# MULTI-SPECTRAL HIGH-RESOLUTION 3D-ACQUISITION FOR RAPID ARCHAEOLOGICAL DOCUMENTATION AND ANALYSIS

*Hubert Mara, Bernd Breuckmann and Claudia Lang-Auinger*

IWR – University of Heidelberg
Interdisciplinary Center for Scientific Computing
Im Neuenheimer Feld 368
69120 Heidelberg, Germany
phone: +49 6221 54 4949
fax: +49 6221 54 8850
hubert.mara@iwr.uni-heidelberg.de
http://www.iwr.uni-heidelberg.de

Breuckmann GmbH
Torenstraße 14
88709 Meersburg
Germany
phone: +49 7532 4346 0
fax: +49 7532 4346 50
bernd.breuckmann@breuckmann.com
http://www.breuckmann.com

Austrian Academy of Sciences
Inst. for Studies of Ancient Culture
Bäckerstraße 13
1010 Vienna, Austria
phone: +43 1 51581 3485
fax: +43 1 51581 3489
claudia.lang@oeaw.ac.at
http://www.oeaw.ac.at

## ABSTRACT

The demands of state-of-the art documentation and analysis of our cultural heritage motivated us for interdisciplinary cooperation between various countries and institutions. This includes a wide range of possible partners, which are a company supplying us with adapted hardware and software for Cultural Heritage; archaeologists working in the field as well as those taking care of objects already within a museum; and the faculty of mathematics and computer science for development of new methodologies utilizing new technologies.

The main focus of this paper is on documentation and analysis of ancient artworks found as frescoes on the Villa *Oplontis* in Pompeii, Italy and white grounded vases (*Lekythoi*) of the *Kunsthistorisches*[1] *Museum* (KHM) in Vienna, Austria. Both finds are of fragile nature and permanently endangered by the environment. In-situ we demonstrated how we can rapidly acquire the tremendous amounts of square-meters of frescoes, while we showed a similar efficient work-flow for ceramics within the KHM. This was done also maintaining a high-resolution in $\mu m$-range for 3D-data for in-depth analysis for detection of fakes, traces of old restauration attempts and ancient manufacturing techniques. For both methods an important outcome for archeology is the exact localization and quantization of structures/points of interest. For architecture we can also show an approach for damage prediction, which is essential for damage prevention. Due to ongoing cooperations and new projects we will show methodologically related work on objects of other periods of Cultural Heritage.

Future work already began by embedding the outcomes of our projects into daily work of archaeologists. For our cases these are the publication of two volumes of the *Corpus Vasorum Antiquorum* book series of ceramic documentation. Further future work considers additional means of 3D-visualization and analysis.

## 1. INTRODUCTION

Motivated by the challenges in archaeology and especially archaeometry [Leute, 1987], we are developing different kinds of contact- and radiation-free systems for field application. These fully-automated [Kampel and Sablatnig, 2003] and semi-automated system [Lettner et al., 2006] help archaeologists to get efficiently and accurate their daily work done. On the other hand-side gives us this kind of work interesting challenges as there often exists no ground truth about these human-made objects of Cultural Heritage.

Having at least a decade of experience in inter- and trans-disciplinary projects [Sablatnig et al., 1991], this paper presents state-of-the-art methods and hardware for in-situ rapid and high-resolution 3-dimensional documentation of painted surfaces. As test-case we choose the Villa Oplontis [Carcavallo, 1980] – also known as Villa Poppaea – with hundreds of square-meters of walls decorated with roman frescos [Clarke, 1991] of high-value for art-history.

Before we show our work in Villa Oplontis the next section shows previous work within the *Kunsthistorisches Museum Wien*. On a first glance the work done in these projects are related as they both utilize the keywords *Multispectral* and *3D-Acquisition*. If one take a closer look the aims are different as well as the methodologies and the outcomes, but we have to stress that they are not mutually exclusive and can be combined.

## 2. MULTISPECTRAL ANALYSIS – KHM, VIENNA

For 3D-acquisition we always use a 3D-scanner based on the principle of structured light [Cosmas et al., 2001]. Typically 4 to 6 3D-images, which are registered and background objects supporting the ceramics are removed [Mara, 2006]. The result is a 3D-model describing the surface of the ceramic. For archaeological publication and further analysis, we had to estimate a profile-line. This is the longest elongation around - or cross-section through - the wall of a vessel defined by the rotational axis (also called axis of symmetry). The term rotational axis relates to the fact that rotational wheels (plates) have been used for thousands of years for manufacturing ceramics. Therefore we base our work on using the rotational axis to orient a vessel (or its fragment) to estimate the profile line as it is done manually in drawings. As the creation of manual drawings is a time-consuming task requiring expert-skills our system helps to dramatically reduce the time for documentation. Additionally estimated profile lines represent an objective drawing, while manual drawings can have a notable derivation from the real objects due to human interpretation during drawing.

Due to the fact that ceramics also have painted surfaces an important research question concerns the recipe of the paint. This question can be answered by analyzing the pigments of a color. During our project we acquired 105 multi-

---

[1] History of Arts

spectral readings of 17 lekythoi (vases) having a painted surface. The surfaces of these vessels have been measured on a *Perkin-Elmer Lamda 900 UV-VIS-NIR (UltraViolett, VISible Light, Near InfraRed) Spectrometer* applying the diffuse reflectance technique using a 60mm integration sphere. The reflectograms have been measured from 190nm up to 2500nm in 10nm steps. The chosen method has some limitations concerning the evaluation of the intensity of the measurements: Due to the restricted setup and the varying size of the objects, the distance between object and slit could not be kept constant; since the objects are not flat, different curvatures also result in a variation of the measured intensities; due to the fixed size of the measurement area given by the slit of the Spectrometer in certain cases the pigmented area is smaller than the measurement area which results in a measurement of a mixture of background and pigment.

These limitations do not allow an exact measurement of the absolute reflectance. Still the measured curves can be evaluated, since the relative reflectance at a different wavelength can be used to identify pigment specific characteristics without any post-processing. As this is not satisfactory for future analysis and especially not for automated analysis we decided to determine the geometry of the setup by 3D-acquisition of the setup for each multi-spectral reading of every vessel. Therefore we have to register and estimate the location of the measurement area on the 3D-models.

To register (combine) the spot measurement of the Spectrometer we used the same techniques and the same 3D-scanner as for the acquisition of the 3D-models. Having the 3D-models of the vessels already available which were acquired in an earlier documentation phase, we needed only one 3D-scan per multi-spectral reading. The following steps are performed for determining the geometry of the scene:

1. Acquisition of a complete 3D model (as done for profile estimation).
2. 3D-Acquisition of the "beam" and object at measurement position. The beams position was estimated by placing an elongated calibration object with prismatic shape into the beam, and marking the position of the Spectrometer slit. The 3D-scanner setup must not be changed between the acquisition of the beam and the acquisition of the measuring scene.
3. Registration of vessel 3D-model with vessel and beam, calculate the intersection between beam and object in order to determine the measurement position.

As the Spectrometer can only acquire multi-spectral readings at certain spots (points) and due to time constraints (10 minutes/reading) we selected points of special interest. It turned out that even samples which appear the same for the human eye can show a significant difference in the reflectograms, e.g. the red colour used for the depiction of hair between 1400 and 1500*nm* (infrared) (see Figure 1). This indicates that different ingredients have been used. An application of this analysis can help to determine fake objects or recent – but not documented – restauration without taking samples.

In general the acquired data and this technique in combination with a pigment database will assist in further analysis. We planned to set up a database of colour pigments in collaboration with experts of chemistry, similar to the work done within the project *Casandra* (FWF-Project P15471-MAT, [Asinger et al., 2005]).

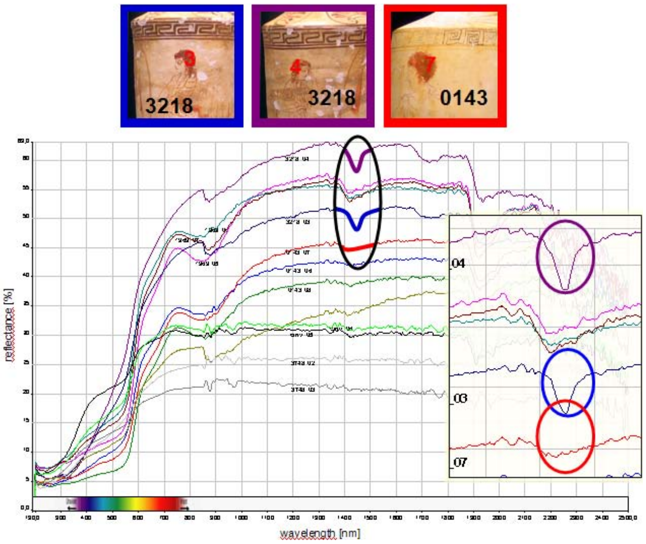


Figure 1: Reflectogram of the red colour used for the depiction of hair on white ground lekythoi

## 3. MULTISPECTRAL 3D-ACQUISITION – OPLONTIS, ITALY

Conducting two different experiments, we used to different *Breuckmann HighDefinition* 3D-scanners for acquisition having a spatial resolution of $10\mu m$ and accuracy $\approx 2\mu m$ in height/depth. These 3D-scanners consist of 5 Megapixel cameras, which allows us to achive up to 2.400 $dpi$ (dot per inch) for flat surfaces.The first experiment concerned the rapid documentation of large areas of frescos covering hundreds of square-meters, while maintaining high accuracy for restoration planning and long-time surveys of weathering effects. Related work about the virtual restoration of weathered ancient laws of Ephesos can be found in [Kalasek et al., 2008].

The main features of the *triTOS-3D/smartSCAN-3D-scanner* by Breuckmann GmbH are: two digital colour cameras, each one with 1.4 Megapixel; synchronous acquisition of 3D-shape and colour (texture-map); and a variable field of view (FOV): between 90*mm* and 650*mm* image diagonal.

Concerning the performance regarding overall documentation time, we used a larger field of view having a 600*mm* image diagonal for the 3D-acquisition in room 10 of the Villa Oplontis. This particular field of view maximises the acquired area and therefore performance enabling the acquisition of expected details of the frescos. These details are seams and corrections introduced at the time of painting; modern restoration artefacts; and cracks due to weathering. This setup covered an area of $480 \times 360mm$ per acquisition having a spatial resolution of 0.35*mm* and a depth/height resolution of $\approx 20\mu m$.

The 3D-acquisition and the post-processing were done using the *OPTOCAT* software-package by Breuckmann. As the single 3D-scans have to be stitched, they were also aligned and registered [Besl and McKay, 1992, Chen and Medioni, 1992] using the geometry of the surfaces. Finally all 3D-scans were merged, resulting in a single (polygonal) 3D-mesh [Hoppe et al., 1992]. We have to stress, that the result –- the polygonal mesh –- is scaled with the accuracy depending on the calibration of the scanner and its field of view. For our experiments using the *triTOS-3D* system with a field of view (600*mm*) typically has an accuracy of 100$\mu m$ or less.

### 3.1 The new prototype - a modified optoTOP-HE 3D-scanner

This novel prototype is also known as *MSS-3D* multi-spectral 3D-scanner. It is developed as cooperation between Breuckmann and Tondo. It was first introduced in [Végvári and Breuckmann, 2008] for an application in art history, where previously hidden signature of a famous artist could be revealed. At present day the *MMS-3D* allows 3D-acquisition of objects with painted surfaces in different wavelength from near Infrared to Deep Blue.

Similar to the previous setup only one 1.4 Megapixel monochrome camera is used for acquisition having a smaller field of view with 100*mm* image diagonal. This small field of view was chosen to maximize the spatial resolution to 60$\mu m$ and a depth/height resolution of 5$\mu m$. For the optimal scanning distance of the fresco this corresponds to a planar resolution of $\approx 400dpi$.

## 4. EXPERIMENTS

Having a time frame of a few working hours for these preliminary experiments, the experts selected two important points of interests. The first experiment was the acquisition of opposing frescos with mirrored content in room 10 – the *Triclinio* (formal dining room). This was a two-folded task as these frescos cover several square-meters and therefore the first part was to demonstrate a fast and easy work-flow. The second part concerns the fact that one of the opposing frescos is supposed to be from a later period and/or another workshop, which require a highly focused inspection on points of interest, which for our examples were the bird in the lower area as this artistic painting requiring a highly skilled craftsperson, which means a high probability to find characteristic workshop features.

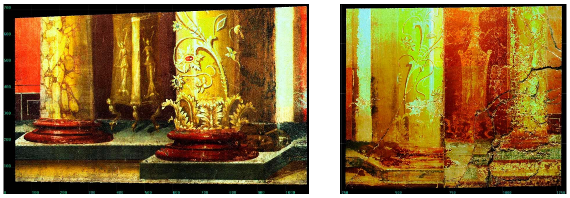
The second experiment was the acquisition of the faded fresco under the arch in room 11 – the *Cubiculum* (sleeping room) – to determine its current state. It was excavated and documented by a drawing in a very well preserved state in the 1960's. As it has suffered heavy weathering in the last 4 decades, by today only small fractions are barely preserved. Furthermore it is difficult to access for human inspection as well as for other means like photography as it is located near the ceiling in a dark environment (as preventive measure).

Both tasks split into the following work-flow. First the complete fresco is 3D-acquired using a regular 3D-scanner (*triTOS-3D*). Secondly specific areas of interest are selected using expert knowledge and 3D-acquired in higher resolution with our new prototype multi-spectral 3D-scanner (*MSS-3D*). The following sections show results for these two steps of our two experiments.

### 4.1 White Light 3D-Acquisition

Figure 2 shows a photograph of a part of the acquired area and our 3D-scanner. Figure 3 shows a visualisation of the polygonal mesh (3D-model) with texture-map. Figure 4 shows the same polygonal mesh without texture-map. We have to mention that the heights and depths of the surface details (z-values) were magnified by a factor of 5 for this visualization.

Figure 2: Fresco on the west wall with triTOS-3D scanner – Note: the bird on the left-hand-side was also acquired using the MSS-3D multi-spectral scanner.



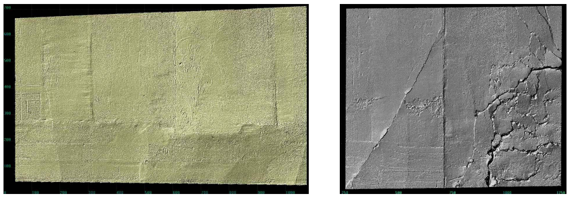
(a) (b)

Figure 3: Visualisation of the recorded 3D-data of the (a) west and (b) east wall with texture-map.

An alternative visualisation of the 3D-mesh of the fresco is shown in Figure 5. The Figure shows the height as a pseudocolor plot, where the different colours represent different $z$-values according to the corresponding colour-scale (bar top-left). The reference ($z = 0$ or $xy$-plane) is estimated as best-fit plane of the surface. As the surface was globally smoothed using the low frequency domain the colours in the Figure show the global deviation of the shape of the fresco to an ideally flat plane. The deviation can be introduced by three reasons: First of all and trivial: man-made objects are never flat. Secondly the deviation could have been introduced during restoration. Finally it can also be a sign of weathering like water dispersing into the wall. Practically combinations are very likely.

A second possibility is a comparison to a curved surface described by a polynomial function having higher degrees. Figure 6a shows for example using a degree of 13. This curved surface is also used as reference – like an ideal plane – and aligned using the same best-fit algorithm. This approach mainly shows the medium frequency parts of the z-values.

The third possibility is to show only high frequency parts



(a) (b)

Figure 4: 3D-data (fresco relief) without colour ($z$-values magnified by a factor of 5).

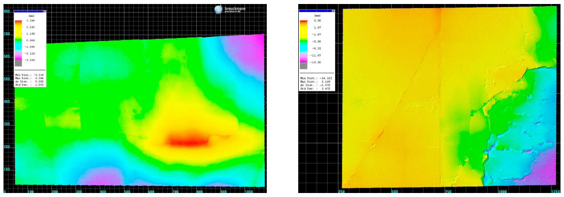

(a) (b)

Figure 5: Pseudocolor plot of the height/depth (compared to a flat plane in the low frequency domain) for the (a) west and (b) east wall.

adapted using high pass filters – removing the low frequency domain (see Figure 6b).

However, the best choice of visualization using different references and filters depends on the application. Regarding our experience of previous applications for cultural heritage domain a best practice guide for daily fieldwork will be determined considering e.g. *The London Charter* [Beacham et al., 2006, Ogleby, 2007].

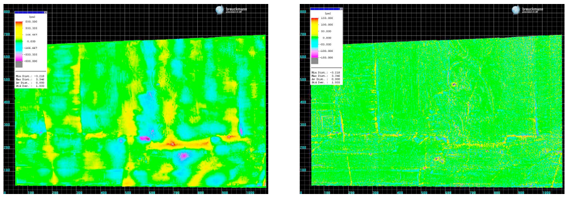

(a) (b)

Figure 6: West wall: (a) Comparison with a curved surface of degree 13, medium frequency domain. (b) Visualization of the high frequency domain of the 3D-mesh.

### 4.2 High-Resolution Multispectral 3D-acquisition

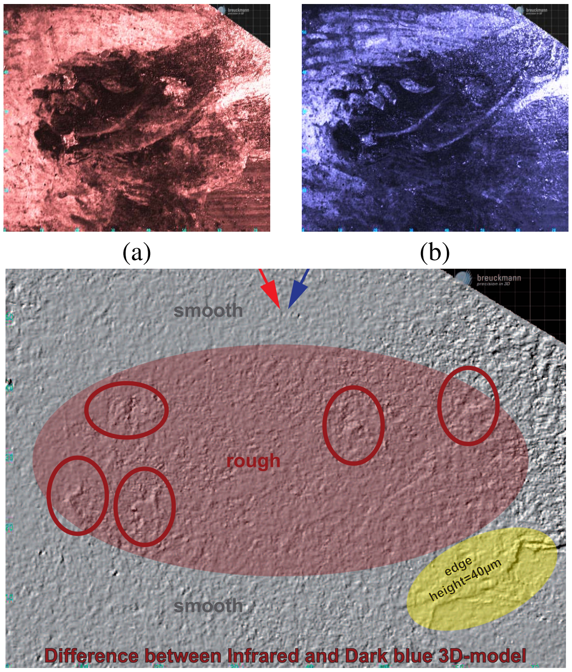
Bird on the west wall. As the east and the west fresco in room 11 contain a painting of a bird, we acquired its plumage using the *MSS-3D* as it has the most artistic details. Figure 7a,b shows the 3D-scans using an Infrared and a dark blue filter ”close ultraviolet”. Figure 7c shows the difference in height between these two scans. In the lower right corner an additional layer of paint can be detected having an average height of 40$\mu m$.

## 5. RESULTS

An area of about $1.000 \times 600mm$ has been digitized by 3D-acquisition of 6 overlapping areas on the west wall of room 10. The empiric overlap typically is $\approx 15\%$ depending on surface details. The total acquisition time for this area was 15 minutes. On the opposite (west) wall a slightly larger area of $1.000 \times 900mm$ has been digitized by 3D-acquisition of 9 overlapping areas within 20 minutes.

The same performance, while maintaining the high-resolution in the $\mu$m- range was demonstrated for the weathered fresco in room 11. The arc-shaped fresco under the ceiling in a height of 3m was digitized by 3D-acquisition of 15 overlapping areas requiring half an hour. Figure 8b shows the final 3D-mesh with and without texture-map.

Beside high-resolution and high-performance, we could also give the experts of archeology a precise and therefore


(a) (b)

(c)

Figure 7: 3D-mesh of the bird’s plumage acquired using (a) Infrared and (b) dark-blue filters. The texture-map shows the reflection of the filtered light. (c) Difference of height between the Infrared and dark-blue 3D-meshes. The lower right corner shows a height of 40$\mu m$ of an additional layer of paint. No texture-map is shown.

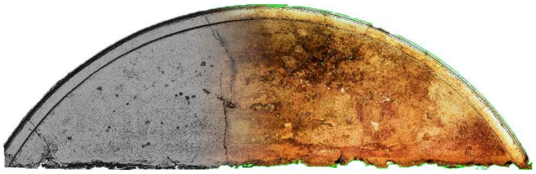


Figure 8: 3D-mesh (left) without and (right) with texture-map of the fresco in room 11.

objective measurements of important features. Just to mention a few, theses features are ancient traces of the paint-process (seam), paint-strokes of ancient corrections of the images as well as modern changes from restauration. Especially for these features the possibility of ”seeing thru” of layers of paint proofed valuable for determination of drawing styles, which is important for classification e.g. of workshops or time-periods.

Another concern is the comparison to other types and generations of 3D-scanners. For the application of fresco documentation an in-situ comparison was not possible due to budget and time constraints. Having experience of more than a decade of documentation of small objects – typically ceramics [Sablatnig and Menard, 1997] – we can assess that 3D-scanners no older than three years (e.g. used for [Lettner et al., 2006]) cannot reach the accuracy shown in this paper by a factor of 10 or more. This means the level of required accuracy [Shannon, 1948] for frescoes is not met. Vice versa we can assess that this new generation of 3D-scanners will extend the documentation of any other type of painted surface known in Cultural Heritage (e.g. fine-ware ceramics) by adding information of the height of a the paint.

## 6. CONCLUSIONS AND OUTLOOK

We could show that even large frescos having several square meters in size can be done in reasonable time, e.g. during one or two excavation seasons (of typically 4-6 weeks). It has to be stressed that this is not only a course documentation, which could be done by photographs, because we achieve a resolution and accuracy in $\mu m$-scale. This enables not only the documentation of the artistic content, it also enables the documentation of the production technique of frescos like seams and paint strokes, as well as it reveals modern, but old restoration attempts. As also degeneration features like cracks or bended surfaces are documentation we can propose a degeneration prediction, which can focus and optimize restoration in an accurate predictive way.

For future work we also propose a cooperation using mid-range 3D-scanners to embed the highly accurate fresco 3D-scans within a proper 3D-model of the complete site. This will answer all the preservation questions from an architectural point of view as well as for preservation of the frescos themselves in reality and virtual reality.

## ACKNOWLEDGEMENTS

We thank John R. Clarke from the University of Texas for the invitation to the Villa Oplontis and his expert advises. We also thank him and his team for providing in-situ organization of the administration and infrastructure.

## REFERENCES

[Asinger et al., 2005] Asinger, C., Kammerer, P., and Zolda, E. (2005). Classification of Color Pigments in Hyperspectral Images. In Hanbury, A. and Bischof, H., editors, *Proc. of the 10th Computer Vision Winter Workshop*.

[Beacham et al., 2006] Beacham, R., Denard, H., and Niccolucci, F. (2006). An introduction to the london charter. In et al., M. I., editor, *The e-volution of Information Communication Technology in Cultural Heritage: where hi-tech touches the past: risks and challenges for the 21st century, Short papers from the joint event CIPA/VAST/EG/EuroMed*, Budapest, Hungary. Archaeolingua.

[Besl and McKay, 1992] Besl, P. and McKay, N. (1992). A Method for Registration of 3-D Shapes. *IEEE Trans. on Pattern Analysis and Machine Intelligence*, 14(2).

[Carcavallo, 1980] Carcavallo, S. (1980). *Oplontis: The Villa Poppea*. Weald Publishing Agency.

[Chen and Medioni, 1992] Chen, Y. and Medioni, G. (1992). Object Modelling by Registration of Multiple Range Images. *Image and Vision Computing*, 10:145—155.

[Clarke, 1991] Clarke, J. R. (1991). *The Houses of Roman Italy, 100 B.C.-A.D. 250: Ritual, Space, and Decoration*. Berkeley, University of California Press.

[Cosmas et al., 2001] Cosmas, J., Itagaki, T., Green, D., Grabczewski, E., Gool, L. V., Zalesny, A., Vanrintel, D., Leberl, F., Grabner, M., Schindler, K., Karner, K., Gervautz, M., Hynst, S., Waelkens, M., Pollefeys, M., DeGeest, R., Sablatnig, R., and Kampel, M. (2001). 3D MURALE: A Multimedia System for Archaeology. In *Proceedings of the International Conference on Virtual Reality, Archaeology and Cultural Heritage*, pages 297–305, Athens, Greece.

[Hoppe et al., 1992] Hoppe, H., DeRose, T., Duchampy, T., McDonaldz, J., and Stuetzlez, W. (1992). Surface reconstruction from unorganized points. In *Proc. of 19st Annual Conference on Computer Graphics and Interactive Techniques, SIGGRAPH*, pages 71–78.

[Kalasek et al., 2008] Kalasek, R., Mara, H., and Taeuber, H. (2008). Reading weathered ancient laws in 3rd dimension. In *Proc. of the 13.* Int. Tagung: Kulturelles Erbe und Neue Technologien, page to appear.

[Kampel and Sablatnig, 2003] Kampel, M. and Sablatnig, R. (2003). An Automated Pottery Archival and Reconstruction System. *Journal of Visualization and Computer Animation*, Vol. 14:111–120.

[Lettner et al., 2006] Lettner, M., Mara, H., Mueller, A., Sablatnig, R., Singer, M., and Krenn, M. (2006). Pat: Profile analysis tool for the documentation of archaeological finds. In Sablatnig, R., Hemsley, J., Kammerer, P., Zolda, E., and Stockinger, J., editors, *Digital Cultural Heritage - Essential for Tourism, Proc. of 1st. EVA 2006 Vienna Conference*, volume 211 of *Schriftenreihe der OCG*, pages 83–90, Vienna, Austria.

[Lettner et al., 2006] Lettner, M., Mara, H., Müller, A., Sablatnig, R., Singer, M., and Krenn, M. (2006). Pat: Profile analysis tool for the documentation of archaeological finds. In *Proc. of Electronic Imaging & the Visual Art – Digital Cultural Heritage – Essential for Tourism (EVA Wien)*, pages 83–90.

[Leute, 1987] Leute, U. (1987). *Archaeometry: An Introduction to Physical Methods in Archaeology and the History of Art*. John Wiley & Sons.

[Mara, 2006] Mara, H. (2006). Documentation of Rotationally Symmetrical Archaeological Finds by 3D Shape Estimation. Master's thesis, Vienna University of Technology, Institute of Computer Aided Automation, Pattern Recognition and Image Processing Group. Supervisor: Robert Sablatnig – see also PRIP technical report nr. 83.

[Ogleby, 2007] Ogleby, C. (2007). The "truthlikeness" of virtual reality reconstructions of architectural heritage: concepts and metadata. In *Proc. of the 2nd ISPRS International Workshop 3D-ARCH 2007: "3D Virtual Reconstruction and Visualization of Complex Architectures", International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences Volume XXXVI-5/W47.*

[Sablatnig and Menard, 1997] Sablatnig, R. and Menard, C. (1997). 3d reconstruction of archaeological pottery using profile primitives. In Sarris, N. and Strintzis, M., editors, *Proc. of Intl. Workshop on Synthetic-Natural Hybrid Coding and Three-Dimensional Imaging*, pages 93–96, Rhodes, Greece.

[Sablatnig et al., 1991] Sablatnig, R., Menard, C., and Dintsis, P. (1991). A Preliminary Study on Methods for a Pictorial Acquisition of Archaeological Finds. Technical Report PRIP-TR-010, Vienna University of Technology, Institute of Computer Aided Automation, Pattern Recognition and Image Processing Group.

[Shannon, 1948] Shannon, C. (1948). A Mathematical Theory of Communication. *Bell System Technical Journal*, 27:379–423 and 623–656.

[Végvári and Breuckmann, 2008] Végvári, Z. and Breuckmann, B. (2008). High definition 3d-surface scanning and applications in arts and cultural heritage. In *Proc. of the 36. Computer Applications in Archaeology – "On the Road to Reconstructing the Past" (CAA)*, page in press.