light: the apse of the church was built against the town-enceinte and the façade was oriented to the north. This structure, which dates to the end of the eleventh century AD, was constructed with well-cut squared tuff small blocks and is typologically very similar to the church of San Pietro a Tuscania[3]. Due to the relevance of this specific structure, it became the focus of structural and topographic research activities, which were carried by a topographic team of the University “Sapienza” in Rome[4].

The methods employed in these analyses follow the founding principles of ancient topography. As a matter of fact, this discipline, which was born with the aim of mapping the historical elements on the Italian territory, has, since the beginnings, a tight bond to technology and consequently to the

[3] Letizia Ermini Pani, “Cencelle” in “*Lo sguardo di Icaro, le collezioni dell’aerofototeca nazionale per la conoscenza del territorio”*,Roma, 2003.

[4] The team was selected in order to develop a cooperation project during the period 2006-2008 between the University “Sapienza” in Rome (Department of Historical, Archaeological and Anthropological Science) and Leica-Geosystems. Members of this research team are: Giulia De Persiis, Manuela Manfrè, Giovanna Liberotti, Daniele Nepi, Ambra Naspi, Annalisa Falcone, Alessandro Blanco, Alessandro Vella, Fabrizio Danieli, Cristiana Ruggini, Michela Danesi, Veronica Galluzzi. The present author coordinates the activities on the field and in the computer laboratory. Special thanks are due to Gabriele Del Fra, person in charge for Leica Geosystems in Italy and to his collaborators Antonello De Amicis (TPS), Giampaolo Servodio (GPS), Federico Uccelli e Michele Curuni (laser scanner).

developments of survey technologies and data analysis.

Both technologies and competences at the point, and a deep "humanistic" knowledge of the archaeological problems mark the history of ancient topography. This binomial feature, the humanistic and the scientific, which characterizes this discipline, should be mirrored by researchers and scholars in this field and mainly should be part of their training. Hence technological innovation and archaeological analysis join a third and basic element: education. In fact, the activity presented here shows not only that a group of post-graduate and PhD students is able to "learn" new competences and apply them, but also, that they can gain the professional know-how to a level which is the current requested standard. This knowledge provides the students with the necessary tools for their professional career in archaeology. However, it should be pointed out here that the new technologies should be used in a critical way, knowing the premises and goals of a project, checking the procedures, choosing methods and instruments, which suit better a specific need. The use of a laser scanner in the analysis on the medieval church at Cencelle provides a very useful example for the risks which are connected to the introduction of new automatic survey procedures.

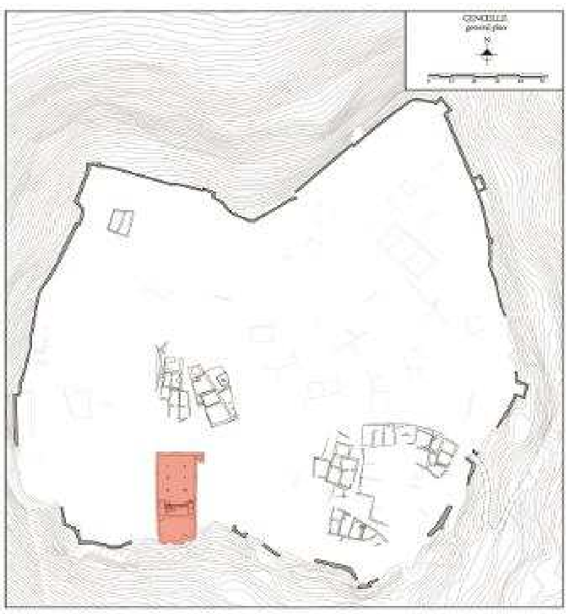

Figure 2. Plan of Leopoli – Cencelle.

As it will be clear from the description of both procedures and of their results, the main aim of this research was to create a 3D model using secure and precise data obtained both by laser scan and by other sources of information and documentation[5]. The use of the laser scanner shows promises: it can potentially solve all problems[6] related to precision measures and represent objects whose graphic documentation was previously extremely difficult, usually incomplete and disappointing. If the researcher analyzes the data obtained from the laser scan without an analytical approach, he tends to believe that the laser scan solves all problems of representation. But, due to the fact that representation is only a mean of understanding the structure, it is not important to produce a "nice" or an "impressive" model, rather it is important to comprehend the structure in its architectural and historical contexts. No machine would ever be able to replace the human eye-brain connection.

In conclusion the structure which is the focus of the research should "suggest" to the scholar the best methods to document its architectural features; an architectural survey is like a tale: as it is not important whether a tale is typed or hand written, rather its content is relevant, in the same way, the technologies used in a survey are not basic, rather the result (i.e. the survey itself) is decisive. Hence, once the laser scanner as well as other instruments will be a common tool for archaeological research, the role of the archaeologist, who is able to control them, will be even more decisive.

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[5] Due to the features of the structure and its volumetric elements the use of the laser scanner has achieved its best results in documenting the crypt, a well defined and preserved volume.

[6] One of these is the documentation of the vertical dimension of the structures.

2 The field survey

The aim of this project is to highlight the need for the integration between different surveying techniques in order to obtain the best result for a specific context. Assuming that realizing a good graphical representation of an ancient building is an excellent manner to understand its story and that providing a very accurate 3D model of an ancient structure may make it more easily accessible for further research, we choose the medieval church of Leopoli-Cencelle to carry out a 3D model. In fact, studying the design and construction methods of the medieval church of Leopoli-Cencelle suited this purpose very well. Because of the complexity of the structure, completion of this model has required the integration of many different types of measuring devices (hand measuring, total station, orthophotography, GPS, laser scanning) with various kinds of modeling and information software, while measuring as precisely as our instruments would allow. Moreover, the need to transcribe a building into digital models forces the archaeologist to take up a stance on theoretical architectural problems. Therefore, goal of this research is also to point out a method to generate digital models, which includes irregular surfaces: this is usually the shape of the ancient structures, which have been modified by seismic or ground settling actions.

The field work for the project lasted two years, from 2007 to 2009. First, the original 2D plan of the church, which has been drawn by archaeologist during the last excavation campaigns, was high quality scanned, inserted and digitalized in AutoCAD. The analysis of the original drawings was very important during this preliminary phase, as they illustrate the interpretation of the archaeologist. As stated before the original layout of this structure is well preserved while several later construction phases have modified its upper parts. These elements can be well-documented only by means of traditional surveys. A topographic survey has been performed in the church area with a total station Leica TPS 1203, locating points for the perimeter of the church. The data were stored and downloaded in AutoCAD as points. The raster image of the handmade 2D plan was then aligned with these total station points. In this way, the handmade 2D plan built the base for the 3D model. This procedure made us also aware of significant architectural elements which provide good examples of various architectural problems, as the alignment of pillars, columns and semi columns, the position of the entrances and the number of missing steps in the stairway of the presbytery.

Once the geometry of the church's plan was reconstructed, we worked on the prospect of the crypt's northern wall (see fig. 3). The crypt consists of a row of seven arches, placed between semi columns with carved capitals all different from each other. The graphics presented here focus on the three central niches (see fig. 4). The arches at the ends of the wall open to staircases, while the others are closed and host five niches. This wall is well preserved and shows traces of white plaster, while the wall collapse of the presbytery from the upper level in this area provided us with relevant information on the materials used for the conglomerate of the crypt. Due to these elements we have chosen this part of the structure in order to point out several typical architectural features. We measured points all over the wall with total station and we took images of the wall using a Fuji S5 digital camera with a resolution of 12 mega pixels. The images have been orthorectified using specific software and loaded in AutoCAD in order to map the materials (see fig. 5). From this simple but very accurate elaboration we were able to get some interesting preliminary results: first, there was no straight symmetry among the niches, each of them show several little differences; second, different and various materials were used in the construction, and this implies that have been positioned probably on the basis of their morphological features.

Figure 3. Northen wall of the crypt.

Figure 4. Capital on the semicolumn.

On a second phase, we planned a topographical network for the laser scanning stations. Due to the fact that connecting the upper part of the church with the lower part was very challenging, extreme care was taken in the positioning and measuring of the reflecting targets through the total station. All point coordinates have been first referred to a local spatial system, which allowed us to better control point coordinates while measuring and performing analysis on the monument. This spatial system has been later geo-referenced using GPS Leica 1200.

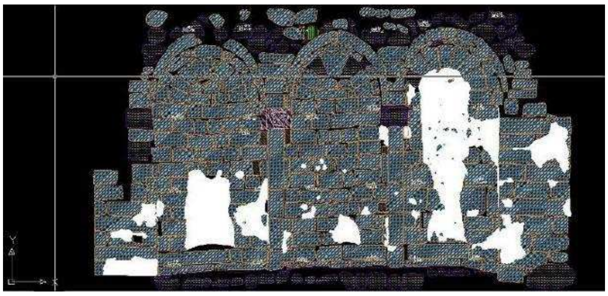

Figure 5. Northen wall of the crypt.

The techniques of classic topography and GPS survey allowed us to position the site in the territory and also to geo-reference the laser scanner data. The GPS survey has been realized with static and real-time techniques of satellite positioning (see fig. 6). This process was carried in three steps: first we searched and inserted the cartographic documents, second we carried out land survey and then we processed the data. We used as referential geodetic network the national GPS network IGM95, which is part of the European Terrestrial Reference Frame 1989 (ETRF89). Technical regional 1:10,000 scale map has been inserted together with aerial photos of the site, which were taken during the 90's by the Military Geographic Institute and the 1:500 scale photogrammetric image. Before the data collection, detailed measurement has been performed by means of Leica GPS System 1200, either from the national grid geodetic point at 7 km from Cencelle or from the permanent station located on the archaeological site. This procedure guaranteed the accuracy of the survey. During a second phase, detail points have been selected using the Smart Antenna on a pole and the RX1210 controller through Real-Time Kinematik System. RTK measures the positions of the points with centimeter accuracy within few seconds. All data are stored in the same database on the Compact Flash card. During a third phase the data have been processed using Leica Geo Office and Verto software in order to transform point coordinates, to load them in AutoCAD and to extract land form patterns for the 3D digital model.

As stated above, the church deserved a complete building record, i.e. a 3d model. As a matter of fact, a 3D model has integrated information that can be analyzed, increased and used to better understand a specific structure, but only after that a correspondence between simple geometry and real object has been verified on the field. With the aim of testing two different scanners in the same context, we carried out two scanning sessions using Leica ScanStation 2 for the upper part of the church, and Leica HDS 6000 in the crypt. The first one, with a 50,000 points/sec maximum instantaneous scan rate, has a full dome field-of-view, which enabled us to capture overhead, vertical, horizontal and sub-level geometry easily. It is also fitted with an integrated high-resolution digital camera providing the true-color map. We decided to use it for the upper part of the church because its 300 meters allowed us to address a wide area such as the three naves. The second one, with a 55 meters range and a 500,000 points/sec maximum instantaneous scan rate, is very fast and easy to use. Since it has higher scan density, it has been employed for the crypt scans in order to obtain better quality data. Subsequently the two data sources have been integrated.

Figure 6. A satellite photograph of Cencelle area.

The first step in the laser scanning data collection has been dedicated to the positioning and measurement of the reflecting targets using the total station. Therewith it was possible to refer the coordinates of the 20 point clouds captured (7 in the crypt and 13 in the church naves) to the topographic reference system (see fig. 7). Then, both targets and laser scanner stations coordinates have been also referred to the GPS reference system.

Figure 7. Topographical network for the laser scanning stations.

Giovanna Liberotti

3 The 3D reconstruction

Besides the analysis of the structure, aim of this work was to experiment the use of not only the topographic scanning equipment but also of the software needed to process the data collected on the field. The project was divided into various discrete phases, each using an application specific for the purpose (geo-referencing, topographic surveys, managing and processing laser-scanner data, vector graphics, and 3D modeling, lighting and rendering).

After finalizing field operations, the raw data were imported into Leica Cyclone 5.8, which processed the data and exported them to a format compatible with other applications. The post-processing phase was extremely complex, due to the enormous quantity of information to be managed and it required significant hardware resources. Cyclone 5.8 created two internal databases: one for the data captured by the Leica ScanStation 2 and one for the data captured by the Leica HDS 6000. It was particularly important to be able to decrease the raw data, while importing them, and at the same time reduce the number of data points to the level of detail needed for the final results.

In order to generate the point cloud derived from the 20 scans, the points that were acquired from the HDS 6000 (at a scan density equivalent to 3.1 mm by 3.1 mm at 10 meters) were reduced by sub-sampling at 1/16 skips every four points: this procedure creates a reduced copy of the cloud in the *.zfs file. However, due to the fact that the architecturally-relevant parts of the architectural score require a high-resolution mesh, part of the data were imported without any loss of information by selecting 100% in the Sampling list. This process generated a cloud of over 500 million points for the survey of the crypt. After the data import, the next step consisted of register them (see fig. 8): this procedure implies a complex set of operations to unify the various point clouds, in order to create a model view. The ScanStation 2 has auto-match target function that significantly speeds up the process. Targets are viewed directly in the registration space and it is possible to automate the union of discrete point clouds and quantify alignment errors.

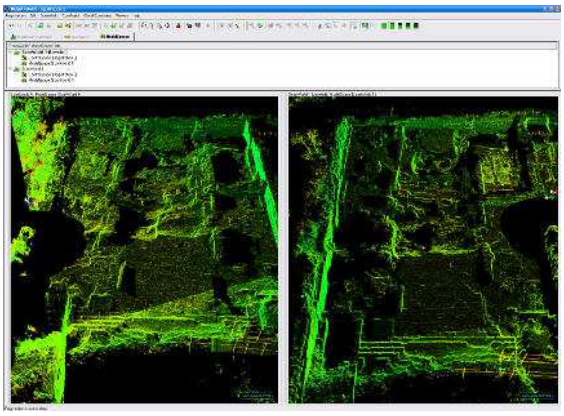

Figure 8. Screenshot of the registration.

In order to process the data acquired from the HDS 6000, it was necessary to manually align the point clouds, based on the acquired targets. To ensure correct alignment, each scan needed to have at least three targets and each scan had to overlap the next one. With the Cyclone 5.8 software, it was possible to import a .txt file that contained the absolute coordinates of all the targets. These coordinates are based on the WGS84 geodetic system and were acquired using the Leica GPS System 1200. By these means, it was possible to unite inside a new database the point clouds generated by the ScanStation 2 for the upper part of the church with those generated by the HDS 6000 for the crypt and then geo-reference the survey. It was then necessary to clear elements that were not pertinent to the survey from the data set. A user coordinate system was assigned to the cloud, which by now contained more than 174 million points: this procedure allowed us to generate personalized views and to create cross-sections (see fig. 9).

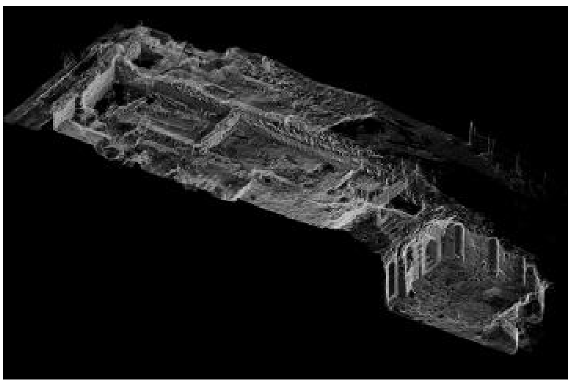

Figure 9. Cross-section of the church.

Further on we modeled a complex high-resolution mesh, with 2mm-sided polygons: this was generated for the most architecturally-significant features, without reducing the number of points (see fig. 10). However, for the reconstruction of the entire crypt the mesh was simplified in order to manage the 3D model.

Figure 10. High detailed mesh of the crypt.

The Cyclone 5.8 software was used to export GEOTIFF files (a text-based interchange format for geo-referenced raster imagery), to create plans at various heights, necessary for the 3D model reconstruction. For this type of processing, the *Cloud Silhouette* view was particularly useful, due to the fact that it enabled us to hide all the points with an ortho-normal to the viewpoint. Autodesk AutoCAD Map3D software was used to extract the principal construction lines from the elevations, integrate missing parts and create orthographic projections. This procedure allowed importing this model into Autodesk 3ds Max (see fig. 11).

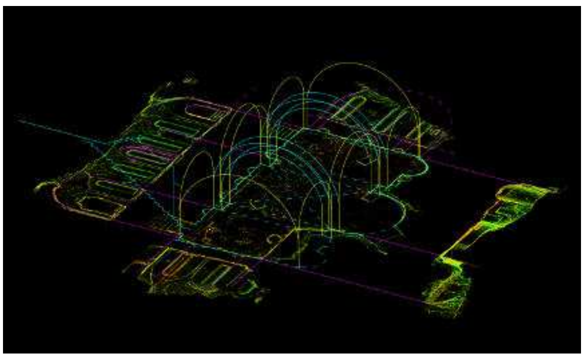

Figure 11. Orthographic projections and feature lines.

Further on, the 3d-model was built in 3Ds Max by adding to the CAD model architectonic decorations, whose elaboration in CAD would be more time-expensive. Four area lights enlightened the crypt: two were placed in the staircases, which are naturally lit from the upper floors of the church; and two were placed in the windows of the lateral walls. The aim of this procedure was to obtain a realistic lighting, computed using global illumination algorithms with lights positioned exclusively in accordance with existing openings. This process simulates lights and shadows in an area that, due to its very sacred nature, was dimly-lit (see fig. 12).

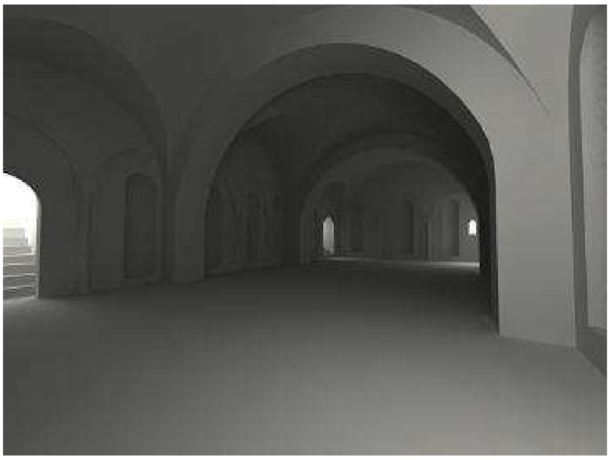

Figure 12. Rendering of the crypt, interior view.

According to the architectural and structural features of the building, the construction of the three-dimensional model maintained the architectural irregularities and asymmetries in the alignment of the walls. It served as an architectural study of the crypt and was necessary for the reconstruction of the roofing. Therefore, although the model was the goal of this project, it is also a mean for further analysis. All the data used in the reconstruction are directly derived from survey equipment, which has allowed the determination of the vault directrices, the generatrices, skew-backs, elevation of the vault crown and consequently of the level of the floor above the presbytery. The reconstruction of the elevation of the church, rendered in transparency to calculate the volume of the structure, is still in progress (see fig. 13). Given the scarcity of significant information and the poor state of preservation of the vertical elements, the data will be derived principally by analogies with churches having similar plans, similar topographic locations, and same period of construction.

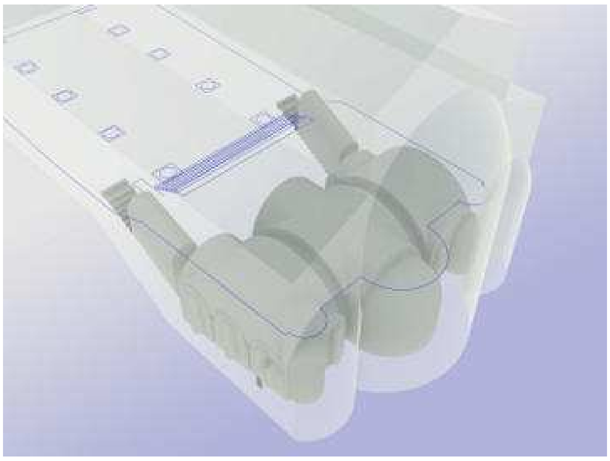

Figure 13. Rendering of the crypt, exterior view.

In conclusion, the use of laser-scanning technology emphasizes a paradox: on the one side, the data-collection on the field is extremely fast, on the other side, data processing requires many hours of work, both because of the complexity of the operations and of the large number of data to be processed. Due to the fact that during this long phase of data analysis, which was carried at the computer, there is no direct physical connection to the analyzed structure, and is more detached from the object than a direct survey on the ground, a risk exists: the archaeologist is led to general inductive hypotheses, rather than locally-relevant deductions. Only an adequate training at the university in the use of these technologies inside an archaeological context can reduce the risk. This could be achieved through gradual step-by-step training: from the use of manual survey techniques to a professional use of the most modern topographic equipments, and then to a critical approach to study of ancient monuments including the autoptical examination of the structures.

Daniele Nepi

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