COMBINED 3D AND MULTISPECTRAL FRESCO DOCUMENTATION OF THE VILLA OPLONTIS, POMPEI
High-Resolution and High-Performance Digitization of Cultural Heritage

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Abstract: Motivated by cultural heritage, industry, medicine we are developing 3D-scanners and post-processing systems for rapid and precise documentation of surfaces with curvature. By constantly increasing resolution and accuracy of our system we can enable the documentation of small deviations of even flat surfaces – like frescos. This enables documentation of important features for restoration like small fractures or topology of paint-strokes for scientific research. The 3D-documentation can be done in-situ, radiation-free and contact-free using a structured (coded) light-source and a digital camera. Using light for documentation of colourful painted surface lead to the integration of colour-filtering techniques to ”see thru” the first layer(s) of paint. This approach, typically known from photography, is used to reveal under- drawings of paintings. While photographs suffer from lens distortion lacking a precise scale, we can provide the height of paint-layers in μm in a properly calibrated scale. This method has already been successful tested on synthetic data and medieval paintings and statues, which cover not all painting techniques known to art historians. Therefore we conducted experiments in Pompei to determine the capabilities of our system for fresco paintings. Results shown in this report cover traditional close-range 3D-acquisition for larger fields of view (m^2) and multi-spectral 3D-acquisition for paint layers having a field of view of $\approx 600cm^2$. Regarding performance – having a tremendous amount of frescos – we could show that 3D-acquisition can be done in $\approx$ 15 minutes per m^2. Multi-spectral 3D-acquisition can be applied in a similar fast manner by using expert-knowledge to narrow down the areas of interest.

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.

Our *Topometrical HighDefinition* 3D-surface scan-

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ners are optimized for the requirements of arts and cultural heritage. Our scanners allow the 3-dimensional digitization of art objects and paintings with state-of-the-art spatial resolution of $10\mu m$ and accuracy $\approx 2\mu m$ in height/depth. As cultural heritage objects are often colourful objects, the colour is acquired as so-called texture-map. The benefit of this texture-map compared to photography is the correspondence between 3D coordinates and colour information. This is important e.g. for long-time surveys of colour degradation. Depending on the cultural heritage application our 3D-scanners can be tailored using a wide-selection of fields of view, triangulation angles and resolution. Using 5 Megapixel cameras we can achieve up to 2.400 dpi (dot per inch) for flat objects. As all our systems consist of robust modules they can be adjusted by the user for a wide variety of applications ranging e.g. from laboratories and museums to field-use at archaeological excavations.

The 3D-models recorded with our systems can be used for virtual reality visualization; documentation and archiving; and for scientific analysis. Typical examples for using 3D-models of our partners in cultural heritage are:

- Documentation and archiving of art objects.
- Virtual reconstruction of art objects.
- Virtual presentation in museums and in the internet.
- Manufacturing and rapid prototyping of scaled copies and replicas.
- Scientific analysis of palaeontological and archaeological findings.
- Quantitative mapping of damages on sculptures and monuments.
- Generation of Identity Cards and Digital Fingerprints.
- Manufacturing of tailored transportation packages.

2 ACQUISITION

Conducting two different experiments, we used to different Breuckmann HighDefinition 3D-scanners for acquisition. The first experiment concerned the rapid documentation of large areas of frescos covering hundred 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), while an alternate use of multispectral 3D-survey can be found in (Mara et al., 2007). Figure 1 shows these two different 3D-scanners in standard configuration.

(a) (b)

Figure 1: (a) AsmartSCAN-3D scanner and (b) optoTOP-HE scanner either for a large field of view (top) and a small field of view (bottom).

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 $90mm$ and $650mm$ image diagonal.

For the performance biased experiments in room 10 of the Villa Oplontis a field of view having a $600mm$ image diagonal was used. 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 $0.35mm$ and a depth/height resolution of $\approx 20\mu m$.

As 3D-acquisition using the principle of structured light (Cosmas et al., 2001) works better in darker environments, while colour acquisition requires brighter illumination the best solution are controllable lights, which are supported by our system. As this is a well approved method and due to time and space constraints of this field-trip we decided to use simple Halogen lamps already on-site. Even with this quality drawback the texture maps of the 3D-models are sufficient for most documentation and analysis tasks. For a full-scale 3D-acquisition campaign we advice to use controllable lights as we expected, that future scientific analysis and restoration will have a noticeable benefit using state-of-the-art illumination.

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 100μm or less.

2.1 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 60μm and a depth/height resolution of 5μm. For the optimal scanning distance of the fresco this corresponds to a planar resolution of $\approx 400 dpi$.

3 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.

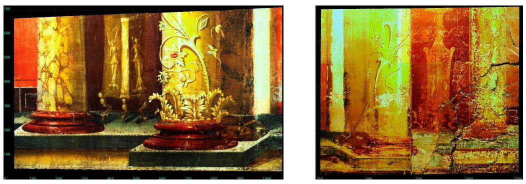
The second experiment was the acquisition of the faded fresco under the arch in room 11 – the *Cubiculum* (sleeping room) – to determine its current state. It was excavated and documented by a drawing in a very well preserved state in the 1960's. As it has suffered heavy weathering in the last 4 decades, 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.

3.1 White Light 3D-Acquisition

Figure 2 show 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.

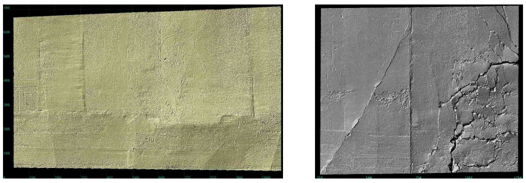
Figure 2: Fresco on the west wall with triTOS-3D scanner Note: the bird on the left-hand-side was also acquired using the MSS-3D multi-spectral scanner.



(a) (b)

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

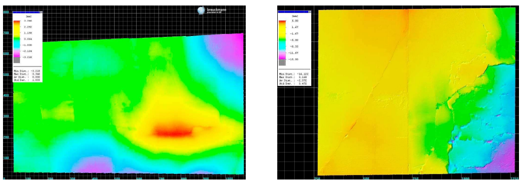
An alternative visualisation of the 3D-mesh of the fresco is shown in Figure 5. The Figure shows the height as a pseudocolor plot, where the different colours represent different *z*-values according to the corresponding colour-scale (bar top-left). The reference ($z = 0$ or *xy*-plane) is estimated 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



(a) (b)

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

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) (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.

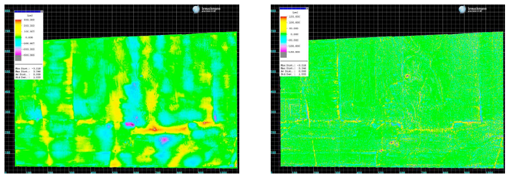
A second possibility is a comparison to a curved surface described by a polynomial function having higher degrees. Figure 6a shows for example using a degree of 13. This curved surface is also used as reference like an ideal plane and aligned using the same best-fit algorithm. This approach mainly shows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

The third possibility is to show only high frequency parts 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).

3.2 High-Resolution Multispectral 3D-acquisition

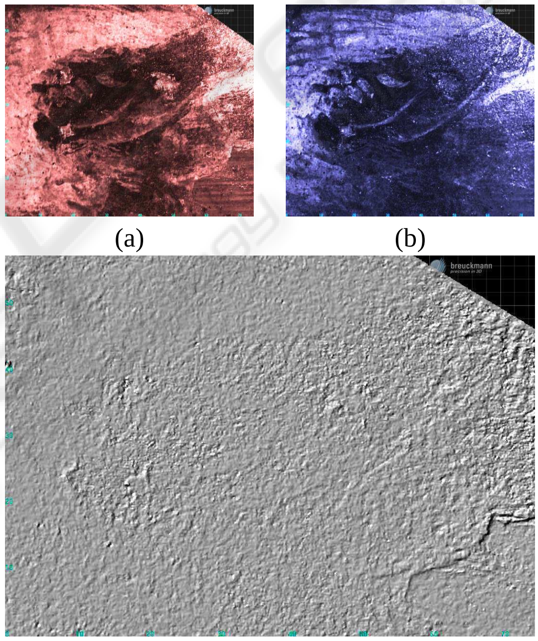
Bird on the west wall. As the east and the west fresco in room 11 contain a painting of a bird, we acquired its plumage using the *MSS-3D* as it has the most artistic details. Figure 7a,b shows the 3D-scans



(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.

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 $40\mu m$.



(a) (b)

(c)

Figure 7: 3D-mesh of the birds 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.

4 RESULTS

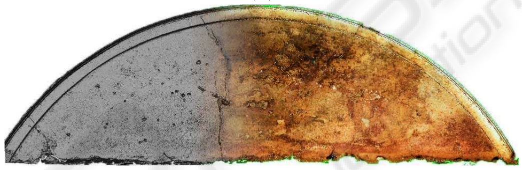
An area of about $1.000 \times 600mm$ has been digitized by 3D-acquisiton of 6 overlapping areas on the west wall of room 10. The empiric overlap typically is $\approx 15\%$ depending on surface details. The total acquisition time for this area was 15 minutes. Using - as previously proposed - controlled lights will only slightly affect the time for setting up the 3D-scanning equipment, which typically require 15-30 minutes (per room and/or day). On the opposite (west) wall a slightly larger area of $1.000 \times 900mm$ has been digitized by 3D- acuqisition of 9 overlapping areas within 20 minutes.

The same performance, while maintaining the high-resolution in the μm- 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. Due to the lack of photographic illumination the texture-map of the fresco acquired by the 3D-scanner lacks proper colour representation including highlights from the halogen lamps. To overcome this we took 9 extra photographs with a *Nikon D300* (at 18mm f/3.6, 12 Megapixel Camera-RAW) to estimate a panoramic image, which has been used as alternative texture-map. This procedure shows an alternate way for colouring a 3D-mesh in case a higher resolution for the texture-map is required. Alternatively old manual drawings or photographs can also be mapped for comparison. In this case we can use the mapped drawing as an overlay to determine the parts of the fresco lost during the last four decades. The whole documentation including setup of the hardware, post-processing and the acquisition of one multispectral 3D-Image was done in less than 4 hours. Half of the working-time – for post-processing – can be done in a remote location. Figure 8a shows the stitched panoramic image of the fresco used as texture-map. Figure 8b shows the final 3D-mesh with and without texture-map. Figure 8c shows the distance in comparison to a flat plane.

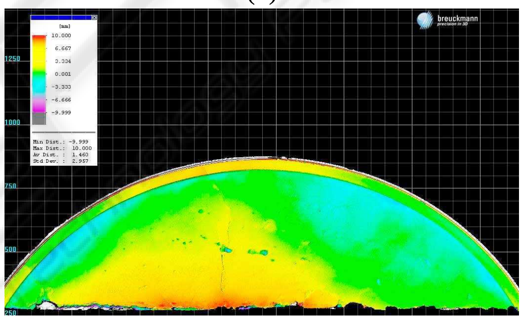
Beside high-resolution and high-preformance, we could also give the experts of archaeology a precise and therefore objective measurments of important features. Just to mention a few, theses features are anicent traces of the paint-process (seam), paint-strokes of ancient corrections of the images as 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 frescos 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.

(a)



(b)



(c)

Figure 8: (a) Panoramic image used as texture-map, (b) 3D-mesh (left) without and (right) with texture-map and (c) 3D-data compared to a flat plane of the fresco in room 11.

5 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 2-4 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 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.

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