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HIGH DEFINITION 3D-SCANNING OF ARTS OBJECTS AND PAINTINGS

Devrim AKÇA[1], Armin GRÜN[1], Bernd BREUCKMANN[2], and Christian LAHANIER[3]
[1]Institute of Geodesy and Photogrammetry, ETH Zurich, Switzerland,
(akca, agruen)@geod.baug.ethz.ch
[2]Breuckmann GmbH, Meersburg, Germany
bernd.breuckmann@breuckmann.com
[3]Centre de Rcherche et de Restauration des Musées de France, France
christian.lahanier@culture.gouv.fr

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ABSTRACT
3D documentation and visualization of Cultural Heritage and Arts objects is an expanding application area. The selection of the right technology for these kinds of applications is very important and strictly related to the project requirements, budget and user's experience. In this contribution, we report our experience in the 3D digitization of three objects: a Herakles statue, a Khmer head and a painting. We cover all the necessary steps of the 3D object modeling pipeline with structured light technique and we discuss the capabilities of the used technology.

1 INTRODUCTION

Topometrical high definition 3D-scanners, optimized for the requirements of arts and cultural heritage, allow the 3-dimensional digitization of art objects and paintings with high resolution and accuracy. Moreover, the texture and/or color of the object can be recorded, offering a one-to-one correspondence of 3D coordinate and color information.
Topometrical scanners are based on the principal of optical triangulation using structured light: A special projection unit projects a known pattern of light onto the object. A digital camera records the image of the object together with the projected pattern.
State of the art systems (as Breuckmann optoTOP-HE, optoTOP-SE, triTOS) use special projection patterns with a combined Gray Code / phaseshift technique, which guarantees an unambiguous determination of the recorded 3D-data with highest accuracy. The time for a single scan takes about 1 second for a 1.4 M pixel camera and a few seconds for high definition cameras with 4-8 M pixel.

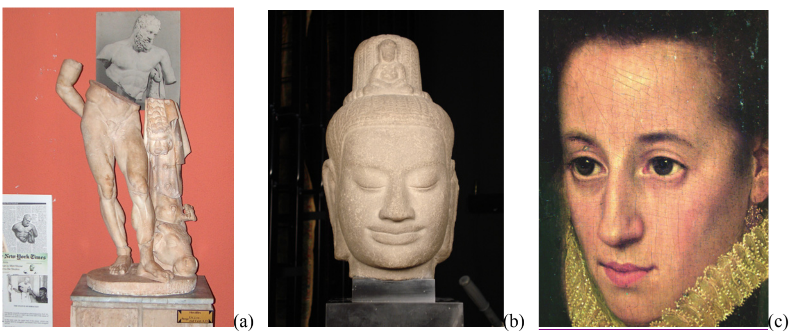

Figure 1. (a) Weary Herakles statue in the Antalya Museum, (b) Khmer head in the Rietberg Museum, Zurich, (c) Lady Praying painting in the Louvre Museum, Paris.

This paper reports about three case studies where three different models of Breuckmann topometric scanners (optoTOP-HE, optoTOP-SE, and triTOS) are used for the precise 3D digitization and documentation of Cultural Heritage and Arts objects. It includes all necessary steps of the 3D object modeling pipeline from data acquisition to 3D visualization.
The first study is the 3D modeling of a part of a marble Herakles statue, named "Weary Herakles" (Fig. 1a), which is on display in the Antalya Museum (Turkey), digitized with an optoTOP-HE system. The second case is about the 3D modeling of a Khmer head sculpture (Fig. 1b), which is in the collection of Rietberg Museum (Zurich, Switzerland), digitized using an optoTOP-SE sensor. The third study is the high definition digitization and modeling of the painting Lady Praying (Fig. 1c) in the Louvre Museum (Paris, France) using a triTOS sensor.
The next chapter introduces the scanner with emphasis on the working principle and technical specifications. The following chapters explain the data acquisition and modeling workflow of the Weary Herakles, Khmer head and Lady Praying projects, respectively.

2 DATA ACQUISITION SYSTEM

2.1 Coded Structured Light System

The active stereo vision method, also called the structured light system, deals with the 3D object reconstruction task. The key feature of the system is the replacement of one of the cameras by an active light source, which illuminates the object with a known pattern. This solves the correspondence problem in a direct way. Many variants of the active light source exist (Beraldin, 2004; Blais, 2004).
The coded structured light technique, also called topometric technique, is based on a unique codification of each light token projected onto object. When a token is detected in the image, the correspondence is directly solved by the de-codification. It requires a complex light projection system. There exist many codification methods (Salvi et al., 2004; Dipanda and Woo, 2005).

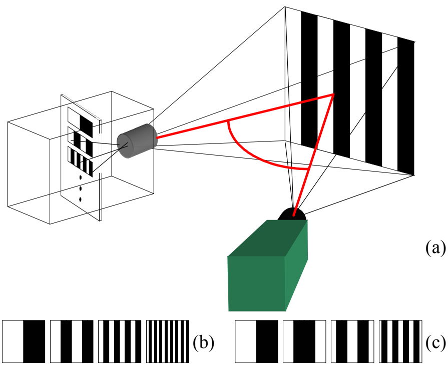

Figure 2. (a) Setup of a fringe projection system with the natural binary codification, (b) natural binary code, (c) Gray binary code.

The time-multiplexing, also called temporal codification, with a combined Gray code and phase shifting is the mostly employed technique. The optoTOP-HE/SE and triTOS sensors use the same technique.
A Gray code is a binary numeral system where two successive values differ in only one digit, i.e. 000, 001, 010, 011, … in natural (plain) binary codes, and 000, 001, 011, 010, … in Gray binary codes. It was invented and patented by Frank Gray (Gray, 1953) in Bell Labs. For the case of coded structured light systems it is superior to the natural binary codification, since it resolves the ambiguity better at the edges of consecutive patterns (Fig. 2b and 2c).
A sequence of Gray coded binary fringe patterns is projected onto the object (Fig. 2a). This divides the object into a number of 2^n sections, where n is the number of pattern sequences, e.g. 128 sections for $n = 7$. Thus each pixel is associated with a codeword, which is the sequence of 0s and 1s obtained from the n patterns. The codeword establishes the correspondences relating the image pixels to the projector stripe numbers. The object space point coordinates are calculated using the spatial intersection provided that system

calibration is known. All pixels belonging to the same stripe in the highest frequency pattern share the same codeword. This limits the resolution to half the size of the finest pattern.
An additional periodical pattern is projected several times by shifting it in one direction in order to increase the resolution of the system. For each camera pixel the corresponding projector stripe number with sub-stripe accuracy is yielded by a phase shift method Gühring (2001).

2.2 Brecukmann optoTOP-HE, optoTOP-SE and triTOS systems

The optoTOP-HE system (Fig. 3), as a high definition topometrical 3D-scanner, allows the 3-dimensional digitization of objects with high resolution and accuracy. The optoTOP-HE system uses special projection patterns with a combined Gray code and phase shift technique, which guarantees an unambiguous determination of the recorded 3D data with highest accuracy (Breuckmann, 2003). The sensor of the optoTOP-HE system can be scaled for a wide range of Field of Views (FOV), by changing the baseline distance and/or lenses, typically between a few centimeters up to several meters. Thus the specifications of the sensor can be adapted to the special demands of a given measuring task.

(a) (b)

Figure 3. (a) The optoTOP-HE sensor, (b) and its first 3 fringe projections.

The optoTOP-SE (Special Edition) series are the identical systems. The major difference is that the optoTOP–SE sensors have only three different FOV cases with a fixed 300 mm base length. The triTOS sensors are specially designed for the Cultural Heritage tasks. Details are given in Table 1.

Table 1. Technical specifications of the used optoTOP-HE/–SE and triTOS sensors.

	optoTOP-HE	**optoTOP-SE** [(3)]	**triTOS** [(3)]
Field of View (mm)	480x360	400x315	80x60
Depth of View (mm)	320	260	40
Acquisition time (sec)	<1	<1	<1
Weight (kg)	2-3	2-3	2-3
Digitization (points)	1280x1024 [(1)]	1280x1024	1280x1024
Base length (mm)	600	300	50
Triangulation angle (deg)	30^0	30^0	30^0
Projector	128 order sinus patterns	128 order sinus patterns	128 order sinus patterns
Lamp	100W halogen	100W halogen	100W halogen
Lateral resolution (µm)	~350	~300	~60
Feature accuracy (relative) [(2)]	1/15000	1/10000	1/10000
Feature accuracy (µm)	~45	~50	15

[(1)] Current optoTOP-HE has a 1380x1040 dimension, ([2]) According to image diagonal.
[(3)] These systems are meanwhile replaced by the advanced product lines smartSCAN-3D and triTOS-3D

3 WEARY HERAKLES PROJECT

A part of a Herakles statue, named "Weary Herakles" and located in the Antalya Museum, Turkey was scanned by a structured light system. This is a statue of the Greek demi-god Herakles, which dates back to the 2nd century AD. The upper half was first seen in the USA in the early 1980s. It is currently to be found at the Boston Museum of Fine Arts (MFA). The lower part was found in an excavation site in Perge (Antalya, Turkey) in 1980. It is now on display in the Antalya Museum, along with a photograph of the top half (Fig. 1a). According to the mythology Herakles is the symbol of power. He killed the Nemean lion, which was a nuisance in Greece. He used the skin of the lion as armor.

Because of the Turkish laws, the government has asked for restitution of the upper half so that the two fragments can be joined. The MFA has refused to consider Turkish petition. In 1992, casts of the two fragments were placed together. They were found to match perfectly. The MFA says the statue may have broken in ancient times, and the upper torso may have been taken from Turkey before Turkish law established state ownership of archaeological finds (Gizzarelli, 2006).

Since both parts are unfortunately separated geographically, our aim was to record and model both the lower and the upper part and bring these partial models together in the computer, so that at least there the complete statue could be seen, appreciated and analyzed. With the help of the Turkish authorities and the Antalya Museum we were able to complete our work on the lower part, but access to the Boston Museum was denied.

The digitization of the lower part of the statue was done in 19-20 September 2005 in the Antalya Museum with a Breuckmann optoTOP-HE structured light system. The system was kindly provided by the Turkish reseller InfoTRON, Istanbul. Further information can be found on the project webpage: http://www.photogrammetry.ethz.ch/research/herakles/.

3.1 Scanning in the Antalya Museum

The scanning campaign was completed in one and a half days of work. The statue is around 1.1 meters in height. The whole object was covered with 56 scans of the first day work. The remaining 11 scans of the second day were for filling the data holes and occlusion areas. Totally 83.75M points were acquired in 67 scan files.

3.2 Pointcloud registration

The pairwise registration was done by use of an in-house developed method, called Least Squares 3D Surface Matching (LS3D). The mathematical model is a generalization of the Least Squares image matching method, in particular the method given by Gruen (1985). It provides mechanisms for internal quality control and the capability of matching of multi-resolution and multi-quality data sets. For details, we refer to Gruen and Akca (2005). The pairwise LS3D matchings are run on every overlapping pairs (totally 234) and a subset of point correspondences are saved to separate files. The average of the sigma naught value is 81 microns. In the global registration step, all these files are passed to a block adjustment by independent models procedure, which is a well known orientation procedure in photogrammetry. It concluded with 47 micron a posteriori sigma naught value.

3.3 Surface Triangulation and Editing

After the registration step, all scan files were merged and imported to Geomagic Studio™ 6 (Raindrop Geomagic Inc.) modeling package. The data set was cropped to include only the area of interest (AOI), concluding with 33.9 M points. A low level noise reduction was applied. The number of points was reduced to 9.0 million by applying a subsampling procedure based on curvature information. This operation eliminates points in flat regions but preserves points in high curvature regions to maintain detail. The surface triangulation concluded with 5.2 M triangles (Fig. 4). Because of the complexity of the statue and occlusions, some inner concave parts could not be seen by the scanner. This resulted in several data holes on the triangulated surface. They were interactively filled by use of the corresponding functions of Geomagic Studio.

3.4 Texture Mapping and Visualization

Separately taken images, with a 4M pixel CCD Leica Digilux 1 camera, were used for the texture mapping. The Weaver module of the VCLab's 3D Scanning Tool (ISTI-CNR, Pisa, Italy) was used here. The VCLab's Tool is a bundle of modules, which comprise the fundamental steps of the 3D modeling. The algorithmic details of the software can be found in Callieri et al. (2003).
The visualization of the final model was done with the IMView module of PolyWorks™ (InnovMetric Software Inc., version 9.0.2). It gives better shading than Geomagic Studio. The textured model was visualized with the viewer of the VCLab's Tool (Fig. 4).

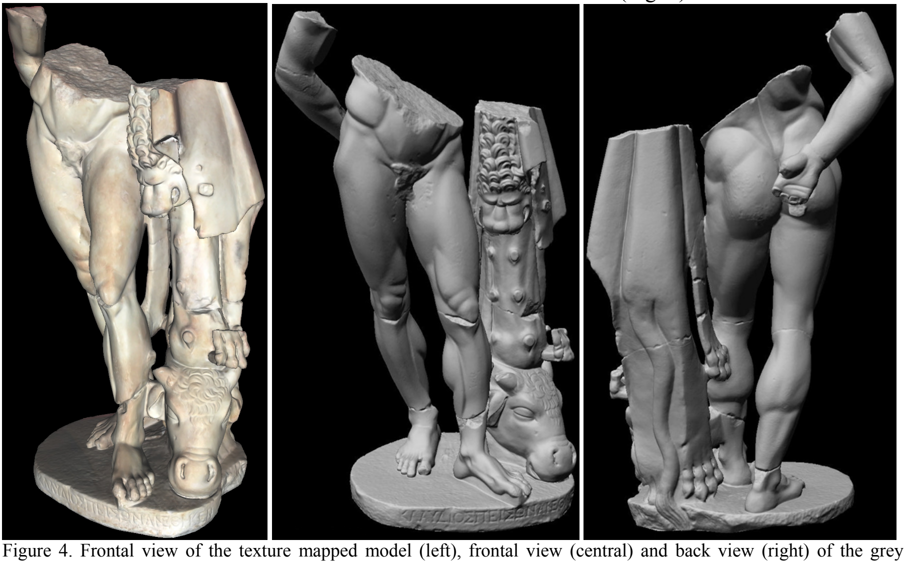

Figure 4. Frontal view of the texture mapped model (left), frontal view (central) and back view (right) of the grey shaded model.

4 KHMER HEAD PROJECT

A bodhisattva head from the late 12th or early 13th century carved in the Bayon style was scanned in Museum Rietberg Zurich (Fig. 1b). It is Lokeshvara or Avalokiteshvara, the "Lord of compassion who looks down (on the suffering of the world)," an emanation of the Buddha Amitabha as demonstrated by the seated Buddha on his hair ornament. Further information can be found on the project webpage: http://www.photogrammetry.ethz.ch/research/khmer/.

4.1 Data Acquisition in Museum Rietberg

The head is made of sandstone and 28 centimeters in height. The data acquisition was done in Museum Rietberg on 4 May 2006. A Breuckmann OptoTOP-SE fringe projection system was used for this purpose. The scanning and imaging took four hours on site work. The head was covered with 18 point clouds, totally 23.6 million points.

4.2 Pointcloud registration

The point cloud registration was done again with the LS3D surface matching method. 52 pairwise LS3D matchings for all overlaps gave an average sigma naught value of 60 microns. The global registration with the block adjustment by independent models solution concluded with 28 microns sigma naught value.

4.3 Surface Triangulation and Editing

The surface modeling was done by use of two commercial packages, namely Geomagic Studio and Polyworks. The aim was to compare the capabilities of both softwares. Registered point clouds were imported in the proper formats. Accordingly, the registration steps were skipped in both softwares.

Geomagic Studio offers fully automatic data import functionality provided that data is given in one of the appropriate point cloud formats. Totally 18 point clouds were imported, merged into one, which gave a very dense (denser than 50 microns inter-point distance at some locations) point cloud. After discarding the no data or scanner signed erroneous points and points belonging to background and other non relevant objects, 3.2 million points remained.

The noise reduction ensures that points coming from different views in different quality will finally have the similar signal-to-noise ratio. Here a slight (low level) noise reduction was applied. After this step, the model contains highly redundant points coming from the multiple views. A curvature based subsampling procedure was performed, reducing the number of points to 1.9 millions.

The surface triangulation in Geomagic Studio is fully 3D and automatic, with limited user interaction. Hence, the resulting mesh will have topological errors and holes. On the other hand, it can preserve the high frequency details of the object geometry successfully by considering all points in one processing sweep. In general, surface triangulation quality is highly related to the point density and homogeneity.

Figure 5. Shaded view of the model from Geomagic Studio (left) and PolyWorks (centre), texture mapped 3D model (right).

PolyWorks has a significantly different workflow. Each step is represented as a module inside the package. Data import is not automatically performed. Each point cloud is individually imported, subsequently converted to the surface form by applying a 2.5D triangulation, similar to the terrain modeling case. Therefore, the user should interactively rotate the point cloud to a position where the viewing angle is close to the one at the acquisition instant. It substantially reduces the topological errors. On the opposite side, such a stepwise surface generation strategy does not utilize all the available information properly. For example, there might be some object parts with thin point

distributions in individual views, whereas the combination of all views together provides a good solution.
At the next step, separate surfaces were merged as one manifold using the IMMerge module. This part is highly automated, and additionally offers a noise reduction option. During the process, triangulation is also optimized especially at the overlapping regions by associating dense triangles to high curvature areas and sparse at flat areas.
The IMEdit module offers many surface editing functions, e.g. cropping the AOI, filling the data holes, correcting the wrong triangles, boundary cleaning, etc. However, it is less flexible and user friendly than Geomagic Studio.
The resulting models from both software packages meet the project requirements. PolyWorks model (0.6 million triangles) has substantially less number of triangles than Geomagic model (3.9 million triangles), thus having a better and optimized triangulation algorithm. However, the model from Geomagic Studio preserves the small details and structures slightly better than the model of PolyWorks (Fig. 5).

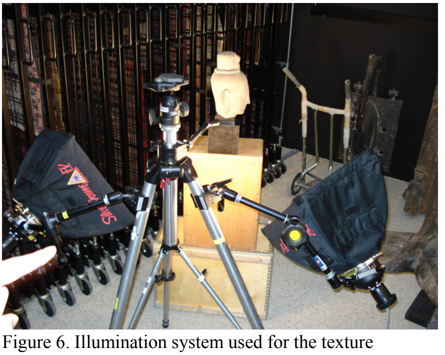
Figure 6. Illumination system used for the texture mapping

Although surface digitization is a very easy and straightforward task, the surface triangulation and editing, which is the key step of the whole modeling chain, is still cumbersome and needs heavy semi-automatic or manual work. The management of large data sets is another aspect. Geomagic Studio crushed several times while filling the holes interactively, whereas PolyWorks did not.

4.4 Texture Mapping

A photographer type of professional illumination system consisting of two diffuse lights on a tripod was used (Fig. 6). It reduces the radiometric differences between the images and shadow effects at the complex parts and object silhouettes. Images were taken by a Sony DSC-W30 6 megapixel digital camera. The PolyWorks model was used for the texture mapping in the original resolution. An in-house developed texture mapping method was employed. Details can be found in Akca et al. (2007).

5 LADY PRAYING PROJECT

Topometrical sensors can be scaled for a wide range of Field of View´s (FOV), typically between a few centimeters up to several meters. Thus, the specifications of the sensor can be adapted to the special demands of a given measuring task. The third case study reports about one of the first attempts for the high definition digitization of paintings, Lady Praying (Fig. 7), Louvre museum, inventory number RF 2090, anonymous artist, 1575-1599. For this work, which was carried out in collaboration with the Centre de Rcherche et de Restauration des Musées de France (C2RMF), a triTOS sensor with a 1.4 MPixel color camera and a field of view of 80 x 60 mm has been used, resulting in a spatial resolution of approximately 60 µm and a depth resolution of about 3 µm. The painting with a size of about 200 x 300 mm has been digitized with about 25 images. Although the depth differences of the painting (including background) is only in the order of 100 µm up to 1 mm, it is possible to align the different images unambiguously just by using this small 3D-information.
The associated software of the scanner (OPTOCAT) offers a bundle of post processing functions, e.g. for the generation of a combined polygon mesh (merging), calculation of cross sections, data

reduction/compressing, filtering and hole filling. For the detailed analysis of the relief of paintings, additional functions are available, which allow to separate the relief to be analyzed from the background structure by compensating the overall shape of the painting. The resulting depth information of the relief may be magnified and displayed quantitatively as shading plot or via pseudo colors.

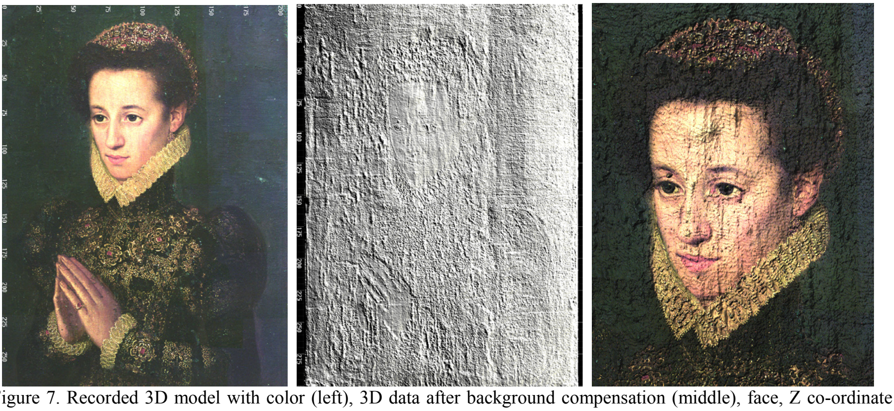

Figure 7. Recorded 3D model with color (left), 3D data after background compensation (middle), face, Z co-ordinate magnified by a factor of 50 (right).

6 CONCLUSIONS

Active sensors are used for many kinds of 3D object reconstruction tasks, one important area of which is 3D documentation of Cultural Heritage objects. This study presents the results of 3D modeling of three Cultural Heritage and Arts objects, where a close-range coded structured light system was used for digitization.

The systems have acquired high quality point cloud data of the objects. The results of the processing (accuracy of about 50 micron for the Herakles statue and the Khmer head and 15 micron for the painting) are in good agreement with the system specifications. The heaviest user interaction is needed in the editing steps, e.g. for filling the data holes. We have used several commercial software packages in order to carry out the modeling. Each software package has its own particular advantages and functions. A unique package, which fulfills all requirements with sophisticated and automatic editing capabilities, is not available. The usage of all three packages can give the optimal modeling results. Texture mapping is another issue, which is not fully supported by either software. Active sensing with coded structured light systems is a mature technology and allows high resolution documentation of cultural heritage objects.

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