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Combined 3D Scanning and Photogrammetry Surveys with 3D Database Support for Archaeology & Cultural Heritage. A Practice Report on ArcTron´s Information System aSPECT^{3D}.

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ABSTRACT

For more than 20 years now, ArcTron 3D has been working on the digital documentation of archaeological objects and historical monuments. Instead of representing the surveying or photogrammetric point of view, this paper was written from the perspective of archaeological practice.

ArcTron has been operating 3D scanning technologies since 2000 – especially terrestrial 3D laser scanning and high-resolution structured light scanning. The 3D information system aSPECT^{3D} has undergone more than 10 years of development and is especially suited for use in archaeology, monument and art preservation as well as restoration sciences. As a 3D surveying suite with interfaces for total stations, GPS, 3D scanners and photogrammetry, this software is also appealing to different engineering branches. Its latest version includes various features for combining data from 3D scanning and 3D photogrammetry.

A whole new SFM application (aSPECT^{3D} ImageScan Module) resulted from the integration of different state-of-the-art University developments. Thanks to these latest algorithms, SFM photogrammetry can be effectively integrated into specific 3D surveying and data processing workflows. Especially projects of monument preservation often profit from a combined airborne (e.g. using MAV-camera-copters) and terrestrial (3D scans) documentation. The resulting SFM point clouds can easily be scaled and georeferenced via ground control points or combined terrestrial scans. Different analytical reports help verifying the resulting accuracy.

The workflow also includes 3D modelling (triangulation) and photorealistic texturing. The final 3D models can be used for further documentation processes like database-supported 3D damage mapping. aSPECT^{3D} contains a freely configurable PostgreSQL-database, which systematically helps to manage, sort and combine data from various 3D sensors. Finished 3D models can also be segmented, structured and managed in single parts in this database.

The data fusion of different recording technologies seems to be one of the core tasks of future software development – especially for use in archaeology and monument preservation.

1. 3D MODELS IN ARCHAEOLOGY, MONUMENT PRESERVATION AND RESTORATION

Photorealistic 3D models offer various new possibilities for every-day practice in archaeology, restoration and monument preservation[1]. On the one hand, they allow for a comprehensive documentation from all angles; on the other hand, finds and finding places as well as damages can be structured, analyzed and mapped. As objective 3D documentations, these models are a reliable preservation of evidence (Schaich, 2009). This is especially useful for stratigraphically complex archaeological excavations[2] or 3D objects such as humid soil findings, architectural remains, subterranean cavities[3], grave findings, multi-layer findings or during the preparation of block excavations. The technology is less suited for mere plane-based documentations.

These computer-based '3D representations of reality' also offer various possibilities for reproducing models and works of art for publication and presentation purposes. A comprehensive 3D process chain can also result in animations and elaborate computer films (Schaich, 2006; AiD, 2009; Schaich, 2010).

[1] Overview with numerous 3D projects from architecture, monument preservation and archaeology listed in: Ioannides/Fritsch/Remondino et al. (2012).

[2] For comparison see: Böhler (2005) and Remondino (2013).

[3] Especially on cavity modeling: Grussenmeyer/Cazalet/Burens/Carozza (2010).

In archaeological documentations with a complex stratigraphy (e.g. during medieval and urban excavations), respective 3D documentations allow to fully understand these archaeological situations (Fig. 1). Especially the virtual work with the documented findings on the computer (e.g. deliberate cross sections; changing perspectives) allow for a more detailed understanding.

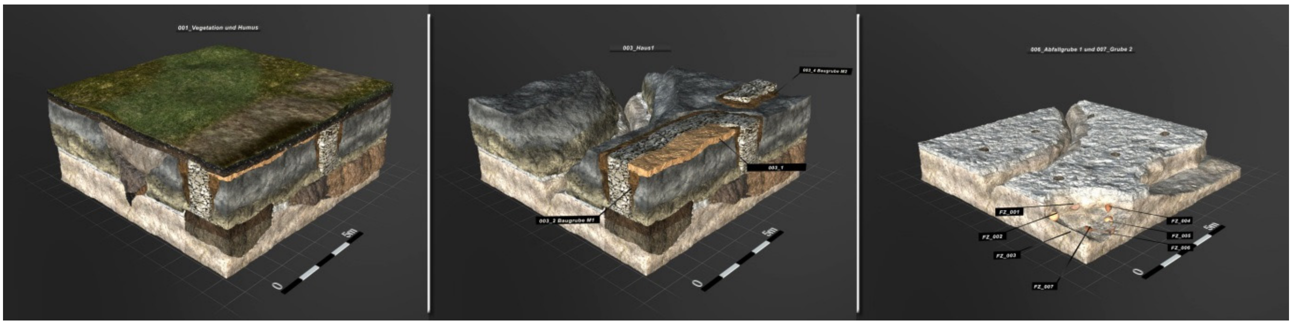

Figure 1: Example of a stratigraphic archaeological documentation; virtually prepared using a 3D database.
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2. LOW-COST 3D MODELS FROM 3D PHOTOGRAMMETRY

Different ways lead to a 3D model. It can be recorded using 3D coordinate measuring machines, total stations or GPS. Due to the low number of recorded coordinates, reality cannot be sufficiently represented with these devices. Other technologies are more suitable: 3D laser scanners with subcentimeter accuracy (e.g. using phase shift or time-of-flight procedures) and high-resolution structured light scanners or light section scanners (using triangulation) with submillimeter accuracy. They scan the object without contact and record it from all angles with millions of measuring points. In practice, such 3D scans are often too elaborate and expensive, because they require cost-intensive equipment and expertise (Schaich, 2009).

For a couple of years now, SFM photogrammetry (SFM – Structure form Motion) has presented a fascinating alternative! All it takes to process a photorealistic 3D model is a series of digital photographs from different perspectives. Objects well suited for this technology have amorphous geometries, structured surfaces, many edges, many corresponding image points and an inhomogeneous colouring – characteristics of typical objects in archaeology and monument preservation. Objects that produce rather bad or no results have unstructured, monochrome, translucent, reflective, and/or self-resembling surfaces, where patterns and characteristics are repeated (e.g. porticos).

A number of software solutions for this issue are available, including free open source solutions[4] or ‘cloud’ applications[5]. ArcTron 3D GmbH has been developing its own software solution for more than 10 years now. ‘aSPECT^{3D}’ is a comprehensive surveying and photogrammetry suite offering

[4] Some applications developed at the University of Washington (Seattle, USA) are very interesting; e.g. the free program VisualSFM (see C. Wu 2011). A powerful bundle block adjustment for computing the camera positions is presented by the Open-Source Bundler-Toolkit (Snavely et al. 2008), which – combined with the PMVS2-Module (see Furukawa/Ponce 2010) – allows ‘Dense Image Matching’, aka. generating a dense point cloud. A critical overview of low-cost and open source solutions can be found in Remondino/Kersten, 2012. Further overview: Kersten/Lindstaedt, 2012b.

[5] Different providers allow working with such cloud solutions; e.g. Microsoft Photosynth (http://photosynth.net/) or 123D Catch by Autodesk (http://www.123dapp.com/catch). The issue of data security and copyrights remains questionable. Uploading images to these providers is hardly doable with large data amounts, sensitive data or operating from remote locations. Another problem is that the 3D model ‘production’ cannot be influenced.

numerous special functions for archaeology, monument preservation and restoration[6]. The new 3D IMAGESCAN MODULE of aSPECT^{3D} allows generating high-quality 3D models from digital image series, recorded with a standard digital camera. The paper will focus on this software package from now on.

2.1. Photographic Recording and Image Quality

First of all, the object needs to be recorded with a suitable image series. This requires basic photographic knowledge about the correlation between exposure time, aperture, depth of focus and the deployment of different lenses. Distorted images taken with 'fisheye'-lenses or extreme wide-angle-lenses can hardly be processed or not at all. Calibrated cameras are not necessary. In order to get precise results, semi-professional or professional digital SLR-camera systems are recommended[7]. Additionally, aSPECT^{3D} supports a camera calibration, which can improve surveying results[8].

The software does, of course, require pictures with depth of focus. Moving shadows, light sources or reflections (e.g. by direct flash) affect the computational process. A homogeneous lighting situation can easily be realized in a laboratory situation, whereas outdoor photography can present many problems. However, experience has shown that even difficult lighting situations (e.g. moving clouds, hard shadows) can still produce useable results. In some situation shielding the object with some kind of canvas can be helpful.

It is crucial during the photographic recording to surround the object 'hemispherically' (from all angles) and record digital images with big overlap (60-80%). You need to take pictures from different perspectives while moving around the object (Fig. 2). Panorama records – with the photographer remaining in one position – will not produce useable 3D results.

2.2. Image Selection

Before aSPECT^{3D} can generate a 3D model, the images need to be checked and sorted according to the criteria above. Large projects often produce several image series differing in perspectives and lighting conditions. It is useful to sort these images according to point of view (airborne/terrestrial), time of day or overview/detail, etc. The same applies to archaeological or restoration projects, which document an object changing over a period of time.

aSPECT^{3D} offers an image database for that: It allows tagging the images and sorting them on a time bar. It also stores all camera and image information (EXIF data) needed for the computation: sensor size, lenses, focal length, exposure time, ISO value etc. If the camera is equipped with a GPS module, these coordinates can be included in and speed up some computational processes.

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[6] Schaich, 2012. The software was originally developed for handling laser scanning data. It has been in production for more than 10 years by head programmer Boris Schütz and a team of computer scientists, surveying and excavation engineers and archaeologists of ArcTron 3D GmbH. More information on the system: http://www.arctron.de/en/products/software/aspect_3d/. New powerful photogrammetric features were implemented from 2011 to 2013 in cooperation with different universities. Due to constant testing in real projects, the software is very suited for documenting complex archaeological findings and objects.

[7] Our tests proved both semi-professional SLR-cameras and small lensless cameras to deliver suitable results. The professional NIKON D800E (with 36 megapixel full format sensor) delivered the best results by far. We recommend the following lenses for this camera: Standard zoom: Nikon AF-S Zoom-Nikkor 24-70mm 1:2,8G. Wide-angle: Nikon AF-S Nikkor 28mm 1:1,8G. Macro: Nikon AF-S Micro Nikkor 60mm/2.8G ED.

[8] For calibration you need to print out certain markers and photograph them on a plane surface. The calibration determines the parameters of the interior camera orientation: focal length, camera constant, radial-symmetric and tangential distortion. This process only needs to carried out once for a camera using leses with fixed focal length.

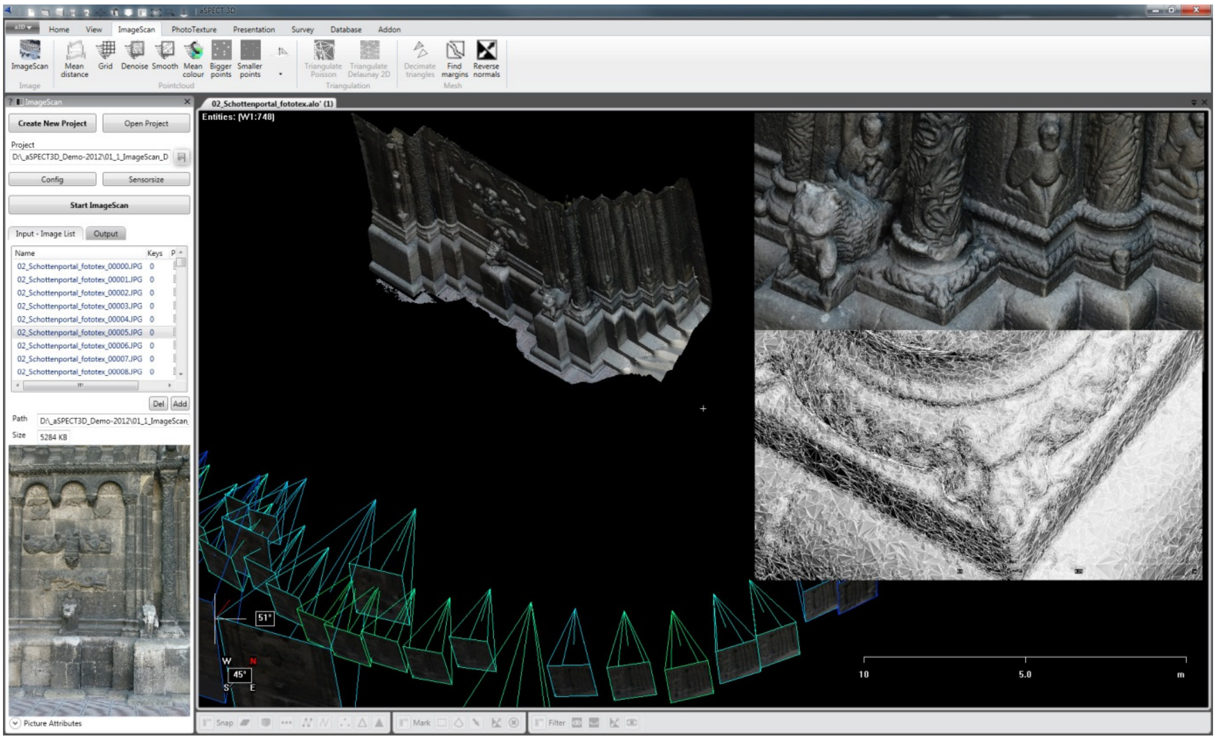

Figure 2: aSPECT^{3D} ImageScan Module. Example: 'Schottenportal' in Regensburg. Left: Screenshot – result after bundle block adjustment with positioned cameras in space. The coloured prisms around the images visualize their neighbouring quality and the focal length. Top right: Detail with photorealistically textured 3D model. Bottom right: Detail with computed and reduced 3D mesh. © ArcTron 3D GmbH, 2013.

2.3. From Image Series to 3D Point Cloud

With the checked, sorted and selected images, the software computes a 3D point cloud. It deploys a technology already established in computer-based image processing: SFM (»Structure from Motion«). This process – called 3D ImageScan in aSPECT^{3D} – can be carried out both ONLINE – during the photogrammetry project on site - or OFFLINE – afterwards at the office. In order to do so, a powerful SFM library by the TU Graz is currently being integrated into the software.
The online processing of 3D ImageScan data uses reduced images and can be realized via an automatic WLAN-transmission from camera to notebook. Instantly – in less than 2 seconds per image – both camera position and orientation are computed and result in a sparse 3D point cloud[9]. This procedure allows verifying the completeness and quality of the survey on site. A coloured visualization of the image coverage quickly shows what areas have not been recorded or need to be recorded again because certain images could not be used for computation.
Different algorithms are deployed for computing 3D object information. They identify characteristic image points – so-called 'features' – from different perspectives. The EXIF-data of the images are taken into account as well: sensor size, focal length, lens parameters etc.
For reconstructing camera positions and orientations, these features are computed in pairs: They are verified and positioned in a global coordinate system using a relative 5-point or an absolute 3-point bundle block adjustment (interior and exterior camera distortion and radial distortion). A very steady result is generated by a RANSAC algorithm. Finally, the features are visualized as a first, sparse 3D point cloud.

[9] The online features described here are currently being integrated into aSPECT^{3D} version 2014. This version will probably be pre-released at the "Intergeo" fair in October 2013.

A further computational step transforms this point cloud into a very detailed, coloured, dense point cloud. For that, aSPECT^{3D} uses the very efficient photogrammetric algorithm SURE, developed by the University of Stuttgart (see Rothermel et al. 2012).

3. DATA PROCESSING AND EDITING

3.1. Fully Automatic Processes

For starting the point cloud generation, the user has to do nothing but select the images for the fully automated computation. Depending on the number of images this takes more or less time and computing power. Large image sets of several hundred or thousand pictures require powerful high-quality hardware. The essential parts of any computer should be a current 64bit multiprocessor construction, a large main memory and it needs to allow parallel processing on the graphic board (GPU)[10]. In general, current 'workstations' fulfill these requirements.

3.2. Surveying and Assembling

At first, the resulting 3D point cloud is neither scaled nor georeferenced. aSPECT^{3D} offers different features for resolving this issue. For simple scaling, the object can be transformed using a defined scale visible in the pictures and thus part of the point cloud. Using GPS or total station, you can georeference the point cloud by correlating it with recorded reference points in a superior coordinate system. The point cloud will then be transformed into the target coordinate system using a multipoint transformation, which allows constant error detection for optimization (Fig. 3).

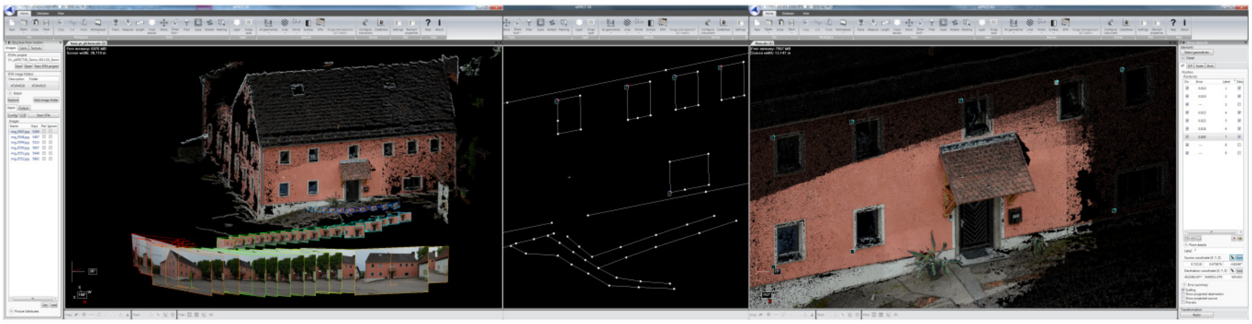

Figure 3: Scaling and georeferencing in aSPECT3D. Left: SFM image series and point cloud of a façade (company building). Middle: Single reference points measured by total station and processed in aSPECT3D. Right: Scaling and georeferencing via multipoint transformation with displayed errors. © ArcTron 3D GmbH, 2013.

Larger objects may have to be assembled from several point clouds, because they had to be recorded from several perspectives (e.g. airborne and terrestrial). aSPECT^{3D} includes a so-called ICP-algorithm for fusing overlapping point clouds (see Rusinkiewicz/Levoy, 2001; Nistér, 2004; Pottmann/Leopoldseder/Hofer, 2002).

3.3. Creating Photorealistic 3D Models

Before processing point clouds into polygon mesh 3D models, they should be filtered and rid of non-relevant objects (e.g. scaffoldings, persons). aSPECT^{3D} offers different editing tools for reducing

[10] aSPECT^{3D} often uses the CUDA features of nVIDIA graphic boards and supports multi-threading (parallel computation on several processors). Our hardware recommendation is a current workstation with Intel Xeon Processors with at least 16 GB RAM.

noise or deleting dispersive points. Afterwards, using a so-called 'Poisson-Triangulation' – alternatives are a 2,5D or 3D 'Delaunay-Triangulation' – a closed 3D mesh is computed for the point cloud.

Simultaneously, the software generates a 'vertex-texture'. That means each triangle is coloured according to the medium RGB colour value of its points. The resulting mesh is equipped with an already quite realistic colouring.
For generating models with full photorealistic texturing, another editing step is necessary. This process uses the oriented and optimized pictures of the 3D ImageScan and maps them onto the object geometries. The resulting high-quality photorealistic texture is shown in the example of an Italian apsis-fresco above (Fig. 4).

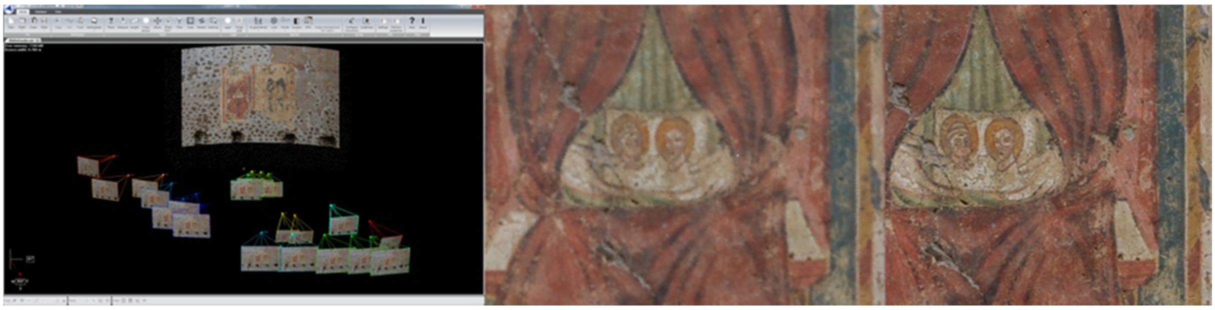

Figure 4: Project 'Ninfa-3D' (in cooperation with the German Historical Institute in Rome). Left: SFM-documentation of an apsis-fresco. Middle: 3D model with vertex texture. Right: Texture with high-resolution images on the 3D model. © ArcTron 3D GmbH, 2013.

3.4. Handling Large Data Sets

aSPECT^{3D} is equipped with interfaces for importing and editing very large point clouds and textured 3D objects. Depending on the hardware, aSPECT^{3D} can work with point clouds of several hundred million points as well as large photorealistically textured polygon meshes – data sets that most common 3D software solutions cannot handle effectively!

4. HOW ACCURATE ARE ASPECT^{3D} 3D-IMAGESCAN MODELS?

The generated 3D models have to be an exact representation of the original object for conservational, archaeological and restoration purposes. Deviations from original to model should be as little as possible. These accuracies can vary depending on the deployed 3D measuring technology (total station, laser scanner, structured light scanner, photogrammtry etc.), camera equipment and software packages.
This issues the question of how accurate 3D models generated by the 3D ImageScan Module of aSPECT^{3D} are (computed from SFM image series). Of course, a lot of factors have to be verified depending on each respective case.
Over the past few years, we have carried out accuracy analyses for aSPECT^{3D} models during different documentation and research projects. The results show that very precise models can be generated for both small and large objects. Conditions are a careful project strategy and suitable photogrammetric camera equipment. Two selected reference projects shall illustrate this:

4.1. Example 1 – Veitsberg (Lower Franconia)

– wall fragments resembling urban structures; area: app. 75 m²; depth: up to 1,5m.

In 2011, ArcTron 3D recorded a representative area of foundations and wall fragments at the Veitsberg (Carolingian-Ottonian Palationate in Lower Franconia). The project was commissioned by the Archaeological Institute of the University of Jena. The accuracy analysis compared the aSPECT^{3D}-generated models to those based on different surveying technologies (Fig. 5).

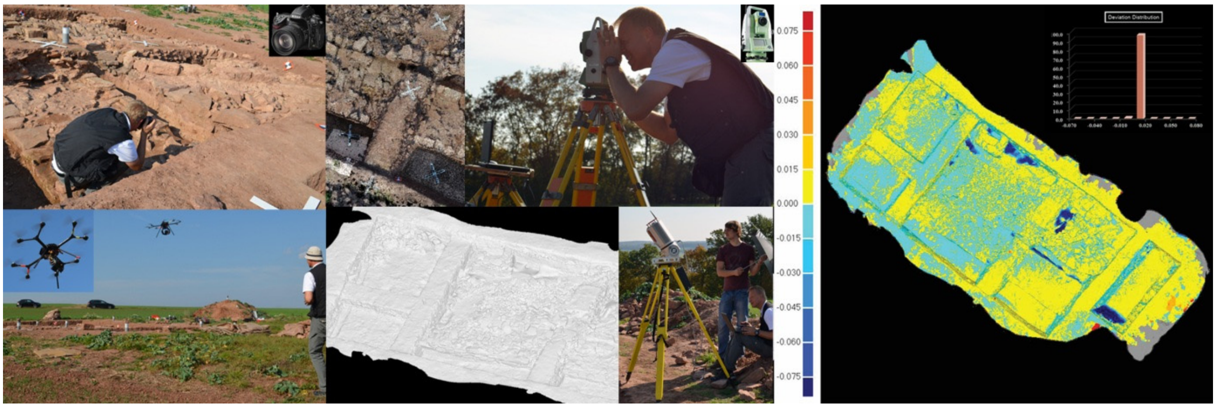

Figure 5: Project "wall documentation". Veitsberg, Bad Neustadt a.d. Saale (in cooperation with the University of Jena, Professorship for Prehistoric and Protohistoric Archaeology). Left: Photographic documentation airborne and from the ground. Middle: Reference surveys with total station and laser scanner. Right: Deviation result after a "best fit" registration of the SFM point cloud onto the terrestrial laser scan; standard deviation of below 1 cm. © ArcTron 3D GmbH, 2013.

For one test, various control points placed in the area were recorded via total station. For another test, the reference area was scanned using a terrestrial 3D laser scanner (Riegl VZ-400) with an accuracy of 3-5 mm.
The aSPECT^{3D} 3D ImageScan model was generated out of images taken from the ground and airborne with an 'octocopter drone'. The comparison of SFM point cloud and laser scan data showed a very small standard deviation of about 1 cm. If only a total station is deployed, the standard deviation still remains smaller than 3 cm. When a single reference measurement (e.g. a scale photographed with the object) is the only device for scaling the point cloud, excavation findings of the respective size provide accuracies of around 5 cm.

4.2. Example 2 – „Bread Loaf Idols" – Exhibition Manching 2011

– numerous archaeological objects; size: max. 20 cm.

Another accuracy test showed that the software is also suited for small objects. It was carried out in cooperation with the "celtic + roman museum" Manching during the project 'Aenigma 3D'[11]. More than a hundred of so-called "bread loaf idols" and other small archaeological objects were recorded (Fig. 6). Professional camera systems with macro lenses produced accuracies of 0.2 mm for the

[11] Schaich, M. »Aenigma 3D«. Zur Generierung hochaufgelöster 3D-Modelle mit Fotos einer handelsüblichen Spiegelreflexkamera – eine Fallstudie mit ArcTron's Software aSPECT3D am Beispiel der »Brotlaibidole«, in: W. David (Ed.), Aenigma. Ausstellungskatalog. in press.

resulting SFM-point cloud. A high-resolution structured light scan with a resolution of 0.05 mm served as a reference.

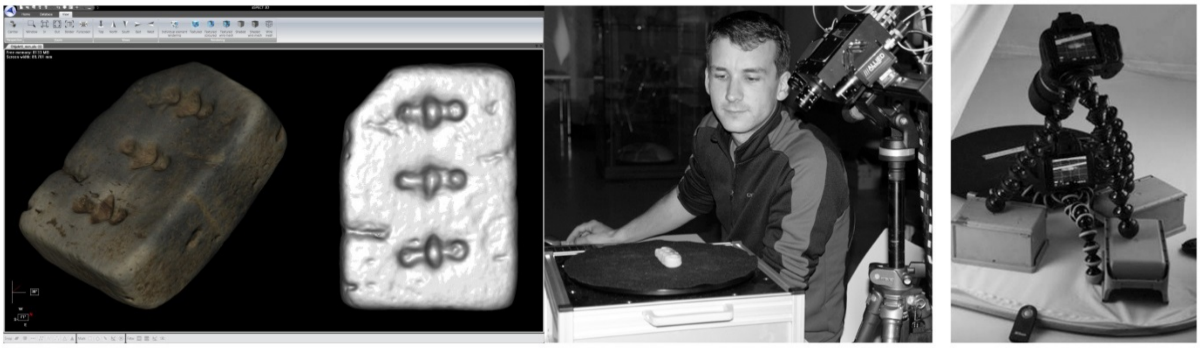

Figure 6: Project "Enigma 3D" (in cooperation with the "celtic + roman museum" Manching). Left: Angular "bread loaf idol" in photorealistic and shaded depiction. Right: The highly precise structured light scanner PT-M 1280 serves as reference measuring device. For the automated, photographic SFM-documentation, two Nikon cameras with macro-lenses and a turn table were set up in a homogenous white light room. The deviation analysis proved accuracies better than 0.2 mm. © ArcTron 3D GmbH, 2013.

5. LASER SCANNING COMBINED WITH TERRESTRIAL AND AIRBORNE PHOTOGRAMMETRY

ArcTron 3D is a well established specialist for cultural heritage projects using airborne and terrestrial 3D laser scanning and high-resolution structured light scanning. For larger projects (e.g. castle documentations), we currently work with a combination of terrestrial 3D laser scanning and terrestrial as well as airborne 3D photogrammetry.

The advantage is that the photogrammetry data can be registered onto the laser scanning data with subcentimeter accuracy. This is quickly done using a best-fit-operation, which also allows a deviation analysis. Using this combination, the number of laser scanning positions can be significantly reduced, which minimized the project costs.

If no laser scanner is available, the registration could also be realized using reference markers spread out throughout the area. These markers should be separately recorded using dGPS or a total station. aSPECT^{3D} provides a tool for carrying out a steady multipoint transformation into the target coordinate system. The accuracy relies on the clear identification and allocation of reference points in the point cloud. Therefore, it is essential to integrate all markers spread out around the object into the photographic strategy to depict them clearly.

For larger projects, the images are not only taken from the ground but also from airborne devices like octocopters (Fig. 7). These images from various altitudes deliver a dense overlap and very suitable geometries for a qualitative photogrammetric matching process.

Using only photogrammetric images, a precise workflow and suitable hardware, our software aSPECT^{3D} can deliver reliable surveying results! Accuracies of 1-3cm (for large objects) can easily be achieved using a professional full format sensor SLR camera and high-quality lenses. Especially for large objects (e.g. landscapes, buildings, excavations), a thorough project strategy needs to consider all factors for quality achievement: lighting, image scale, recording parameters, camera resolution, lenses and the accuracy of reference measurements.

5.1. Photogrammetry with Airborne Camera Robots

During the past few years at ArcTron 3D, a combination of airborne and terrestrial documentation technologies was established for comprehensive 3D surveys. In targeted survey flights, an ultra-light paraglider trike is deployed by the company (since 2006). Up to 90 % of all required information can be gathered by aerial surveys. That is why ArcTron has also been using and developing a remote controlled "camera drone" since 2010 (Fig. 7).

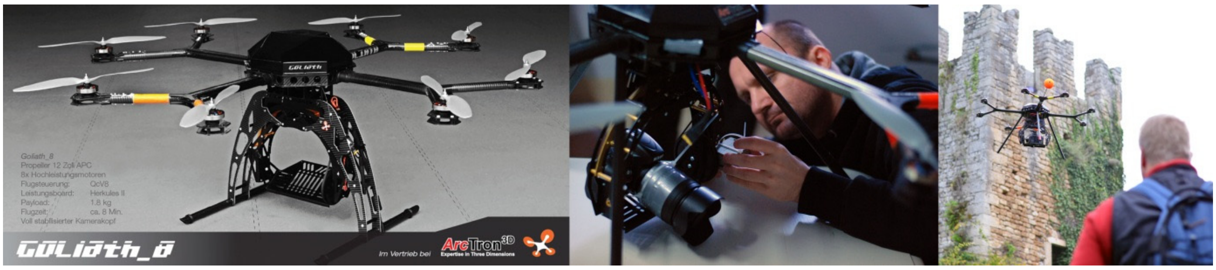

Figure 7: Project "Ninfa 3D" (in cooperation with the German Historical Institute, Rome). Left: Cadmicopter Octocopter; camera drone with a fully stabilized camera platform. Right: Technology in practice. Deployment of the system for the 3D documentation of medieval remains of the city Ninfa (Italy). © ArcTron 3D GmbH, 2012.

These airborne robots can be controlled completely autonomously by a ground station and are especially configured for taking software-specific, photogrammetrical survey images. The systems are able to carry photogrammetric cameras of over 2 kg for up to 20 minutes. They are equipped with a fully stabilized and separately controllable camera platform.

These camera copters are able to realize very complex close-range recordings. They can usually replace bulky lifting platforms and even reach and record remote objects very precisely (e.g. the gothic embellishment of dome spires).

The described tasks are also among the services ArcTron provides for the archaeology and monument preservation sector. For many archaeological situations, these airborne photogrammetric 3D documentations can lower project costs significantly.

6. DATABASE-SUPPORTED DATA MANAGEMENT AND EVALUATION

aSPECT^{3D} contains a freely configurable PostgreSQL-database, which systematically helps to manage, sort and combine data from various 3D sensors. Finished 3D models can also be segmented, structured and managed in single parts in this database.

There are several templates of database structures for archaeological, architectural or restoration purposes. However, each structure can be individually adjusted or built completely new using a hierarchical object system ('part of relation system') and an additional classification scheme.

6.1. 3D Surface Mapping and Damage mapping

aSPECT^{3D} enables you to connect 3D geometries with various kinds of additional information. One example is damage mapping, which can occur directly on the photorealistically textured 3D surface. Using a notebook or a tablet-PC, the 3D mapping can occur on-site in front of the original object. This guarantees an exact documentation – especially for very complex 3D structures. For creating a comprehensive documentation, the 3D objects can be linked to further metadata also stored in the database: e.g. texts, CAD-data, images, films, PDFs.

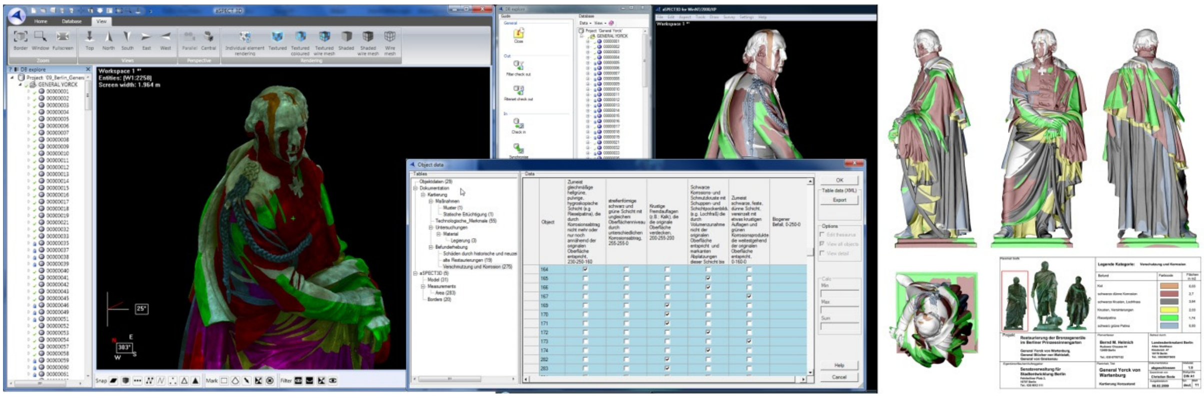

Figure 8: Damage mapping of the Bronze Statue of general Yorck of Wartenberg (1759-1830), Berlin. The complex 3D mapping of all damage areas with the integrated database was carried out by the restoration office Helmich (Berlin) with the 3D GIS system aSPECT3D. It allows database enquiries of deliberate 3D damage mappings and restoration planning. Graphics: © Landmark Preservation Authority Berlin & restoration office Helmich, based on a laser scan by the company Laserscan, Berlin. Software screenshots: ArcTron 3D GmbH, 2009.

6.2. Print-Out Results

For print-out documentations, the software can produce various views as CAD-files (Fig. 9) or create scaled high-resolution images (orthophotos) comprised of tiled single images.

7. PRESENTATIONS IN STEREO 3D

The 3D models can be rotated or presented in a film for presentations. The films are rendered from individually defined camera waypoints. Excavations and buildings can be entered like a video game in full-screen mode. Using respective 3D monitors and glasses, all models in aSPECT^{3D} can be depicted in stereo 3D.

8. CONCLUSION AND OUTLOOK

ArcTron 3D has continuously been developing aSPECT^{3D} for the past ten years. It offers numerous applications for engineers and surveyors as well as specific tools for archaeologists, monument preservers and restorers.

The current developments focus on optimizing the workflow of combining 3D scanning and SFM-photogrammetry. Special attention is paid to optimizing SFM-functionalities (online and offline), 'dense image matching' and 'texture mapping'. A further goal is integrating more functions for flight planning and photogrammetric recording using MAVs (Micro Aerial Vehicles) i.e. camera copters (Schmid et al. 2012)!

We are convinced that the cost-effective image-based 3D documentation – combining methods from computer vision and photogrammetry – will be of great importance for future documentation projects in archaeology and monument preservation. The time seems ripe for it!

A completely three-dimensional documentation can already be accomplished with current technical means. The advantages are manifold and bring obvious improvements to scientific work, publications, exhibitions and presentations.

All necessary technology is available and can be used in cost-effective and practicable ways. However, it is still limited for use in special research projects. Making three-dimensional

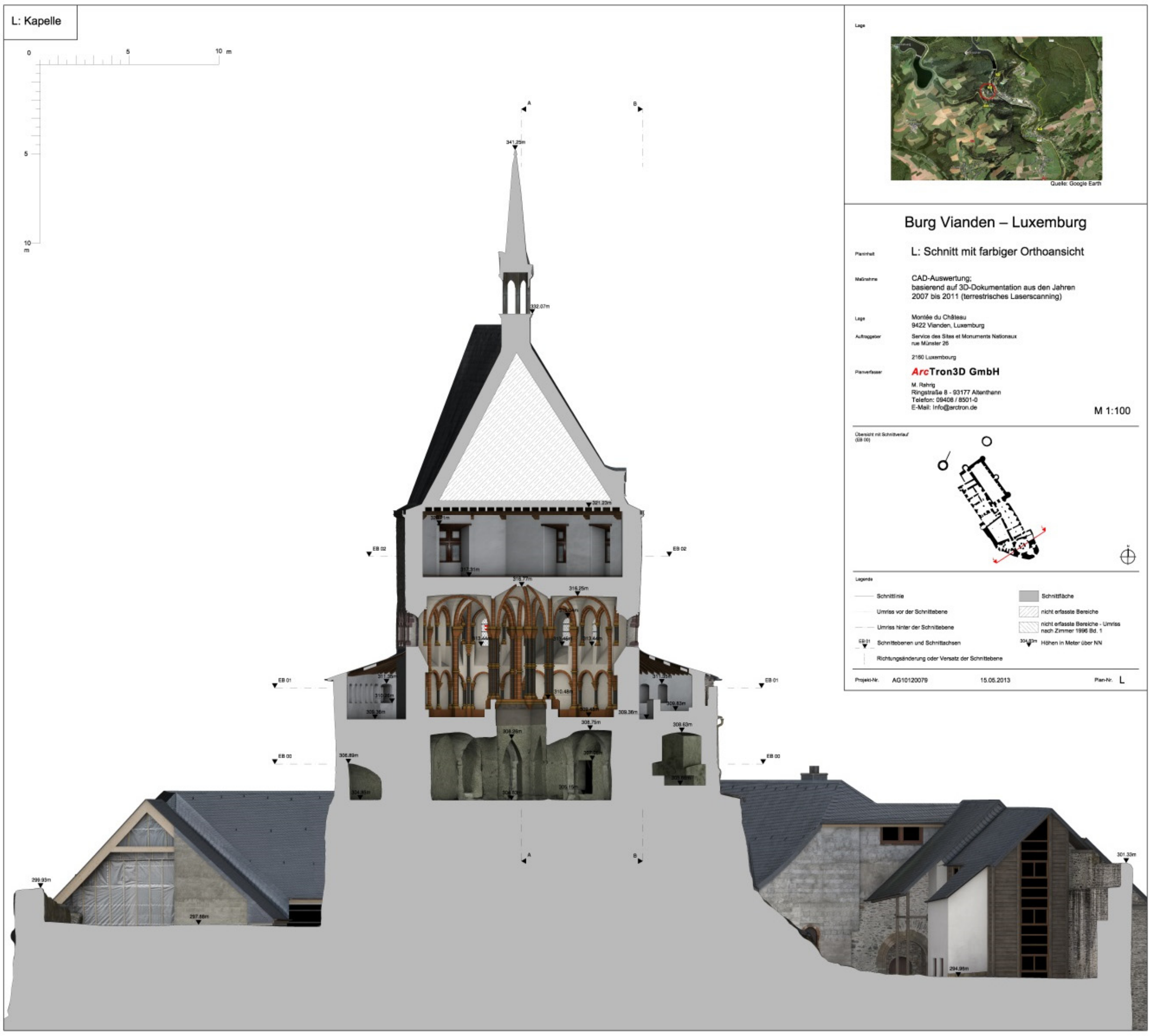

Figure 9: Vianden Castle (Luxemburg). Using aSPECT^{3D}, complex CAD-drawings can easily be generated: e.g. by creating deliberate sections through the model and combining them with orthophotos. Standard CAD-formats allow data tarnsfer to common CAD-applications. © ArcTron 3D GmbH, 2013.

documentations a standard procedure in archaeology is most of all a ‘political’ decision of monument preservation authorities.

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