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Showing the Invisible – Documentation and Research on the Roman Domitilla Catacomb, Based on Image Laser Scanning and 3D Modelling

Abstract: The possibilities offered by new technologies do not automatically substitute for traditional techniques. Particularly in the collaboration between humanities and natural sciences, not all that is technically possible is also helpful for a study. In this paper, an archaeological project is presented that connects both solid basic research and the newest technologies, offering a new way of perceiving historical space by creating three-dimensional virtual reality models. An overview of the technical aspects of the first year of the Domitilla project is presented: the first part introduces the catacomb, previous studies and the present research concept, whilst the second part reports on the strategy and the initial results of the documentation.

The Domitilla Project and its Structure

The Roman catacomb of Domitilla, close to the Via Ardeatina, with some 15 km of galleries in as many as four levels, is the largest catacomb in Rome. It represents all phenomena and degrees of catacomb development, from isolated pagan tombs and the earliest community burials to the huge 4th century necropolis and the later pilgrimage sanctuary with its subterranean basilica. Furnished with some 80 painted tombs, it is one of the most important catacombs in terms of the development of early Christian painting. Even after 400 years of research, it has still not been studied in its entirety but with an abundant bibliography covering numerous aspects of the site, using various methods of research developed in more recent times, it represents a typical case of the current status quaestionis concerning the catacombs. Mostly what is lacking is a complete documentation allowing all kinds of scientific debate on these monuments. Now 3D laser scanning opens up a new dimension for documentation and perception.

In 2006, the Domitilla project was begun at the Institute for Studies of Ancient Cultures at the Austrian Academy of Sciences[1]. It is financed by the Austrian Ministry of Education, Sciences and Infrastructure and administered by the Austrian science fund FWF. The work is done in cooperation with the Institute of History of Art, Building Archaeology and Restoration at the Vienna University of Technology. The interdisciplinary team consists of archaeologists and architects, supported by geodesists and mathematicians[2]. In Rome, the partners are the Pontificia Comissione di Archaeologia Sacra[3] and, for logistical support, the German Archaeological Institute and the Austrian Historical Institute. The main goal of the project is to produce high quality documentation of the architecture and the paintings of the catacomb, based on 3D laser scanner data, and to combine all methodological approaches for a synthetic archaeological debate.

The Catacomb as an Archaeological Monument and Research Object

The Roman catacombs were dug by the early Christian communities of Rome for the burial of their members from the late 2nd to the early 5th century AD (Fiocchi Nicolai / Bisconti / Mazzoleni 1998). Until the relocation of the relics of martyrs in the 7th century, they remained places of pilgrimage. Forgotten in the Middle Ages, they were rediscovered from the late 16th century onwards, just as the Catholics began their counter-Reformation activities.

The first scientific study of 1632 attempted to give an integral documentation of all objects, findings such as lamps, sculptures, inscriptions and paintings, and the architecture (Bosio 1632). The galleries accessible at Domitilla at that time were illustrated in a ground plan, the rooms with paintings were shown in full sections and detailed views of all walls and vaults. Even if the study remains of interest only for scientific history, until today no other documentation has shown a comparable density of information.

During the last 150 years, different methodological approaches were refined. In the case of the frescoes, a corpus from 1903 shows watercolours of some 200 painted units from all catacombs (Wilpert 1903) but includes only two-thirds of the Domitilla paintings. In 1956, some 5000 inscriptions from Domitilla were published (Silvani / Ferrua 1956). In recent years, emphasis was laid on topographical studies, marking seven pagan hypogea as the nucleus of Domitilla and the basilica as a later cult centre (Pergola 1997; Pergola 2006). Since 1987, new corpora of catacomb paintings have been published for the catacombs of Marcellino e Pietro, Anapo and Commodilla. These finally offer plans and sections of the painted rooms, showing in black-and-white sketches the relationship between the paintings and their architectural setting.

Based mostly on the results of 20th century research, we now know essentially when catacomb burial started, how long it was practised and how it developed. Of nearly 70 catacombs in Rome with a total extent of about 175 km, Domitilla is the biggest. But in the last 100 years, no new ground plan has been developed and no plan maps the current state of the galleries and their geographic extent. The inscriptions have never been studied as an entire group. The paintings are only known in part, the total number of burials has never been counted exactly and then only for some small areas. Objects fixed near the graves have not yet been studied. It is barely possible to discern their archaeological context or to comprehend the interaction of art history and history. The various methods for topography, iconography and epigraphy are widely scattered, often following different aims. Thus, a few specialists aside, we are accustomed to not knowing the catacombs: they remain literally invisibile. We do not make use of these extraordinary monuments in a manner appropriate to their value as a mirror of late Roman society undergoing a profound change of mentality.

Documentation as the Key to Research

If the catacombs were only just now discovered, they would probably attract much more attention for their excellent preservation and the many interesting research possibilities they offer. First of all, basic data would be collected, such as the catacombs' dimensions, the number of tombs and burials, the age, name and sex of individuals, their social status, as well as the typology and distribution of burials, the architecture and paintings. Only an accurate documentation offers a platform for pluridimensional research.

Some suggestions can be made for various developments that can be followed in the history of Domitilla from the 3rd to the 4th century. The development of the inscriptions, from Greek to Latin, from traditional pagan to new Christian messages, from private votes to institutional pilgrimage poems. The development of architecture, from small burial rooms in simple green- and red-lined painting systems to monumental architecture with columns, vaults and representative burial spaces. It is even possible to follow the iconographic and iconological development of representations of the afterlife, from bucolic landscapes or symbols to images of personal salvation or to expectations of eternal salvation.

The basis for such a systematic study is complete documentation, consisting of ground plans and sections for the architecture, a catalogue of the paintings that offers a contextual reading of iconography and architecture, and an analysis of inscriptions connecting topography and social data. Until now, it has not been possible to grasp the three-dimensional development of the net of galleries, to simulate the incoming light and the circulation of air nor to animate the factor of time for the growth of galleries or the development of cult centres. All these questions are not new at all, of course, and many of them have been confronted at other catacombs. It is mostly a problem of time and money that prevents substantial progress. And so, from Bosio onwards until recent times, the catacombs remain, measured by their potential, invisible monuments.

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[1] http://www.oeaw.ac.at/antike/institut/arbeitsgruppen/christen/domitilla.html

[2] The archaeologists are N. Zimmermann and V. Tsamakda, the architects are G. Eßer, J. Kanngiesser and I. Mayer. Further technical support is provided by the TUW-ILScan Center of Competence of TU Vienna and Riegl Laser Measurement Systems (Horn, Austria).

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Documentation of the Catacomb of Domitilla – Disposition of Work

A characteristic feature of the catacomb is its complexity. It covers a space of roughly 300 x 300 m. This very large monument must be examined as a whole as well as in detail. It was dug into the local tuff ground, connected by an irregular system of light shafts and staircases. The different levels do not follow a common master plan. The expansion adheres to varying development patterns: far-reaching areas for community burials organized in long orthogonal corridors, as well as narrow, winding core areas. The intermingling of formerly independent cemeteries leads to incoherencies in today's structure.

A prominent aspect when surveying is grasping the spatial complexity of surfaces, which can now be achieved by 3D laser scanning. The technical equipment used here comprises an IL-Scanner Riegl LMS-Z420i with the following specifications: measurement range 1–800 m, accuracy ±10 mm (standard deviation), measurement rate up to 12,000 pts/sec, field of view 80 x 360°. As a project standard, single scans are operated implementing a resolution of 0.12° resulting in a medium 4 mm point distance on the wall surface of a normal burial environment. By extracting a minimum of five known reflecting targets, scan positions of delimited areas can be registered one to another with an average error of about 5–6 mm (standard deviation).

In addition to geometric measuring, coloured textures are also to be recorded. In the less important unpainted areas, the recording of coloured pixels can be taken care of by a calibrated digital photo camera, in this case a 6 megapixel Nikon D100 with a 14 mm lens, mounted on the scanner. Its images are mapped onto the geometry, simply by using the texturizing tools of Riegl's processing software RiScanPro (see Jansa et al. 2004; Bouramond / Studnicka 2004). Problems related to 3D scanning and colouring point clouds by using oriented digital images have widely been discussed in previous publications.

Special attention, however, must be drawn to the approximately 80 painted rooms. Their iconography cannot be fully determined without a precise knowledge of the paintings' adherence to their architectural environment. True-colour surface models preserving the full 3D geometry of the architecture and high-resolution, photo-realistic texture of the paintings were chosen to be the most effective tools for documentation. To achieve that aim, free images are produced under studio-like conditions, thus ensuring a smooth and shadow-free lighting of the painted surfaces, an indispensable prerequisite for satisfactory visual results of the desired 3D models. All images were exposed by a calibrated 10 megapixel Canon 1Ds with a 20 mm lens. Mapping free images to complex geometries has rarely been treated in publications concerning the documentation of cultural heritage contexts; some examples can however be found (El Hakim / Fryer / Picard 2004; Vassallo / Moro / Vico 2006). The approach developed in this project will be described later.

For documentation of the close-up range, the combination of both techniques, laser scanning and photogrammetry, should be sufficient. Problems arise, however, due to the enormous size and limited visibility of the site as a whole. In order to avoid the accumulation of registration errors inherent in laser scanning in tunnel-like environments, a tacheometric overall measurement was introduced, performed on a Leica TCRM 1103i total station. Thus, along main corridors, traverses with wide baselines were erected in order to form a distortion-free triangulation net of control points. Simultaneously, reflecting targets were measured along the main corridors, constituting the global coordinate system of the catacomb. The registration tool "find corresponding points" within RiSCAN PRO allowed the automatic transformation of measured point clouds into that global coordinate system.

Plain Geometry Data of 3D Scanning

In order to obtain the final documentation, a number of finishing steps needs to be taken apart from the described activities of measuring. For users of scanning technologies, such as architects and archaeologists, however, some easily-achieved intermediate results are of great importance. After simply cleaning up the raw point clouds of delimited spatial units and gathering them in a Riscan-Pro view, geometric 3D data can be exported as stl-files and thus be used in further CAD-based design procedures, creating floor plans and sections. A typical result is shown by the example of a complex room, called "King David". Following a common ground plan of catacomb rooms, a nearby square rectangle extended by a restricted number of arched tombs, "King David" can be sufficiently scanned by adopting 4 to 7 scan positions inside the chamber *(Fig. 1)*. When scanning with an approximate

Fig. 1. Point cloud cluster of cubiculum with inserted scanner symbols, perspective view, top view and side view.

density of 4 mm measured on the object surface, the complex geometry of the volume in all its irregularity can be portrayed. The resulting point-based model is distortion free. For the first time in the history of catacomb studies, the various types of rooms can be fully described three-dimensionally.

Models of the Painted Areas in True Colour

One main goal of our documentation is the creation of true-colour models of the painted areas. As mentioned earlier, the architectural surfaces are photographed during laser scanning and the coloured pixel data obtained can subsequently be mapped onto the geometry data. This results in a preliminary 3D true colour model, allowing the quick visualization of complex structures. But the resulting textured point cloud is still a model of single measurements in space, and difficulties in perception arise due to the quality of the coloured dots: at close range, we begin to see through the dots and the texture that was formerly visible disappears.

This problem can be solved by triangulating 3D point data into a continuous mesh and subsequently texturing the mesh. The process is characterized by a number of processing steps that, to the authors' knowledge, cannot be solved efficiently using only one software package. A very effective tool in the processing chain, however, is the software QT Sculptor by Polygon Technology (Germany), which was used in this project for texturing. QT Sculptor can open Riegl scanning projects. After further optimizing the global registration of the oriented original images, redundancies of about 3 mm are usually achieved. An earlier calculated, quite rough first mesh is now substituted by a second mesh produced using the potent triangulation software GEOMAGIC. Geometry data is imported as xyz text files containing the cartesian coordinates of point clouds. Compared to QTS, GEOMAGIC allows for more comfortable processing features like noise reduction, smoothing, lowering peaks, eliminating occlusions and filling holes. Furthermore, the number of polygons is reduced heavily in order to produce comparatively lightweight and easy-to-move meshes. Triangulation nets produced in this way display a very high quality and can be exported as binary stl-format files. Via conversion to off-files (object file format), they are ready to substitute for the rough meshes of the QTS project.

After creating continuous surfaces, photographs taken under perfect lighting conditions are now mapped onto the models *(Fig. 2)*, a procedure that, when dealing with irregular, non-ideal geometries, is usually done by finding identical points in meshes and images. But, due to the noise of the original Riegl scan data and the already smoothed mesh surfaces, characteristic points can hardly be found in meshes so that registration of free images on mere geometry data appears difficult. A necessary intermediate step consists of automatically mapping the already registered ScanPos images of the original Riegl project. This has to be undertaken in order to prepare our meshes for mapping of the higher quality, but not yet oriented, free images. As a rule, free images can be registered more effectively the more identical points are found. After registration, the Riegl images are deleted and free images are masked in order to hide picture areas that do not satisfy our visual demands. QT Sculptor allows for calculating quite large textures. Limitations arise due to the computing capacities of our computers, so at present, textures are calculated adopting a medium image size of 4096 pixels. Textured 3D models can then be loaded into the QTS viewer or exported into various 3D file formats.

As indicated above, these post-processing procedures allow the creation of virtual yet distortion-free architectural models that include the real colours of

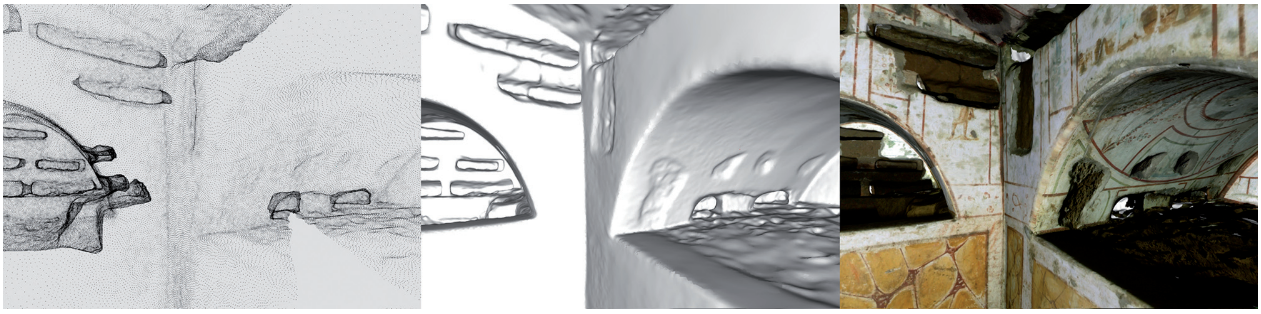

Fig. 2. Point cloud, shaded mesh and textured mesh; example of the Cubiculum of King David.

the surfaces. These models can be animated for presentation as short films. Additionally, the models are available for study purposes. They are ready to be opened in standard VRML viewers and turned and viewed as desired. With that step, a primary objective of our research project has been achieved.

Reducing 3D Models to Plans

Another part of the project deals with reducing the coloured 3D models to 2D plans, that is colour orthophotos. These 2D photo plans are needed for surveying, measuring and mapping relevant aspects which are evident in plane wall-surfaces. Furthermore, they will be needed for illustrations in scientific publications. This task can efficiently be addressed using the software tool ASPECT 3D by Arctron (Germany) which allows VRML models to be imported. After selecting the relevant parts of the model and defining a projection plane, all coloured 3D data are projected orthogonally into one drawing plane. ASPECT 3D contains an interesting feature which allows the desired image resolution and scale to be easily selected before processing. As the wall surfaces are usually uneven, a modest and therefore low degree of abstraction must be accepted, just as is the case with conventional drawings. Single orthophotos can then easily be assembled, applying the conceptual standard of unfolding the main elevations of the tomb chamber walls *(Fig. 3)*.

Handling vaultings proves to be more difficult, as they are often only roughly shaped according to ideal geometries. The vaulting of an arched tomb is geometrically most likely to be understood as part of a truncated conical figure. Its vertex line bent downwards towards the back of the arcosol is often not orientated orthogonally to the wall plane. As the ceiling surfaces of arcosols usually deviate from ideal geometries, a simple development of its texture is geometrically impossible and we are again forced to accept abstractions. However, a simulation of the panoramic view of a virtual observer lying in the arcosol's opening gives a reasonable impression of what the painting actually looks like after having been unfolded *(Fig. 3)*. The 3D modelling software FORM Z contains a tool which allows creating an image which is similar to the painting as seen by the antique artist when finishing his drawing. Here, the so-called "cone of vision" has to be fitted as closely as possible to the amorphous geometry of the grave's vaulting, defining the parameters of a virtual camera. After setting lighting features and texture qualities, a 2D image is rendered along the path of the chosen view figure.

Gathering all wall prospects, ceilings and vaultings in one view, it is possible to see how their form and content are related. The advantage of the photogrammetric techniques compared to the older standard of drawn elevations lies in the photo-realistic quality achieved by refraining from reducing any of the inherent information. The method therefore can be considered far more objective.

Description of the Catacomb Organism as a Whole

A further question in documenting the contents of a catacomb concerns the description of large and complex structures in models and plans. As previously mentioned, this project strives to relocate the various groups of findings into the virtual catacomb structure. At the same time, the intention is to depict the complete organism of the catacomb itself. Architectural plans and sections are intended to lead to information such as the core areas and the boundaries separating them, as well as an understanding of the growth processes of the sepulchral areas which has resulted in today's structure. The principles of our approach to processing 3D data have already been discussed. However, difficulties result when dealing with larger amounts of data. The goal of our work is a reliable, non-textured surface model of the catacomb as a whole from which horizontal and vertical sections can be obtained.

Fig. 3. Development of volume surfaces of the Cubiculum of King David and panoramic view of an arcosol's vaulting.

Screenshots of a point cloud cluster from near the Galleria dei Flavi clearly highlight the potential of the scanning technology: three of the four subterranean floors of the catacomb can be observed *(Fig. 4)*. They are interconnected by a system of staircases and vertical chutes for light and the transport of building material. Typical pairs of tomb chambers, which are often accessible from the main gallery, can also be made out very well. The point cloud has its limitations though: on the one hand, sections of the catacomb which are seen in one line of sight overlap disadvantageously. On the other hand, the disproportionately large amount of point data impedes easy rotation of the model.

To solve that problem, heavily reduced point cloud clusters are again processed to create large meshes. With artificial lighting a plasticity of the opaque surfaces is achieved, allowing for an excellent understanding of the complex catacomb structure. Using the ASPECT 3D tool, cross-section surface models can then be reduced to 3D representations containing a series of regular horizontal sections. These are subsequently transformed into 2D top views that represent a kind of ground plan of one storey of the catacomb.

The meshing of whole regions inside the catacomb structure seems to be possible from today's point of view – if potent software and large computer clusters can be used. By the end of the project, as far as today's planning allows, a complete model of the whole catacomb will be available.

Conclusions

3D laser scanning and photo realistic 3D models do not necessarily have to be produced for all kinds of archaeological projects. However, in the case of the Roman catacombs, these technologies open up new possibilities for describing complex building structures geometrically and bringing them to life by mapping real, true coloured textures. At the same time, costs are reduced because the speed of the laser scanner allows greater and faster output.

Therefore, by applying these new techniques, beautifully coloured and complex spatial structures

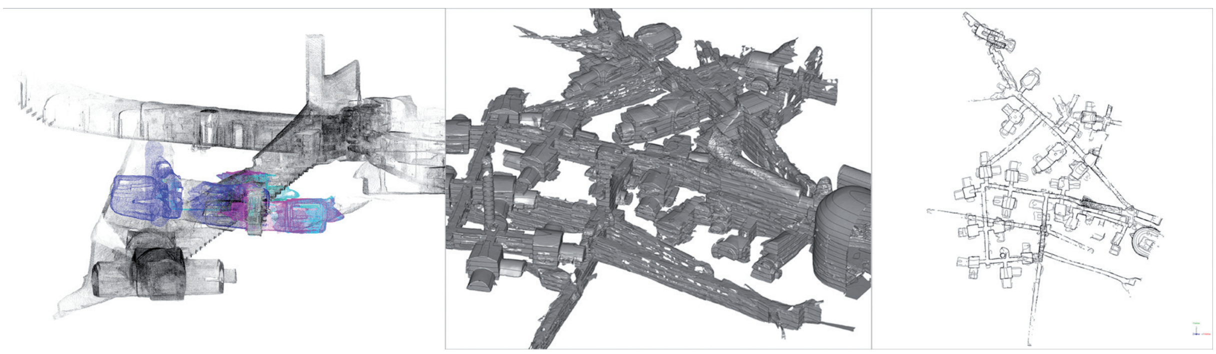

Fig. 4. Full resolution point cloud of the area near the Galleria dei Flavi; mesh and ground plan of the region 'Retro Sanctos'.

become visible for the first time in catacomb research. The 3D and 2D material represents an excellent and highly accurate documentation output which can serve as a new data base for further studies, or alternatively is open to be used in didactical contexts such as virtual museums.

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