Chapter 11
Digital Reconstruction of Archaeological Sites and Monuments: Some Experiences in South-Eastern Sicily

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Abstract Over the past few years, technological innovation has contributed to the development of the methodology to acquire, analyse, use and convey information about cultural heritage. Among all the possible methods for acquiring data, those related to 3D laser scanners (Time of flight or structured light) stand out. By using these technologies it is possible to sample, in a short time and with great accuracy, millions of points from real world objects obtaining a detailed 3D representation. This study presents the results of research carried out on archaeological sites and monuments of South-Eastern Sicily. The case studies presented belong to different type sites and they have been dealt with using methodological approaches chosen for the specific purposes of the study (restoration and conservation project, 3D reconstruction and visualisation, 3D documentation). The comparison between the different case studies might be the starting point for a new standardisation of digital representation of archaeological heritage objects and new methodological procedures.

Keywords Laser scanning · 3D modelling · Virtual archaeology · 3D reconstruction · Conservation · Digital heritage

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11.1 Introduction

Over the past few years, the growing interest of the scientific community, professionals and public corporations in the digital three-dimensional (3D) documentation of cultural heritage has led to several projects for the 3D acquisition, documentation, visualisation, conservation and restoration of large sites and monuments.

Today, capturing accurate and detailed geometric models of real world objects by using range-based (3D laser and structured light scanning) and image-based modelling technologies has become a common process (Andreozzi 2003; Andreozzi 2007; Docci et al. 2001; Gaiani et al. 2000; Guidi et al. 2010; Migliari 2001; Russo et al. 2011; Stanco et al. 2011; Valentini et al. 2004).

The use of these technologies allows for the creation of 3D models which are digital copies of real world objects on which each scholar could conduct various types of cognitive research. Moreover, 3D models are a precious, realistic and accurate documentation through which the object might be passed down to future generations.

The intensive use of these technologies requires the identification of best practise for the definition of standards in 3D digital documentation.

This study presents the results of research conducted on archaeological sites and monuments in South-Eastern Sicily by a team of experts from the Laboratory of Architectural Photogrammetry and Survey “Luigi Andreozzi” of University of Catania. The case studies presented belong to different typologies of monument, and they have been dealt with according to methodological approaches aiming at the specific purposes of the study (including restoration and conservation, 3D reconstruction, visualisation and 3D documentation). They are also in keeping with the Seville Charter principles on Virtual Archaeology (the implementation of the London Charter in the field of archaeology officially approved during the III International Congress Arqueologica 2.0, held in Seville). Those principles are: (1) Interdisciplinarity; (2) Purpose; (3) Complementarity; (4) Authenticity; (5) Historical rigour; (6) Efficiency; (7) Scientific transparency; (8) Training and evaluation.

The 3D laser scanning technology (Time of Flight) and the related software for data management and processing were tested. Both the strong points and the weak points encountered during the different phases of the 3D documentation pipeline were highlighted: from data acquisition to the 3D reconstruction of surfaces, from texturing to the visualisation of the model, from data interpretation to geometric analysis.

Moreover, the opportunity to have a digital copy of the objects studied opened new interpretative scenarios and made possible a dynamic approach to the problems related to restoration and conservation projects (allowing real-time verification and simulation) and highlighted the innovative potential of 3D documentation compared to the traditional 2D approach still used by many scholars.

However, there are still some unresolved issues such as: the problem of how to manage the huge amount of data obtained from 3D surveys; the possibility of creating multi-resolution models with different Levels of Detail (LOD); the need to automate the procedure to move from the point-cloud to a semantic geometric model sorted into component parts (Gaiani and Micoli 2005; Manferdini and Remondino 2012).

This chapter will be structured as follows: Sect. 11.2 will give an overview of current surveying and 3D modelling methodologies for an accurate and detailed reconstruction of archaeological sites and monuments; Sect. 11.3 will provide an in-depth look at three case studies in South-Eastern Sicily (the Roman funerary monument named "Torre Rossa" in Fiumefreddo di Sicilia; the "Terme dell' Indirizzo" in Catania; the catacombs of San Giovanni in Syracuse); discussion and future work will be described in Sect. 11.4; finally, in Sect. 11.5, the acknowledgments and bibliography will conclude the chapter.

11.2 Overview of the Actual Surveying and 3D Modelling Technologies

The documentation of cultural heritage artefacts cannot be based only on 2D graphic representations, due to the intrinsic characteristics of the objects being analysed (irregularities and fragmentary quality of the surfaces, roughness of the materials, missing parts, structural instability, deterioration) (Barbarini 2006; Cherubini 2008; Di Grazia 1991; Giuliani 1976).

Since the first decades of the previous century, stereophotogrammetry has been among the techniques used for the acquisition of 3D information. Over the past 20 years the use of digital technology has renewed the way in which researchers work in this field of study thus making possible the improvement of results and 3D visualisation (Remondino and El-Hakim 2006; Remondino 2005; D'Andrea 2006; Gabucci 2005; Mascione 2006).

However, the photogrammetric procedure, though having the advantage of acquiring immediate information on-site, requires that specific results of the surveyed object must be confirmed. This is particularly evident when the dimensions of the objects or of the site are large.

With the introduction of Laser Scanners—active sensors able to survey real world objects in a relatively short time and with great accuracy—it is possible to reproduce a 3D image consisting of millions of points of *xyz* coordinates in a point-cloud. In this way, the 3D model can be visualised during the phase of the on-site survey, thus improving the accuracy of the spatial characteristics of the object and/or the site. Laser scanners are divided into Terrestrial Laser Scanners (TLS), able to carry out land (close-range) data acquisitions, and LIDAR or airborne able to carry out acquisitions from an airplane (Campana and Francovich 2006; Crosilla and Galetto 2003; Remondino et al. 2009; Remondino 2011; Sansoni et al. 2000; Santana Quintero et al. 2008; Vassena and Sgrenzaroli 2007; Crosilla and Desqual 2006).

There are three categories of terrestrial laser scanners based on three different measurement principles: optical triangulation, Time of Flight (TOF), and phase-based measurement.

Optical triangulation laser scanners are used for objects of small dimension and are based on the principle of trigonometric triangulation. A sensor "captures" the laser light which is reflected by the object, and the system measures the distance between the object and the scanner. These systems, whose scan range goes from 0.1 to 2 m, and whose accuracy is of a few tens of microns, reproduce the scanned object in the form of a polygonal model.

The TOF laser scanner measures the time elapsed between the emission and the reception of the laser beam, the angle of inclination of the emitted beam to the vertical axis of the instrument and the azimuth angle to a reference horizontal axis. The system creates a cloud of 3D points which must be converted into a mesh afterwards. The scan range goes from 2 up to 1,400 m according to the characteristics of the instrument; the dimensional accuracy is between 4 and 25 mm.

The phase-based scanner works in a way similar to the TOF systems but it uses a light beam thus quickening the process of acquisition. The dimensional accuracy is about 1 mm, and the scan range is between 0.6 and 120 m, which is considerably smaller than that of a TOF scanner.

Spatial information (x, y, z) relating to a single point is generally enhanced through the RGB component which is acquired through a sensor inside the instrument or an external camera which may be axial to the instrumentation (for high-resolution acquisitions).

The high quality of 3D models, which today are obtained within archaeological research through the use of laser scanning technology, is documented by experience gained over the years.

The numerous and diverse applications of laser scanning technology have involved several research teams which have contributed to the progress and improvement of the potential offered by the use of this technology within the context of cultural heritage. Among them the following applications stand out:

- The joint project carried out by the CNR-ITABC researchers in collaboration with the Archaeological Superintendency of Rome concerning the Archaeological Park of Via Appia for the reconstruction of the archaeological landscape. The 3D images acquired through the integration of various technologies (laser scanner, remote sensing, photogrammetry) were aimed at the real-time design, reconstruction and exploration of the archaeological landscape (Forte et al. 2005a, b; Gaiani et al. 2007).
- The START project concerning the Roman catacomb of Saint Domitilla, conducted by the Institute for the History of Ancient Civilizations of the Austrian Academy of Sciences in collaboration with the University of Vienna. The use of laser scanner technology aimed at the 3D documentation of the architecture of the catacomb along with its early-Christian funerary painting through the interactive visualisation of the site. Furthermore, the huge point-cloud obtained, both for the wide extent of the site and for the high quality of the data, required a

system of data management able to manipulate and visualise the acquired information. For this purpose an out-of-core octree structure was created, and a number of interactive editing tools were used in order to perform various archaeological tasks on the whole point-cloud (Scheiblauer et al. 2009; Zimmermann and Esser 2008; Zimmerman 2009a, b, 2010).

- The project conducted by the Scuola Normale in Pisa in partnership with the Superintendency of the Archaeological Heritage of Naples and Pompeii and ARCUS SpA (Association for the development of art, culture and entertainment) aimed at the documentation, archival management and communication of the archaeological site of Pompeii. The integrated methodological approach entailed the use of photogrammetry for the extraction of 3D information from the digital photographic images as well as triangulation and TOF laser scanning. The 3D model of the survey was indexed within a Unified Information System for the Superintendency. An experimental multi-resolution semantic approach was tried on elevated structures (building units, decorations, elements of classical order) as well as on single finds classified according to their geometry and typology by creating abaci of architectonic elements which could be analysed individually and/or in context (Apollonio et al. 2012; Benedetti et al. 2009; Gaiani et al. 2009, 2011; Gaiani and Benedetti 2010).
- The research concerning the Archaeological Park of Kaukana in Ragusa (Sicily) is a joint project between the Department of Architecture of the University of Catania and the Superintendency of Environmental Cultural Heritage of Ragusa. The aim of the research is the documentation of various aspects of the site which range from the flora and natural context to the archaeological and architectural data. The heterogeneous nature of the objects to be studied as well as the extent of the area led the research team to use 3D laser scanning technology in order to survey the whole system in a more rapid and accurate manner. The 3D acquisitions were carried out with a TOF laser scanner. During this phase some low-cost spherical targets were tested for the following phase of alignment (Galizia and Santagati 2009; Restuccia et al. 2012).

11.3 Three Case Studies in South-Eastern Sicily

The following case studies, each with their own characteristics, contribute to the current debate on the search for methodological standards and operating protocols within the 3D digital documentation of archaeological heritage by means of laser scanning. Moreover, in the approach to the study of these monuments/archaeological sites a reference was made to the principles stated in the Seville Charter.

The research experiences reported here represent the exemplary phases which have contributed towards structuring and improving the methodological path followed. Overall, the operating protocols are closely linked to technical (objective-instrumental) and operational (individual-interpretative) criteria. The first criterion concerns the contribution of technological innovation within the research to both the instruments and dedicated software. Aspects which affect the research work in terms of time, costs, methods of acquisition and quality and quantity of data. The second criterion takes into account the cultural background of the researchers and their experience in the area of study, besides the characteristics of the object to be documented.

In this context, the methodology is structured according to a procedure which concerns:

1. the acquisition of data on-site, curently still in a standardisation phase, characterised by the identification and/or combination of the most appropriate technologies (Benedetti et al. 2002, 2009; Bohler and Marbs 2003; El-Hakim et al. 2004; Guidi et al. 2002, 2009; Lerma 2010).
2. the processing and extraction of data through the use of various dedicated software according to both the typology of data and the aims set in advance.

There are currently no standardised protocols for these two phases which cover the whole process. In fact, it is possible to define broadly a few key phases necessary for the subsequent processing which is conducted empirically by the researcher:

- *Data filtering*. Elimination of isolated points and noise, calculation of the normals, calculation of the depth and orientation discontinuities.
- *Recording of data in a single system of reference*. Manual collimation of the homologous points on pairs of scans and/or semi-automatic alignment through the use of 2D or 3D targets.
- *Passage from the numerical model to the polygonal model*. Creation of a triangular mesh which follows the topology of the point-cloud and/or a simplified multi-resolution mesh with fewer triangles by modifying some parameters (maximum dimension of triangles, accuracy, proportions of triangles, orientation discontinuity).
- Correction and calibration of photographic images on the model.
- Texture mapping of the model.

Nevertheless, it is still not possible to identify unequivocal procedures due to the diverse variables which come into play and which are closely linked to the characteristics of the object as well as being influenced by the interoperability of the software.

Another fundamental passage is that from the 3D model to 2D information often necessary in the study and documentation of the archaeological artefact. Thus, adequate reference systems are chosen in order to extract 2D orthophotos and outputs such as profiles, plans, views and sections.

Moreover, further processing can be conducted on the high-resolution textured models aiming at, for example, visualisation on the Web (by dealing with the problems of the definition of the various levels of details) as well as the structuring of data in a semantic information system (through segmentation and parametrisation). These latter issues are still under study by the various teams working on the identification of methods and procedures (Guidi et al. 2009; Pecchioli and Mazzei 2011; Fantini 2012; De Luca 2011; Manferdini et al. 2008).

11.4 Digital Survey and Conservation: The Sepulchral Monument Named "Torre Rossa"

The first case study aims to provide information about the Roman funerary monument named "Torre Rossa", located in Fiumefreddo di Sicilia (Catania), for its conservation (Buda et al. 2012; Cluverio 1619; Wilson 2003). The state of conservation of the monument and the difficulty in identifying some of its typological features required a critical interpretation and the integration of the data acquired through various cognitive analyses for a suitable conservation intervention. Probably dating back to the end of the first century and the mid-second century AD, the monument is shaped like a high parallelepiped (about 8 m tall) placed on a three-step podium and with a semi-underground funerary chamber. The chamber has a barrel vaulted ceiling and there are two pairs of niches on three walls, which originally contained cinerary urns.

There was a stairway to enter the sepulchral chamber, of which some traces still exist, along the south-western wall, near the western corner. This led us to think that the entrance door was in this place, where before the restoration there was the largest missing part in the brickwork (Fig. 11.1a, b).

The stairway continued by up inside the southern and eastern walls, until it opened onto the summit. The opening on the eastern side of the structure is modern.

The whole of the lower part had been chiselled and stripped of its brick covering, undoubtedly used by the local peasants for their houses, compromising the stability of the monument.

The severe state of deterioration of the building was already visible in the eighteenth century as depicted in iconographical representations made by Jean Houel (1782–1787). In 1782, the French traveller portrayed the stripping of the brick wall surface of the lower part which gave the monument a mushroom-shaped outline (Fig. 11.2).

Solid retaining brickworks were added later to prop up the east and south corners, thus further changing its formal aspect.

The state of conservation of the monument required an interdisciplinary approach in order to investigate the following features:

- Historic and iconographic.
- Archaeological.
- Geometric-dimensional.
- Chemico-material.
- Geo-structural.

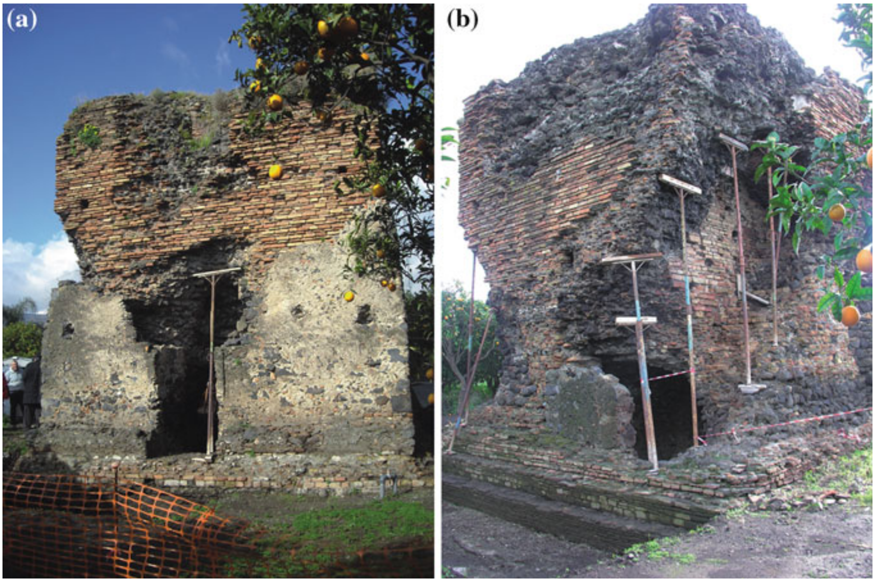

Fig. 11.1 View of the (**a**) South-Eastern Façade and of the (**b**) West corner of the "Torre Rossa"

Fig. 11.2 Guaches by Jean Houel, 1782 (La Sicilia di Jean Houel all'Hermitage 1989) (reprinted with permission)

In particular, the scope was to verify: the typology of the planimetric shape (original entrance, position of the stairway); whether or not the top of the wall complex contained the chamber which Jean Houel had assumed in the description of the monument appearing in his late eighteenth century publication; the building phases (whether the hypogeum and the part above ground, including the stairway, had been built during the same phase); whether any detachments had been the result of movements of the structure as a whole, that is, if it had undergone collapses, fractures or rotations.

The 3D laser scanner model was able to provide accurate documentation on the metric and material characteristics as well as the state of decay of the structure and of its materials. It was also the tool with which to perform and relate the various analyses.

The Leica Geosystem HDS 3000 Time of Flight (TOF) 3D laser scanner was used. The technical specifications are described in Table 11.1.

The scan protocol and the data processing took into account the following steps:

1. Data acquisition;
2. Data processing:

- Registration of data in a single reference system;
- Data filtering;
- Passage from the numeric model to the polygonal model;
- Correction and calibration of photographic images on the model;
- Texture mapping of the model.

1. Data acquisition

The phase of the on-site data acquisition took into account:

- The geometric-spatial and material features of the monument;
- The condition of the structure and the accessibility to the monument;
- The required LOD so as to document the wall surface, the missing parts, the consistency of the cement nucleus and possible fractures in a comprehensive manner. This latter parameter determined the resolution of the cloud of points.

Twenty-one scans were carried out. They were divided into: four station points for the semi-underground chamber; eight station points by the axes and the diagonals of the quadrangle at the base providing a closed polygon for the outside

Table 11.1 Laser scanner HDS 3000 specifications

Accuracy	Position 6 mm; distance 4 mm
Scan rate	4,000 point/s
Field of view	360° × 270°
Range	300 m @ 90 %; 134 m @ 18 % albedo
Spot size	From 0 to 50 m: 4 mm (FWHH-based); 6 mm (Gaussian-based)
Laser class	3R (IEC 60825-1)

lower part; also, four additional station points were planned for completion of the stairway. The survey of the roof entailed five station points: four by the corners and one by the stairway landing. The scans were carried out at a height of 9 m by using a basket lift firmly fixed to the ground.

2. Data processing

Cyclone software, provided by Leica Geosystems (data registration), and Reconstructor by Gexel (following phases) were used for:

- *Registration*. The 21 scans were assembled in one reference system, for a total of 61 million points, through the identification of homologous points between contiguous scans. The average initial maximum error of alignment equal to about 13 mm was reduced to 4 mm by optimising the parameters of calculation (sub-sampling percentage; maximum number of interactions).
- *Data filtering*. Pre-processing of the clouds (noise filtering, calculation of depth and orientation discontinuities, calculation of the confidence interval and of the surface inclination).
- *Passage from the numeric model to the polygonal model*. In order to comprehensively document the roughness and the material characteristics of the artefact high-resolution meshes were created (Fig. 11.3a). This resulted in a high number of triangles which made the visualisation and management of the file difficult.
- *Correction and calibration of photographic images on the model*. High-resolution images using a Nikon E8800 camera with 8 MP resolution were acquired. The calibration of the images on the point-cloud was, then, performed through the collimation of homologous points. A mean deviation of 1 pixel (about 0. 02 % of the image size) error was obtained.

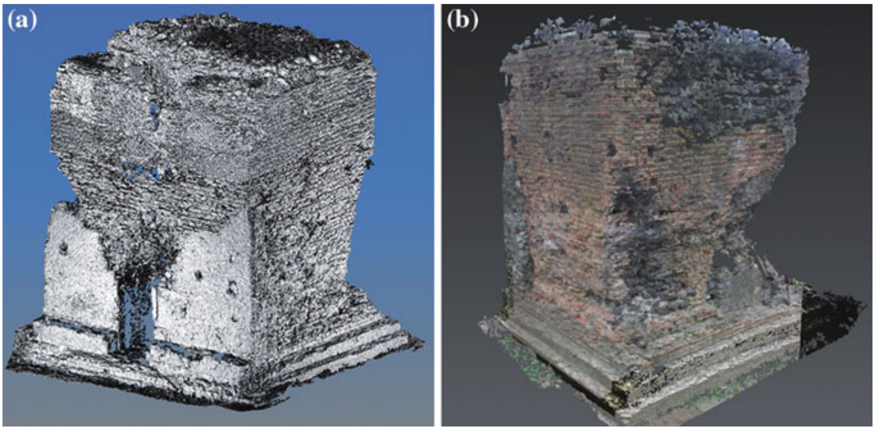

Fig. 11.3 View of the (**a**) mesh and of the (**b**) textured model of “Torre Rossa”

- *Texture mapping of the model*. The images were projected on the mesh model, and a radiometric correction was carried out since they were acquired in various light conditions (Fig. 11.3b). This final phase entailed some issues due to software bugs and the computational capabilities of the computer. Then the clustering of the meshes in one textured model was carried out.

The 3D textured model provided a very faithful record of the monument and was able to detect, to recognise and to map the areas of decay on the wall surface.

Furthermore, the 2D technical drawings (plans, elevations, sections), useful for the geometrical, spatial and material-stylistic knowledge of the construction as well as essential for the drafting of the restoration project, were obtained from the 3D model.

Being able to use a digital copy of the monument on the computer contributed to a more dynamic approach to the interpretative process since it was possible to generate, at any time, new information to compare with hypotheses as they were being formulated (including static characteristics and comparison with Houel's drawings).

We chose to perform the graphic analysis on the monument using Cloudworks, a plug-in of Leica Geosystem for AutoCAD able to extract horizontal and vertical profiles from the numerical model. This protocol was essential for the study of the static behaviour of the construction: for each side of the tower five section-profiles were drawn in order to identify "out of plumb" walls, the alignments and all other information useful to the designers responsible for structural consolidation.

Also, the choice of the heights at which the plans were to be made was defined according to our knowledge of "Torre Rossa" (Fig. 11.4a). Seven plans were made: at 0.70 m from the floor of the chamber (documentation of the underground chamber); at the heights at which two core drillings were made; at the impost of the vault of the chamber, at the height of the roof and at another two intermediate heights.

The 2D and 3D documentation of the funerary monument made the typological features of the construction, now in a severe state of deterioration, clearer and more comprehensible.

Specifically, in order to plan a suitable conservative intervention was necessary to compare the survey and the drawings of the "Torre Rossa" passed down by Jean Houel (the only documentation of the structure).

In the section drawn by Houel the funerary chamber is almost completely above the ground, unlike the current structure in which is semi-hypogeal. Furthermore, the height of the funerary chamber is about 35 cm less than that surveyed and the entrance of the chamber lies along an axis in line with the North-Western Façade, a hypothesis not completely supported by the surveyed data (Fig. 11.4b). This led us to suppose that the entrance should lie on the western corner.

Further diagnostic tests (endoscopy) verified the absence of an additional inaccessible funerary chamber inside the huge wall block (Buda et al. 2012). Moreover, the homogeneity of the composition of the lime mortar samples taken from both the inside and the outside of the brickworks dispelled possible doubts

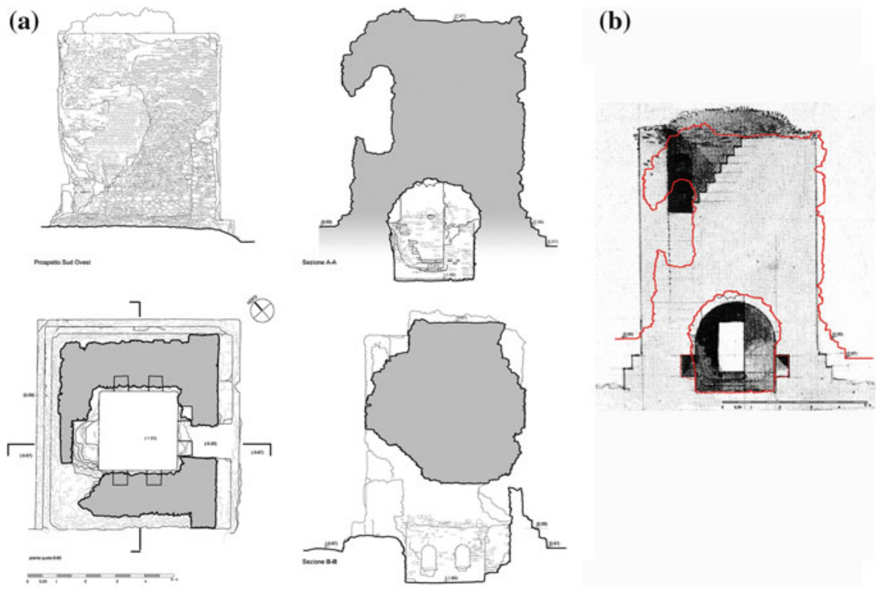

Fig. 11.4 (**a**) 2D graphical representations and (**b**) superimposition of the survey drawings on Jean Houel's drawing

and confirmed that the tomb was built in one phase, even though it must be assumed that because of the presence of the stairway it once had at least one additional floor.

Finally, it was verified that the deterioration progressed only because the wall surface became heavier as a result of vegetation growing on the structure. This was corroborated by the high quality of the mortar and of the bricks and by the absence of relevant structural movements.

The resulting digital model allowed us to simulate the possible phases of the project for the stabilisation and the integration of the original walls and of the small vaults which covered the stairway, whilst also retrieving the original structural scheme.

11.5 Digital Survey and Geometric Study: The "Terme dell'Indirizzo" in Catania

The second case study addressed our knowledge and interpretation of the geometry, building and material complexity of the archaeological site "Terme dell'Indirizzo" in Catania. The characteristics of the archaeological complex required a close examination through the use of digital technologies. Consequently we are able to reproduce a complete 3D documentation of the site.

(a) (b)

Fig. 11.5 View of the thermal complex of S. Maria dell'Indirizzo

The thermal complex (Fig. 11.5) lying in the historic centre of Catania is partially incorporated in the structures of the eighteenth century Carmelite Convent of Santa Maria dell'Indirizzo, now home to the Amerigo Vespucci primary school.

The construction has been dated back to the late Imperial Age (II c. A.D.) by some scholars, although, to this day, the various chronological phases have not been clearly defined. Its proximity to the port has led the scholars to suggest a public use for the thermal complex (Branciforti 2005).

Of the imposing ruins ten rooms, covered with the original vaulted structures, still remain. The wall structure consists of a cement mortar core covered with square blocks of lava rock. The floor is now at a height beneath the street level. The inner rooms can be accessed through a small stairway lying on the north-eastern corner.

Inside the building, the *frigidarium* and the *tepidarium*, along with annexed rooms of smaller dimension, the *apodyterium* and the *laconicum,* can be identified. From the *tepidarium* it is possible to access an octagonal room topped by a hemispherical dome with large openings—the *calidarium*. On the walls of the *caldarium* are three quadrangular niches, *clipei*, covered with barrel vaults. Probably, the *clipei* were originally furnaces for heating the halls, the air in the ducts and the water in the pipes.

To survey the site the Cyrax 2500 Laser Scanner, whose technical specifications are indicated in Table 11.2, was used.

The scan protocol and the data processing took into account the following steps:

1. Data acquisition;
2. Data processing:

- Registration of data in a single reference system;
- Data filtering;
- Passage from the numeric model to the polygonal model;

Table 11.2 Laser scanner Cyrax 2500 specifications

Accuracy	Position 6 mm, distance 4 mm
Scan rate	1,000 point/s
Field of view	40°×40°
Range	100 m
Spot size	From 0 to 50 m: 6 mm
Laser class	2 CFR 1040

- Correction and calibration of photographic images on the model;
- Texture mapping of the model.

1. Data acquisition

The data acquisition project took into account:

- The characteristics of the site;
- The geometric-formal aspects of the thermal complex;
- The characteristics of the instrument being used.

The narrow angular field of view of the instrument, along with the planimetric complexity as well as the small dimension of the rooms, affected data acquisition of the interior (Giuffrida et al. 2005).

The impossibility of applying reflective targets onto the artefact made it necessary to plan a dense mesh of station points so as to carry out both general and high-precision acquisitions in order to identify well-recognisable references for the following phase of alignment of the scans.

Thirty-four scans were planned: 7 external stations and 8 scans (5 land scans and 3 from above); 14 internal stations and 26 scans. In particular, for the survey of the *calidarium*, the acquisitions were carried out according to a radial pattern and by making 2 scans for each station point, thus setting up 8 station points and making 16 scans. A further hyposcopic and barycentric scan completed the survey of the dome ceiling.

2. Data processing

The Cyclone software by Leica Geosystem (data registration) and Reconstructor by Gexel (following phases) were used for:

- *Registration*. The 34 scans were assembled into a single reference system generating 24,000,000 points. The alignment was carried out through the identification of homologous points. The difficulty in finding notable points of reference on lava rock masonry was overcome thanks to the high density of points acquired. From the operational point of view, in order to obtain better error compensation, polygonation was achieved, where possible, by hooking each scan to the scans preceding and tracking in both a vertical and horizontal direction so that the last scan reconnected to the first scan. The optimisation of some parameters (subsample percentage, number of interactions, max search distance), which were conveniently balanced in order not to make the calculation too heavy without losing robustness, allowed us to minimise the alignment error between the scans. This latter remained, in fact, at about 7/8 mm on average, and, in some instances, it decreased to 4 mm.

- *Data filtering*. Pre-processing of the clouds (noise filtering, calculation of depth and orientation discontinuities, calculation of the confidence interval and surface inclination).
- *Passage from the numerical model to the polygonal model*. In this phase both high-definition meshes (useful in 2D representations) and meshes simplified through the definition of multi-resolution parameters were created. The set parameters made the file smaller without losing the geometric precision of some fundamental elements.
- *Calibration of photographic images*. For the image data acquisition a NIKON E4100 digital camera was used. The small dimension of the inner rooms required the use of a wide-angle lens, in order to reduce the number of photographs. The calibration was obtained through the collimation of the homologous points which were well distributed and visible within the margin of a 1.2 pixel error.
- *Texture mapping*. The images were re-projected on the mesh model. The strong contrast between bright and dark areas inside the thermal complex affected the quality of the acquired photographic images thus making their radiometric correction necessary, in order to improve the photographic quality of the overall textured model. Finally, clustering of the mapped meshes into a single textured model was undertaken.

The complete 3D model thus obtained (Fig. 11.6a, b) is a copy of the real object which allowed analysis and control, as well as the measurement and evaluation, of the dimensional characteristics of the thermal complex.

The resulting point-cloud provided the basis for the production of both traditional (plans, views, sections) and 3D (mesh, orthophoto, photographic model) outputs, with the additional advantage of immediate communication for non-experts.

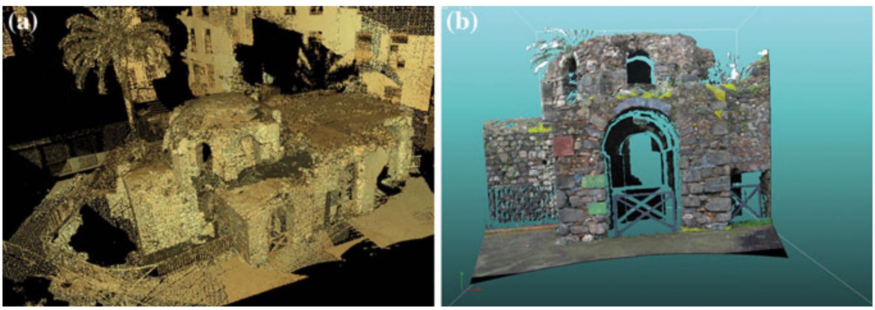

Fig. 11.6 View of the mesh (**a**) and textured (**b**) model

Moreover, the reflectance datum associated with each surveyed point, besides being an essential element for the operations of both the collimation of the points and the texture mapping, allows us to formulate hypotheses on the nature and deterioration of the materials which form the studied surface, thus making possible a further close examination of their state of conservation.

Once the overall model was fine-tuned, its 2D analysis was started in order to describe the geometrical conformation of the thermal complex in a comprehensive manner according to traditional documents. Then, a geometric analysis was carried out of the octagonal room of the *calidarium* and its hemispheric dome.

The identification of planimetric conformation at various levels (under and above ground) was obtained through the use of CAD. The textured model was then re-projected in compliance with selected planes thus obtaining metrically exact orthophotos which enriched the 2D plans as well as documenting the nature of materials, the use of colour and the state of conservation of the artefact. In addition, three vertical cross-sections, traced along the planes regarded as the most significant for the subsequent processing on the room of the *calidarium* (Fig. 11.7), were extracted from the model.

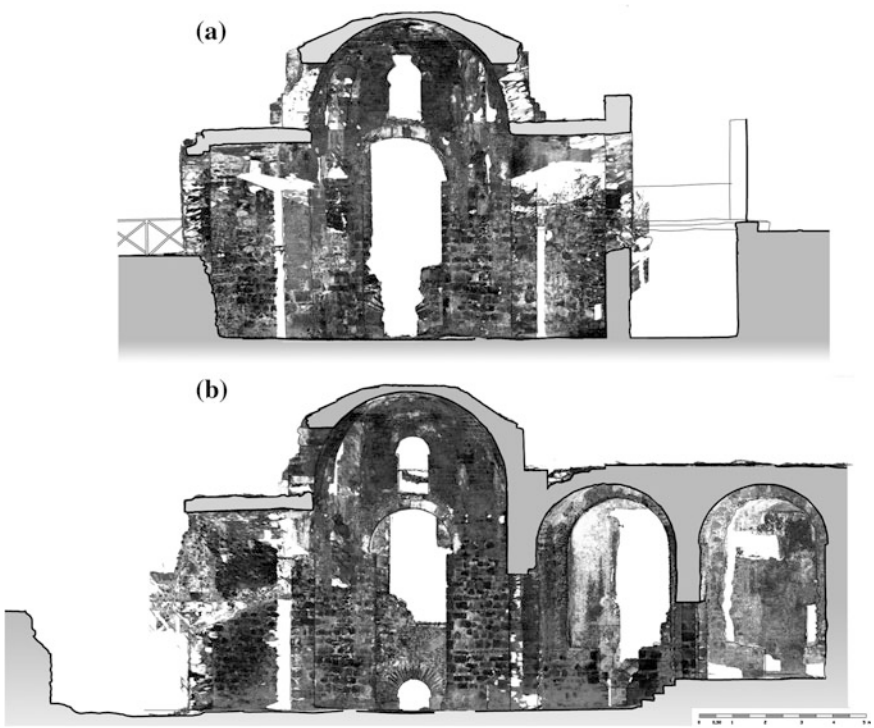

Fig. 11.7 Transversal (**a**) and longitudinal (**b**) cross sections

This latter process proved to be fundamental to the study of the geometric matrix of the dome, making possible the identification of the curvature of the surface as well as its variation between the lower octagonal structure and the upper circular structure.

The hyposcopic plan with orthophotos played a special role in the study of the geometric matrix of the dome (Giuffrida et al. 2007). As a matter of fact it facilitated the interpretation of the octagonal ichnographic structure of the room and highlighted the characteristics of the dome which consists of concentric rings of square stone ashlars linked to staggered joints.

Fourteen horizontal sections with a 20 cm step-scan were then extracted from the 3D model of the dome, thus obtaining the first contour representation of the analysed vaulted surface (Fig. 11.8a, b).

These sections were integrated with five vertical radial sections (along the apothems and diagonals of the octagon) to support geometric descriptions of the profiles representing the hemispheric vault. These sections also allowed us to identify various potential problems.

It was found that the centre of the hemispheric structure lies on a lower level (about 0.39 m) than the plane of the impost block of the dome (height 7.00 m); and that the radius of the impost block is 2.89 m, whereas that corresponding to the vertical radial sections ranges from 2.925 to 2.955 m.

In order to analyse the geometry of the surveyed surface in an accurate manner, and to compare it with the hypothetical, theoretical surface of the structure, the most significant points of the (horizontal and vertical) generating profiles were selected from the points lying on the intrados.

The average of the centres, radiuses and of the height of the impost block of the selected profiles, identified the possible centre of the theoretical sphere and the relevant theoretical radius (2.933 m) and the height of the impost block (6.63 m).

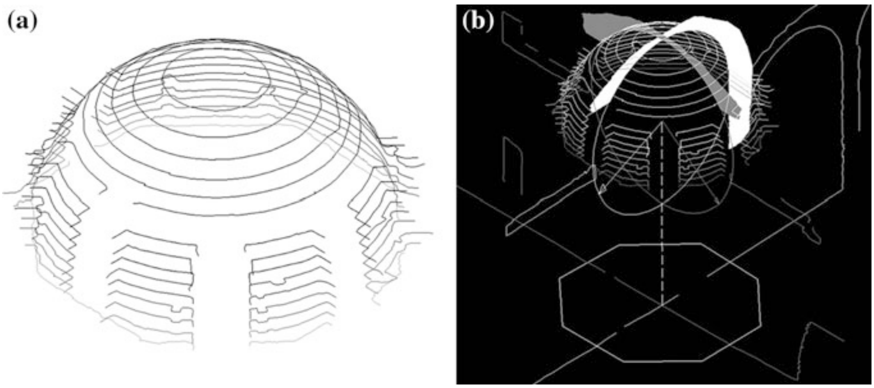

Fig. 11.8 Representation of the *calidarium*'s dome through contour lines (**a**) and geometric study (**b**)

By superimposing the horizontal sections of the intrados of the dome with the corresponding sections of the theoretical half sphere, it was possible to highlight better shifts from the theoretical curve. It can be inferred that the major deformations is north-south along which the shift between the two curves reaches a maximum value of 6 cm.

The analysis of the intrados of the dome which was carried out on the point-cloud, thus highlighting the interruptions, the irregularities, the variations of curvature, the depressions, as well as quantifying, localised partitioning, deformations, or events which have affected the structure over time.

11.6 Digital Reconstruction and Enhancement: The Catacombs of San Giovanni in Syracuse

Whilst the study on "Torre Rossa" aimed to explore its conservation issues and that on the "Terme dell'Indirizzo" addressed our knowledge and interpretation of the archaeological site, the aim of the study on the catacombs of San Giovanni in Syracuse was the understanding and documentation of the building for its enhancement and dissemination across both the cultural tourist network in Sicily and on the web, through the creation of interactive models, virtual reconstructions, etc. (Bonacini 2011; Bonacini et al. 2012). Hence, this study involved different disciplinary areas.

The archaeological complex comprises the catacombs, the ruins of the Basilica of San Giovanni Evangelista and the crypt of San Marciano. These spanned the centuries between that of Classical Greece and Late Antiquity. The archaeological site is a monumental cemetery with various burial types: niches, tombs, *sub divo*, all commissioned by pagans (Fig. 11.9). It was designed with an almost regular urban plan which re-uses pre-existing hydraulic structures (aqueducts, private drains, circular or conical section wells and bell-shaped cisterns) of the ancient city of Syracuse (Collin-Bouffier 1987; Griesheimer 1989; Tolle-Kastenbein 1990; Tolotti 1980; Sgarlata 1996), thus facilitating the construction of tunnels, *lucernaria* (skylights) and private chambers (the rotundas of Marina, Adelfia and *Sarcophagi*).

The considerable historical stratification of the catacomb complex as well as its plano-altimetric and geometric-spatial complexity, required a 3D methodological approach to survey, planning and 3D visualisation. In fact in this example the use of digital technologies (Zimmermann and Esser 2007), including a 3D laser scanner was essential, and was a powerful research tool to support archaeological studies for the enhancement of the site.

The laser scanning survey allowed us to obtain a 3D model that documents and makes the underground space visible through virtual reality models which are metrically accurate and rich in material and dimensional information. During the

Fig. 11.9 View of the rotunda of Adelfia

first part of the project, four adjacent private rooms were surveyed: the Adelfia and Sarcofagi rotundas, which are probably built on pre-existing hydraulic structures, the Eusebio and Paolo quadrangular cubicula and their connecting tunnels (Fig. 11.10).

A Leica Geosystems HDS 3000 TOF Laser Scanner was used, whose technical specifications are indicated in Table 11.1.

The scan protocol and the data processing took into account the following steps:

1. Data acquisition;
2. Data processing:

- Registration of data in a single reference system;
- Data filtering;
- Passage from the numeric model to the polygonal model;
- Correction and calibration of photographic images on the model;
- Texture mapping of the model.

1. Data acquisition

The data acquisition project took into account:

- The complex grid system that is composed of a variety of galleries and large rooms connected together;
- The characteristics of the spaces that contain multiple niches and *arcosolia* cut perpendicularly into the rock walls and laid out side by side.

The surveying protocol involved six scans: one for each area to be surveyed (in a barycentric position) and two transition scans. These latter two were captured

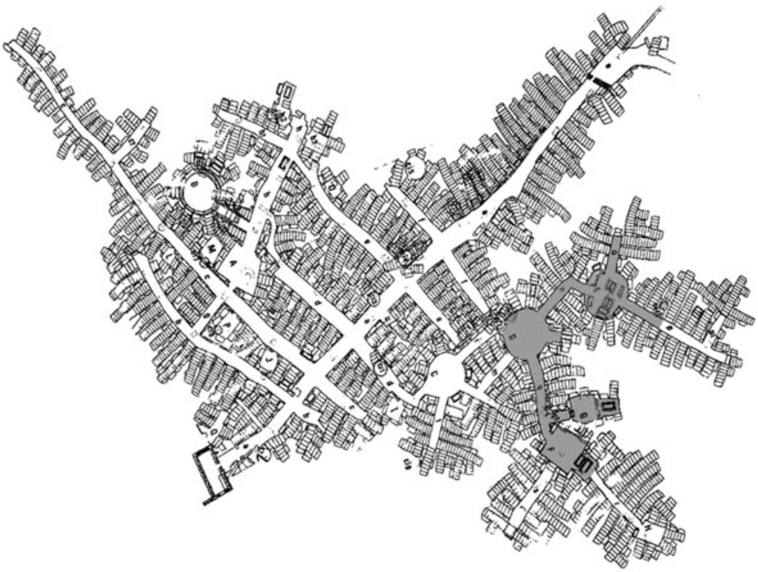

Fig. 11.10 The ground plane of the catacombs where the areas of interest are highlighted in *grey*

from the galleries so as to survey the numerous *arcosolia* in as detailed a manner as possible, while also reducing black areas necessary for scan realignment within a single system of reference.

In the *Sarcophagi* rotunda, the station point was chosen in order to mediate between the option of a barycentric position and the necessity of documenting the seven maidens *sarcophagi* that occupy most of the space. Particular attention was given to the problems of the angles of the laser beam on the walls of the narrow passage tunnels.

In order to optimise laboratory processing a network of reflecting targets was used: 29 targets were scattered across the surface of the walls, and they were detected and acquired by the scanner (minimum of 4 targeted control points for each point-cloud).

2. Data processing

After completion of the metric data acquisition on site the post-processing of the point-clouds was undertaken in the laboratory, using dedicated software (Cyclone and CloudWorks by Leica Geosystems, Reconstructor by Gexcel):

- *Registration*. The alignment of scans in a single reference system was carried out in an automatic way thanks to reflecting targets acquired by the instrument on site (Fig. 11.11a). In the absence of a topographic survey and a closed mesh of stations, the alignment procedure was carried out in order to ensure a uniform error distribution. Specifically, the recording was performed using triplets of

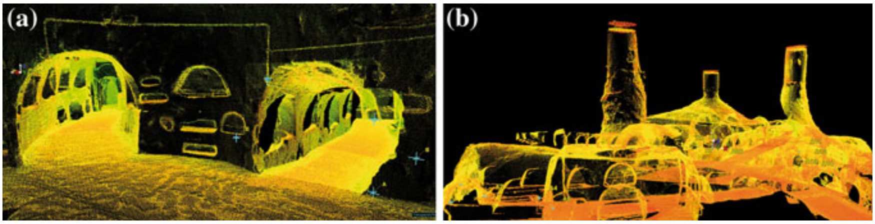

Fig. 11.11 Point-cloud where reflecting targets are scattered across the surface of the walls (**a**); the 3D model of the cubicles of Eusebius and Paul in RGB visualisation (**b**)

clouds, which had been adjusted during scanning of the rotunda of the Adelfia which, when compared with the others, is barycentric and in a transient position. Optimising the calculation parameters (sub-sampling percentage, maximum number of iterations), the 10 mm average initial maximum error of the individual triplets alignment was reduced to 4 mm. Instead, the overall model error is equal to 4 mm. The comprehensive model thus obtained consists of 6 scans and a total of 46,940,251 points (Fig. 11.11b).

- *Passage from the numeric model to the polygonal model*. Two different types of mesh were created. The first one was a tight mesh, in order not to lose important surface information. This was intended to be used to create products such as orthophotos. The other was a simplified mesh used to generate a lower number of polygons and required for better management and visualisation of the files in interactive virtual environments and the Web.
- *Correction and calibration of photographic images on the model*. The photographic acquisitions took into consideration the small areas and low lighting levels of the environment. Specifically, we used a Canon EOS-1Ds Mark III digital camera with 24–105 mm and 14 mm objectives and a maximum resolution of 21 MP. After several attempts to identify the optimal acquisition conditions (with or without the spotlight, with or without a flash, with or without a wide angle, mediating exposure and ISO sensibility), it was used on a tripod and for remote control distance acquisition, operating in a semiautomatic way and using a focal distance equal to 14 mm, an ISO sensitivity of 800 and depth of field equal to *f*/18 by varying the exposure time between one acquisition and the other. Barrel distortion of photographic images was corrected using PTLens software. The calibration of the images to be re-projected on the model was performed by the Cyclone software through the selection of homologous points, between the photos and the cloud of points. The average deviation of re-projection was equal to 1.5 pixels (Figs. 11.12).
- *Texture mapping of the model*. The images were projected on the mesh model, and a radiometric correction was carried out as the images were acquired in various light conditions.

Moreover, a graphic analysis of the point-cloud was needed in order to document the geometry of the archaeological complex in plan and elevation. To draw

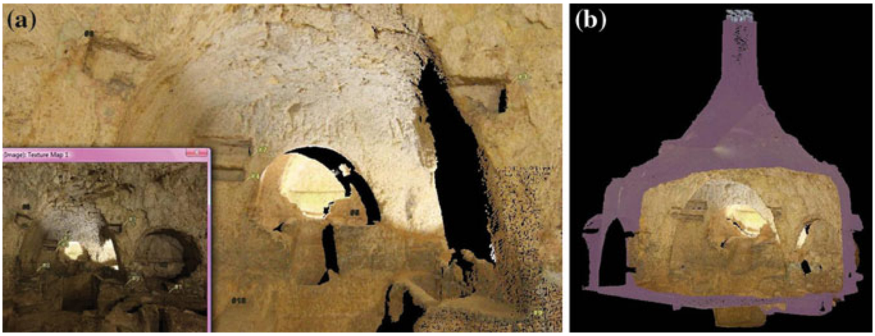

Fig. 11.12 (**a**) Texture map phase and (**b**) re-projection of the calibrated image on the point-cloud

the site plan two horizontal planes taken at different levels of the archaeological site were used, so as to be able to document the most representative typological elements (*arcosolia*, *sarcophagi*, niches, secondary galleries) as accurately as possible (Fig. 11.13). Also, several offset vertical cross-sections were carefully selected, each of them showing specific views of the complex: the axis between the entrances to the galleries, the skylight's axis, the centre of the rotundas and the quadrangular cubicula. Therefore, section planes of the surface of the ceiling intrados were also obtained, as well as the width and depth of the skylights (Fig. 11.14). The arching of the intrados that cover the rotunda has the shape of a somewhat irregular, wrinkled inverted cone, in contrast to that documented in the literature which depict the curved ceiling intrados as a dome (Galletta 2001).

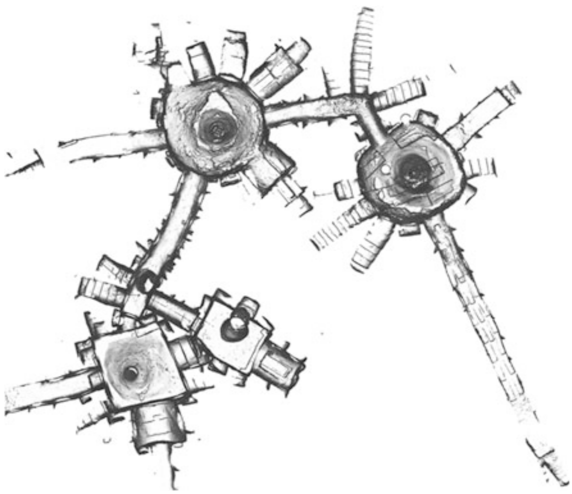

Fig. 11.13 Top view of the point-cloud

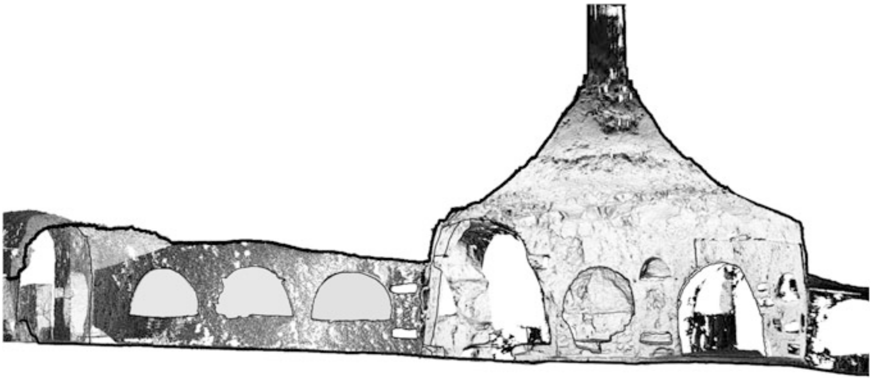

Fig. 11.14 Vertical section of the Rotunda of Adelfia

Work on the complete 3D surveying of the San Giovanni archaeological complex is still underway. To date only a small portion has been surveyed and analysed by means of laser scanning. To complete the project large amounts of data will have to be acquired, modelled and processed using specific procedures and advanced data processing technology.

The 3D data now available allows us to appreciate the spatiality of the rooms and their material characteristics. It provides high quality documentation on which to conduct multi-disciplinary research.

The digital model is also the basis for structuring a 3D information system that contains the available dimensional, archival, bibliographic, documentary, literary, epigraphic, historical, religious, economic and social information. Moreover, it can help retrace the timeline of the various phases of the complex (De Luca 2011), as well as the lighting and ventilation of these underground spaces through interactive 3D visualisation projects, Web-based applications (Pecchioli and Mazzei 2011) or through augmented reality (Inzerillo 2011, 2013; Stanco et al. 2012).

11.7 Discussion and Future Work

The three documented examples are particularly interesting for their various distinctive characteristics. Together they represent a valid example of methodological procedures following the principles of the Seville Charter including the preliminary identification of the final objectives (principle 2); the interdisciplinarity of the work groups (principle 1); the complementarity and integration of instruments (principle 3); and technological sustainability and efficiency (principle 6).

Such protocols are also implemented during the data acquisition phase and are already partly standardised. During the post-processing phase a common pipeline, customised according to the aims of the study as well as the peculiarities of the site/monument, was used and verified.

These experiences highlighted the need to use both traditional and innovative approaches and instruments which, integrated together, contribute to the documentation and understanding of the archaeological heritage. The data obtained through the laser scanner, unlike traditional representations, provided a 3D visualisation which documents and analyses the object being studied through high-resolution photo-realistic models. This latter feature allows us to appreciate the material characteristics as well as the state of preservation of the archaeological structures.

Finally, digital models were obtained which made it possible to carry out detailed studies, to extract sections/profiles and to represent them at according to various scales. In respect of "Torre Rossa," which was concerned with the conservation of the structure, the data obtained through the 3D laser scanner were compared with available iconographic documentation. The only available studies are attributed to the French traveller Houel: guaches in which, despite the well-known rigour of the French scholar, contain evident incongruities (principle 5: Historical rigour). Moreover, by use of 3D models it was possible to interpret deterioration and instability in both qualitative and quantitative terms, and according to various points of view. Also, the accuracy of the metrical data made subsequent geometric analyses possible. The geometry of the vaults/cupolas of the ''Terme dell'Indirizzo'' was studied through the extraction of vertical and horizontal profiles.

Finally, several vertical profiles were surveyed across the Catacombs of San Giovanni in order to understand the geometry of the excavation of the bedrock, which suggested a precise curvature and a possible original use as cisterns for the collection of water. In addition, the 3D model provides the base on which to create an interactive information system. The rigour of the approach makes the cognitive process one which can be repeated and tested by other researchers (principle 7: scientific transparency).

11.8 Conclusions

This work demonstrates that, using 3D laser scanner survey, it is possible to manage high-definition photo-realistic 3D models which, besides revealing the complex morphology of the structure and discontinuities of the material which characterise them, are models on which material, dimensional, geometric and structural research can be carried out through the creation of profiles, sections and orthogonal projections.

The reliability of the data compared with the existing documentation was also demonstrated. For each case study such a methodological approach led to unexpected and new outcomes going beyond the original expectations. Therefore, the 3D digital models thus obtained provide new opportunities for interpretation, conservation and re-presentation in the future.

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