3d-geometry and 3d-texture. Documenting early-Christian wall paintings at the Domitilla Catacomb in Rome.

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Abstract: Wall paintings of the subterranean roman graveyards are a mirror of early-Christian society in late antiquity. Their iconographical content develops as a three-dimensional reference system in architectural space, which can only efficiently be deciphered under optimal laboratory-like conditions.

Our paper is intended to refer what is to become the new standard in catacomb documentation, being evolved as one of the major research strategies of the Austrian START-Project "The Domitilla Catacomb in Rome. Archaeology, Architecture and Art History of a Late Roman Cemetery". The approach is based on image laser scanning and mapping of separately taken photographs, creating photorealistic 3d models, which are to serve as a new kind of data-base for further studies. Problems of orientation and accuracy - created by using two different data-sources of digital images and terrestrial laser scanner outputs - led to a laborious work-flow containing data acquisition, registration, preparation and cleaning, triangulation and texturing, still to be optimized, but finally providing the desired 3d, photo-realistic and high-precision architectural models of the spatially defined burial areas. Problems however arise in some topographically important units, when trying to process even larger amounts of data, thus representing a technological threshold that can hardly be overcome by non-specialist users like architects and archaeologists.

Introduction to the project

The Austrian research project **"The Domitilla Catacomb in Rome. Archaeology, Architecture and Art History of a Late Roman Cemetery"** from its very start has been judged as being innovative for the lucky combination of tempting research topics deriving from two completely different disciplines (ZIMMERMANN, EßER 2007):

On the one hand, there is an important archaeological object of considerable dimensions. From the time of its discovery in the beginning of the 17th century (Fig. 2), it has constantly attracted the attention of generations of scientists but at the same time, because of its vast dimensions, underground location, and structural and geometrical complexity, has prevented a complete, exact and holistic documentation and interpretation. On the other hand, there is a considerably new documentation and measurement technology, which proved to be successfully adoptable in all kinds of fields from topography and city monitoring to as-built-surveying of technical infrastructure: laser scanning. Only a few years ago this technology has started to be applied in the humanities. In archaeology and especially in projects dealing with historical building survey, its capacity of representing the entire three dimensional nature of archaeological objects has initially provoked – and still continues to cause - overwhelming enthusiasm, while its primary products, coloured or plain point clouds, have been addressed with some criticism by archaeologists and architects (WEFERLING, HEINE, WULF 2001, RIEDEL, HEINE, HENZE 2006).

When in 2005, archaeologist Dr. Norbert Zimmermann, leader of the interdisciplinary research team, presented his request to finance a six year long complete documentation and study of the Roman Domitilla Catacomb based on terrestrial laser scanning, reactions revealed high expectations concerning not only new archaeological results, but also expressed the hope that, by working on such a remarkably precious and difficult monument, laser scanning related documentation technologies and post processing procedures could be further experimented and combined, thus determining the inherent potential of existing techniques for one branch of cultural heritage documentation.

The archaeological site

The Roman Domitilla Catacomb is located on via Ardeatina, in the vicinities of a series of other antique graveyards outside the Roman city walls. For its enormous and until today unmeasured extension, it is considered to be the largest catacomb in Rome (Fig. 1). Covering a life span of roughly four centuries, Domitilla incorporates all stages of a typical catacomb evolution. Beginning with some isolated pagan tombs of the second century and the earliest Christian burials, the development later lead to the large Christian graveyards of the 3rd and 4th centuries and finally evolving in an important pilgrimage sanctuary, the underground basilica of Nereus and Achilleus. But Domitilla is not only famous for its underground architecture: with some eighty decorated burial environments, it also comprises one of the world's biggest treasures of Early Christian painting.

Even after 400 years of research and study, this artistically rich and historically important monument – like most other Roman catacombs – has not been studied nor published as one archaeological entity. Here, laser scanning and photogrammetry are truly capable of bridging the gap. As they allow for the combined acquisition of full 3d and colour information, these techniques permit the fulfilment of an urgent desideratum in early Christian archaeology: a complete documentation serving as a database to favour all kinds of scientific debate on the monument.

Fig. 1 – Catacomb of Domitilla, groundplan (A. Nestori, 1975)   Fig. 2 – A. Bosio, 1632: First Documentation of Roman Catacombs

Project structure

In 2006 the Domitilla project was installed at the Institute for Studies of Ancient Cultures, which is located at the Austrian Academy of Sciences. [1] Since then, it has been financed by the Austrian Ministry of Education, Sciences and Infrastructure, and administered by the Austrian science fund FWF. As a national partner, the Institute of History of Architecture and Art, Building Archaeology and Restoration of the Vienna University of Technology [2] has been associated for the documentation work. The project team consisting of archaeologists and architects [3] is further supported by geodesists and mathematicians at TU Wien, the TUW-ILScan Center of Competence [4] as well as by Riegl Laser Measurement Systems in Horn (Austria) [5].

In Rome, our partners are the Pontificia Comissione di Archaeologia Sacra [6], who administers all Roman Catacombs, and, with logistic support, the German Archaeological Institute and the Austrian Historical Institute.

Research goals

The main goal of the Domitilla project is to produce a complete, high quality documentation of the architecture and paintings of the catacomb, based on 3d laser scanning data, and to combine all kinds of methodological approaches to a synthetic, equilibrate use of them for the archaeological debate. While parts of the research can be conducted in a fairly autonomous way and mainly deal with archaeological questions such as the analysis of inscriptions connecting topography and social data, the documentation output aimed at as main measurement products are twofold:

First, there is the ambition to represent the whole catacomb structure using mainly geometrical data that are recorded by laser scanning (Fig. 3 and 4). This task will obviously consume a lot of time in the acquisition phase. Processing a complete surface model of all accessible areas will then require maximum computing capacities. Such a model is considered as the starting point for producing overall ground plans and vertical sections of the architecture. Delivering a complete geometrical documentation of the catacomb has been defined as a long-term goal of the project.

A second task, which is considered as being a primary goal, consists in compiling a repertory of all Domitilla paintings (Fig. 5). Its aim is delivering a 3d model of every single painting unit inside its architectural context, to be made available to scientists for further contextual reading of the paintings iconography and the architecture they are set in. Strategies, that have been developed to obtain these documentation results, represent the main topic of this paper.
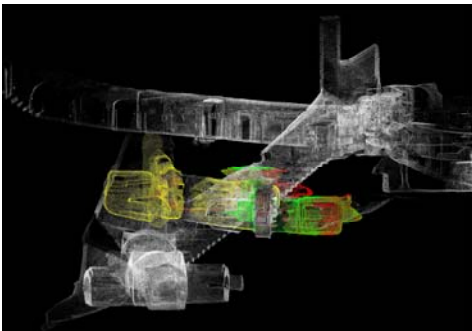

Fig. 3 - Domitilla, point cloud showing 3 storeys   Fig. 4 - Area *Retro Sanctos* in scan   Fig. 5 - Cubiculum of Orpheus in photography

Acquisition strategies

The Catacomb of Domitilla can be classified as a very large and spatially complex monument. It covers a space of nearly 300 by 300 metres and was dug up to four levels deep into the local tufa ground (Fig. 1). Its storeys are interconnected by several antique staircases giving access to formerly isolated underground regions (Fig. 3). Besides that, vertical connections comprise of an irregular system of light wells, which in most cases have recently been closed off. Unfortunately, the single storeys do not follow a regular master plan (Fig. 1 and 4). Underground construction expressed itself in a rather spontaneous digging activity, so that the overall expansion of the catacomb shows a quite complex pattern, not following clear and simple geometries. Typical spatial structures found inside the catacomb are represented by the long galleries for community burials, being estimated to a total length of nearly 15 km. These galleries interconnect a large number of richer burial chambers, some of them decorated by plasterwork and coloured frescos (Fig. 5).

In order to achieve an optimal ratio between acquisition input and documentation output, it was decided to organize the work on site by adopting three different measurement technologies:

First, an overall tacheometric measurement was applied to provide a rigid global coordinate system of the whole organism. Thus, along main corridors, traverses were erected, in order to form a distortion-free

triangulation net with wide base-lines (Fig. 8). Simultaneously, reflecting targets were measured along these corridors in order to serve as reference points for the laser scanning. The measuring was performed on a *Leica TCRM 1103i* total station.

For documentation of the completely amorphous surfaces of all catacomb environments, we used an *Image Laser Scanner Riegl LMS-Z420i* (Fig. 6) with the following specifications:

- measurement range 1 - 800 meters,
- accuracy +/-10mm (standard deviation),
- measurement rate up to 12000 pts/sec.,
- field of view 80 x 360°.

The laser scanner is operated by the scanner own software *RiScan Pro*, which moreover can be used for part of the post-processing tasks. [7] In addition to the geometry data, colour information was recorded by a calibrated digital camera *Nikon D100* with a 14mm lens mounted on top of the scanner. (JANSA, STUDNICKA, FORKERT, HARING, KAGER 2004).

Thirdly, in the more specific cases of painted areas, where high-quality textures had to be recorded, free images were captured under studio-like lighting conditions (Fig. 7). For that purpose a digital camera *Canon EOS 1ds* with a 20mm lens was used. In order to create a homogeneous, smooth lighting of the discontinuous painted surfaces we used the very flexible light panels by *KINO FLO* [8], which are widely acknowledged in professional photography and film productions.

Fig. 6 – Laser scanner Riegl LMS Z420i on site   Fig. 7 – Photography of early-Christian wall paintings at Cubiculum of *Mensores*

Post-processing strategies: from the point cloud to a photorealistic 3d model

In the following it will be referred on necessary procedures leading the way to a 3d model containing photorealistic textures, more specifically the work steps that follow the on-site data acquisition. Special attention will be given to triangulation and subsequent texturing.

Registration

As mentioned above, the vast dimensions and complex structure of the catacomb call for the application of a tacheometric survey. For this, a grid of fix points has been laid out covering the entire catacomb by focussing on main corridors and staircases as major lines of connection between catacomb areas. The complexity of the catacomb until today required the recording of 325 ground control points (Fig. 8). In addition to these and referenced into the same global coordinate system, about 2000 reflecting targets attached to walls and ceilings have been measured thus constituting a dense net of corresponding tie points. After calculating a

final adjustment of all observations, the coordinates of the reflecting targets have been exported into the scanner own software RiScan Pro and are used as tie points for the registration of the scans. In combination with the conventional registration of the individual scan positions, this allows to transfer all the single scans into one global coordinate system.

Fig. 8 – Net of ground control points, software *Geosi*   Fig. 9 – Cubiculum of King David, photography

Selection and cleanup of data for triangulation

After recording the geometry of Domitilla`s approximately eighty painting units being spread out over the entire catacomb, every point cloud model had to be transformed into a triangulated model, that served as a basis for later texturing. Using the so-called *Cubiculum of King David* as an example, the individual steps of the post processing chain will be presented in greater detail (Fig. 9).

The *Cubiculum of King David* shows a typical, almost rectangular ground plan that is further widened by two - in other cases three - arcosols. With an average side length of about 2.5 metres a cubiculum of this size can be surveyed by three up to seven scan positions. These scan positions have to be prepared for a successful and simple processing (Fig. 10 and 11).

At first, all irrelevant points - such as objects not adherent to the catacomb structure and phantom points generated during the scan - are eliminated. In order to facilitate triangulation, a separate RiScan Pro project is created, from which all data that do not pertain to the respective cubiculum are eliminated. This especially applies to all irrelevant scan positions and unused tie point scans and images.
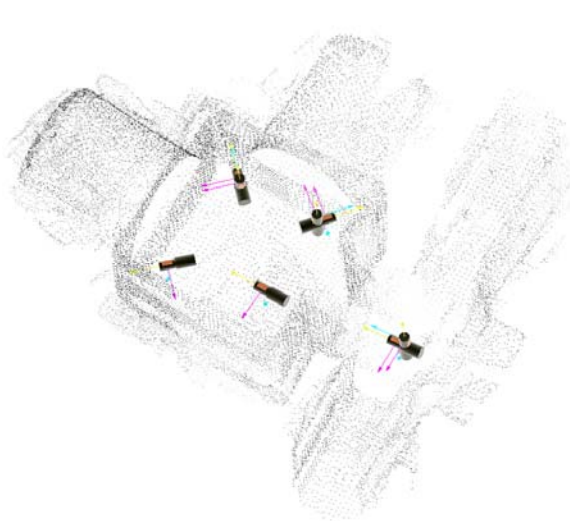

Fig. 10 – King David, Scan positions, software *RiScan Pro*   Fig. 11 – King David, necessary tie points for registration

Triangulation

An immediate first result of the recorded 3d-data and images is the so-called *coloured point cloud*. While scanning, photos are taken from the same positions by a calibrated digital camera mounted on top of the scanner. By help of a *mounting calibration* (BOUROUMAND, STUDNICKA 2004, p. 2-3) the photo information can be referenced to the three dimensional point cloud, each of the XYZ coordinates being supplemented by an RGB value. The coloured point cloud consists of a large quantity of singular measurements that convey a good impression of the architectural space but do not enable further geometric examinations or exact analyses of the paintings (Fig. 12). This problem can be eliminated by triangulating the point cloud, thus producing a meshed surface model. For that purpose, the software *QTSculptor* (QTS) was operated, that originally has been developed by Polygon Technology[9] for the recording and processing of data of a stripe light scanner. During the data import, the position and orientation of the 3d data and photos documented by RiScan Pro are taken over.

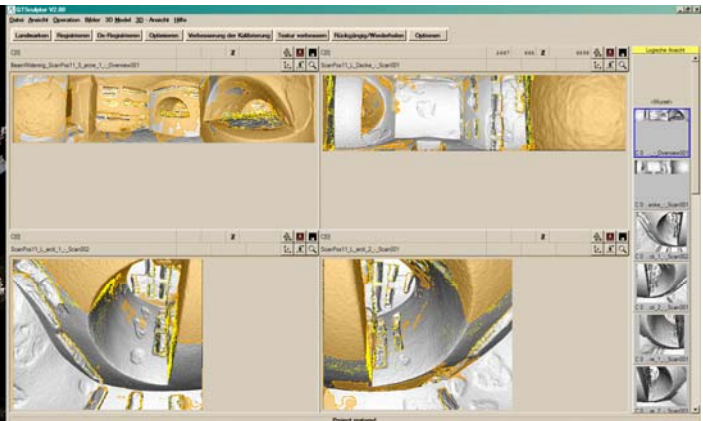Fig. 12 – King David, coloured point cloud of 2 single scans   Fig. 13 – King David, single scans after masking redundancies, *QTS*

The further processing of the data requires the optimization of the registration in QTSculptor. This improves the assemblage of the separate scan positions in reference to each other. During the development of the triangulated model major problems derive from the data *noise* typical of Riegl`s time-of-flight terrestrial laser scanner LMS Z420i with its average accuracy of about 10 mm (standard deviation). In other words: in the point cloud a smooth wall surface is depicted with a depth of about 2 centimetres. QTSculptor`s 2d-filtering offers a potent tool for reducing that noise. The following calculation of redundancies masks all multiple scanned areas, which leads to a significant reduction of the data (Fig. 13). Besides that, QTS does offer the triangulation of point models, but calculating times are extremely high and the quality of its results does not always satisfy the needs. Instead, the modelling software *Geomagic* [10] can be used for triangulation. For the compilation of the model as a point cloud, the 3d data prepared in QTSculptor were imported into Geomagic in form of simple XYZ coordinates. The surface triangulation of a model the size of the Cubiculum of King David containing almost 11 million points, in Geomagic takes about 20 to 30 minutes and almost certainly provides satisfactory results.

Reduction of Data

That way triangulated models still show some defects but they can easily be corrected in Geomagic. Primarily these defects concern spikes and little holes that characterize the mesh. The spikes can almost totally be removed with some simple filters while holes can be closed by a series of alternative algorithms. The few remaining spikes and holes can easily and quickly be eliminated by hand. After the meshing, the model consists of a large number of triangles, depending on the number of points. The triangulated model of

the Cubiculum of King David initially consisted of almost 4 million polygons, so that, for a better manageability it was absolutely necessary to reduce the number of triangles. As a major idea guiding that step, it was most important to find the balance between a sufficient sharpness of the details and a low amount of triangles. For a considerable reduction of the triangles it has proven to be good use to first smooth out the model surface. By that procedure, the above mentioned noise characteristic of the used laser scanner data is minimized once again. Especially adjacent triangles, whose normals deviate by a certain angle, can be reduced to single triangles. Moreover, the smoothing of the surface as well as the reduction of triangles can be applied to only part of or to the entire model. The amount of triangles of the model of King David has finally been reduced to about 840.000. At the same time the design of the surface has been improved without losing essential geometric information (Fig. 14).

By using Geomagic, complete regions of the Catacomb of Domitilla have already been meshed in order to generate plans.
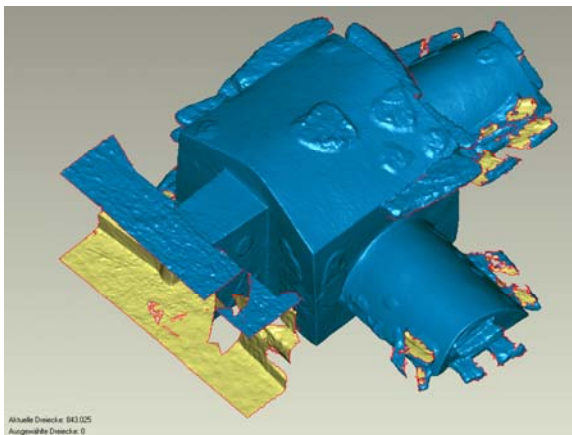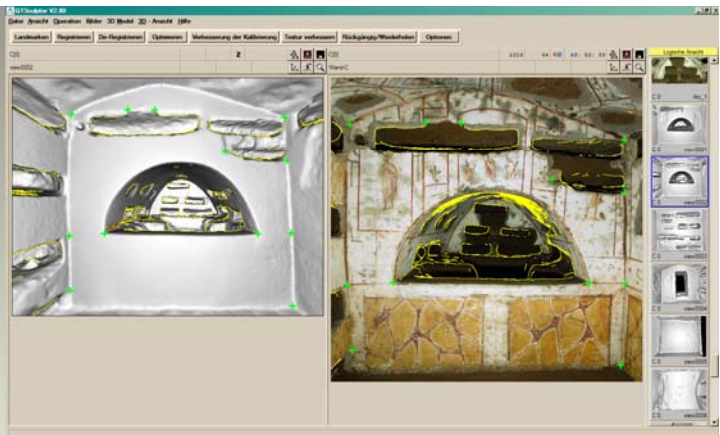

Fig. 14 – King David, mesh processed in *Geomagic*   Fig. 15 – King David, setting of tie points, software *QTSulptor*

Texturing with photos taken under optimal conditions

The entirety of the created triangles results in a continuous description of the amorphous surface of the Cubiculum of King David. A so-called *surface model* was generated starting from the individual points of several single scans. This airtight model considerably helps to understand the geometric form of the architectural space. To obtain an overview of the painted wall decoration in 3d space, however, the texturing of the model is necessary. For this, the entire cubiculum was photographed by a sequence of exposures under optimal lighting conditions using a digital camera operated from an ordinary tripod. To get the best possible visualization results, the brightness and colour values of these photos had to be adjusted in *Photoshop* [11] before mapping the images onto the model (EL-HAKIM, FRYER, PICARD 2004, p. 3).

For the mapping of the photos the model generated in Geomagic was transformed into a *Wavefront* file format [12], converted into a *Object File Format* [13] and inserted into the QTSculptor-project instead of the formerly quickly generated *rough* model. By doing this, the registration of the photos taken during the scanning was maintained, so that these images could have later been used as auxiliary tools for the mapping of the images taken under studio-like conditions.

The mapping of the photos was operated in QTSculptor by manually setting tie points. The number of required tie points here heavily depends on the photographed object and lies between 6 and 30 or more (Fig. 15). But, with no other software known or available to us has it been possible to register non-oriented images onto a 3d model.

The very amorphous and often unstructured surfaces usually hindered an easy setting of tie points, as common points are hardly to be identified in un-textured, grey model surfaces. Here, the already registered

photos taken while scanning have been of great use. By simply setting tie points onto the registered images instead of setting them directly onto the model the mapping of freely taken photos could be facilitated enormously. After registering, all unwanted image areas, such as dark spots in the background, have been masked out, so that these areas were not included into the following calculation of the texture.

QTSculptor offers different resolutions for the calculation of textures. The attainable resolution heavily depends on the size of the model, the number of used photos and the available memory storage (RAM). Textured models with a high resolution very often can only be generated by splitting up large models and processing partial models separately. Models can effectively be split into parts in Geomagic. Walls, room edges and especially monochrome painted areas of the wall paintings offered good dividing lines. In the case of the Cubiculum of King David a division into eight partial models has been operated.

Fig. 16 and 17 – Cubiculum of King David, textured surface 3d model

The here described method enables the calculation of textures of partial models while maintaining the high resolution of geometry and images. Once the texture of all partial models are calculated, the photorealistic textured 3d models are to be transformed into standard *VRML* files [14]. An easy and fast way of assembling partial models without losing their textures can be performed in *RapidForm* [15]. The VRMLs of all partial models are then to be imported with their texture, are marked and are exported as VRML again.

We have, that way, created a photorealistic textured 3d model of the Cubiculum of King David, a highly accurate and informative documentation product, which can not only be used for geometric analysis but also provides the unique opportunity of viewing and examining all of the paintings of one cubiculum under lighting conditions that - neither in reality nor virtually - have been achieved before (Fig. 16 and 17).

Handling of large data sets

The afore said makes obvious that during several steps of the post-processing chain problems arise because of large quantities of data. As long as the almost eighty paintings are viewed as singular, small projects, these problems can be kept under control.

In the course of the six survey campaigns that have been conducted in Rome until now, about 50 percent of the entire Domitilla catacomb has been recorded by laser scanner, among this all 77 known painting units. In total, 1168 scanning positions were necessary. With an average number of 1.3 million points per scan this amounts to 1.5 billion points. Considering the fact that the second half of the catacomb is still to be recorded, this number will even double. Assuming that the recorded data of the entire catacomb including all textured

models of paintings were to be fused in one large file, 77 multiplied by 600 000 polygons had to be added, and it becomes evident that these large quantities of data cannot be handled by standard PCs.

Campaign	RiScan Project	Scan Positions	Number of Points
2006.01	Basilika	43	55.9 Mio.
	Ebene_drei_und_vier	20	26 Mio
	Hypogäum_der_Flavier	92	119.6 Mio
	Outdoor	3	3.9 Mio
	Guter_Hirte	46	59.8 Mio
	Umzubenennender_Gang	23	29.9 Mio
2006.05	Eulalios	42	29.9 Mio
	Guter_Hirte_1_OG	68	88.4 Mio
2006.09	Ampliatus	86	111.8 Mio
	Orpheus	113	146.9 Mio
2007.01	Flavia_07	144	187.2 Mio
	Flavii_Aurelii	48	62.4 Mio
	Retro_Sanctos	124	161.2 Mio
2007.05	Dom_Bäcker	140	182 Mio
2007.10	Dom_2007.10	176	228.8 Mio
		1 168	**1 518 400 000**

Tab. 1 – Scanning Output 2006 / 2007

By way of reducing the point density considerably (octree filtered 20 cm point distance), it became possible to gather scanning data of all until today surveyed areas in one view in order to export them for further meshing. But even so, the necessary resolution of building detail is lost, which becomes evident when zooming in, and still, the textured models of the paintings are missing.

For viewing purposes, M. Wimmer and C. Scheiblauer have developed an intelligent 3d viewer capable of showing points and polygons adopting the concept of viewing different levels of detail (WIMMER, SCHEIBLAUER 2006). An interdisciplinary collaboration has been started to enable this new tool for handling large data sets like the ones produced at Domitilla.

Conclusions

The presented strategy shows one possible way from the point-cloud to a textured surface model, that satisfies highest precision and resolution standards. While the amount of time spent on site – for scanning of a standard painted cubiculum about 1 hour, for capturing free images 8 hours – is relatively low, post-processing requires about 3 to 4 weeks of continuous work. That equals an acquisition – post-processing ratio of about 1:15. While, from our point of view, site work cannot be further optimized adopting the above mentioned technologies, a lot of time could probably be saved during post-processing, if necessary procedures could be simplified or at least be solved inside only one or two software packages. The most time consuming step is momentarily represented by registration of free images, that requires setting large numbers of tie-points manually. Besides that, the described splitting of one homogenous data set into manageable smaller units appears anachronistic. And thirdly, the necessary image editing steps ought to be

realized inside the 3d-modelling software, as one of the foremost problems lies in adjusting images at their joints in 3d space.

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

[2] Homepage TU Vienna, Department of History of Architecture and Building Archaeology: http://www.baukunst.tuwien.ac.at

[3] The archaeologists are Dr. N. Zimmermann and Dr. V. Tsamakda, the architects are Dipl.Ing. G. Eßer and Dipl.Ing. I. Mayer.

[4] Homepage TU-WIL Scan Center of Competence: http://tuwilscan.cg.tuwien.ac.at/ (accessed Feb. 9th 2008)

[5] Homepage of Riegl Laser Measurement Systems: http://www.riegl.com

[6] We warmly thank the secretary of the PCAS, Prof. F. Bisconti, and the inspector of the Roman catacombs, Dr. R. Giuliani, for the commission and all kind support and help.

[7] For more information see Riegl Homepage: http://www.riegl.com/terrestrial_scanners/lms-z420i_/420i_all.htm (accessed Feb. 9th 2008)

[8] Homepage of Kino Flo Inc., Homepage: http://www.kinoflo.com

[9] Homepage of Polygon Technology GmbH: www.polygon-technology.de

[10] Homepage of Geomagic, Inc.: www.geomagic.com

[11] Homepage of Adobe: www.adobe.com/products/photoshop

[12] *Wavefront* is a useful standard for representing polygonal data in ASCII form

[13] *Object File Format* is a standard for simple presentation of 3D objects

[14] *Virtual Reality Modelling Language* is a standard file format for representing 3D interactive vector graphics

[15] *Rapidform* is a brand of INUS Technology Inc., Homepage: www.rapidform.com