3D MODELING OF THE WEARY HERAKLES STATUE WITH A CODED STRUCTURED LIGHT SYSTEM

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ABSTRACT:

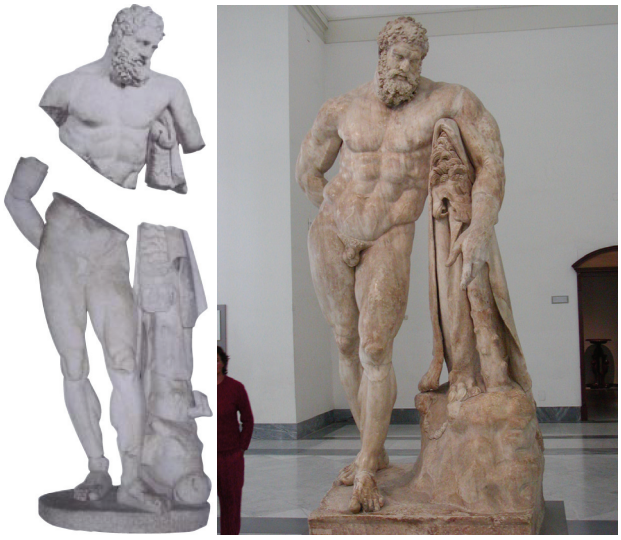
This paper presents the results of a study in which a close-range structured light system is used for the digitization of a cultural heritage object. A Herakles statue, named "Weary Herakles" and located in the Antalya Museum, Turkey was scanned by a Breuckmann optoTOP-HE system. The work comprises the essential steps of the 3D object modeling pipeline, i.e. digitization, registration, surface triangulation, editing, texture mapping and visualization. 3D recording, modeling and visualization of cultural heritage objects is an expanding application area. This paper addresses the capabilities of some of the current technology in this field. Particular emphasis is given to a coded structured light system as an option for data acquisition.

1. INTRODUCTION

Active sensors, e.g. laser scanners and structured light systems are used for many kinds of 3D object reconstruction tasks, one important area of which is 3D documentation of cultural heritage objects.

A part of a Herakles statue, named "Weary Herakles" and located in the Antalya Museum, Turkey was scanned by a coded structured light system. This is a marble statue of the Greek demigod Herakles, which dates back to the 2nd century AD (Fig. 1a). It is a copy of an original bronze statue of Herakles sculptured about 330-320 BC by the Greek master Lysippos of Sikyon. Many artisans devoted their skills to replicating this original around that period. This particular example was probably carved in the Hadrianic or Antonine (Roman) period. The version is identified as the "Herakles Farnese" type on the basis of its similarity to a more complete copy (Fig. 1b) in the Museo Archeologico Nazionale Napoli (Naples National Archaeological Museum, Italy).

In Greek mythology Herakles (or Heracles) was the demigod son of Zeus (Jupiter or Jove, the Roman name) and the mortal Alcmene. In Roman mythology he was called Hercules. He was one of the greatest of the mythical heroes, best known for his superhuman strength and many stories are told of his life. He was made to perform twelve great tasks, called The Twelve Labours of Herakles and became a god. The first task was strangling the Nemean Lion, which was terrorizing the countryside around Nemea. He killed the lion and used the skin of the lion as armor. In ancient art he is mostly portrayed nude and leaning (hence "Weary Herakles") with the lion's skin near him.



(a) (b)

Figure 1. (a) Weary Herakles statue split to upper and lower parts, (b) "Herakles Farnese" type located in Naples. Pictures (a) and (b) are courtesy of Ozgen Acar and René Seindal, respectively.

The statue was broken in two parts (Fig. 1a). We do not know when and by whom it was done. 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. The lower part was found by Prof. Jale Inan (Inan, 1981, 1992) at 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. 2).

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Figure 2. The Weary Herakles statue in the Antalya Museum

According to the Turkish law, Turkish antiques have been state property since Ottoman times 1906. The Turkish government has asked for hand-over of the upper half so that the two fragments can be joined. The Boston Museum has refused to consider the Turkish petition. In 1992, casts of the two fragments were placed together. They were found to match perfectly. The Boston Museum says the statue may have been broken in ancient times, and the upper torso may have been taken from Turkey before the Turkish law established state ownership of archaeological finds (Rose and Acar, 1995; Brodie et al., 2000; Brodie, 2003; 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 September 2005 in the Antalya Museum with a Breuckmann (http://www.breuckmann.com) optoTOP-HE coded structured light system. The system was kindly provided by the Turkish reseller InfoTRON Co. (http://www.infotron.com.tr), Istanbul.

The project was conducted in cooperation with InfoTRON Co. (Turkey), Breuckmann GmbH (Germany), the Division of Photogrammetry of Yildiz Technical University (Turkey), and the Group of Photogrammetry and Remote Sensing of ETH Zurich (Switzerland). Further information can be found on the project webpage[1].

Many of the cultural heritage projects in the literature were carried out by use of laser scanner type of digitizers. Some of the well known ones are relics of the Museum of Quin Shihuang Terra Cotta Warriors and Horses (Zheng and Zhang, 1999), Digital Michelangelo (Levoy et al., 2000), Great Buddha of Kamakura (Miyazaki et al., 2000), Byzantine Crypt of Santa Cristina (Beraldin et al., 2002), statues of Donatello and Giovanni Pisano (Godin et al., 2002), Survey of Dinosaur Skeletons (Bellmann et al., 2005), Eternal Egypt (Rushmeier, 2005), Twelve Divine Generals of Shin-yakushi-ji Temple (Takase, 2006). There exists a small number of cultural heritage studies by use of the structured light method (Maas, 1992; Sablatnig and Menard, 1999; Rocchini et al., 2001; Andreetto et al., 2004). We give particular emphasis to the coded structured light method as a versatile data acquisition option for cultural heritage applications. We give a discussion on the advantages and disadvantages of the system in the following chapters.

For the modeling of the Weary Herakles a total of 67 scans were acquired in order to fully cover the statue. Individual local point clouds were registered into a common coordinate system by use of an in-house developed method, called Least Squares 3D Surface Matching (Gruen and Akca, 2005). The surface modeling was performed in Geomagic Studio, a commercial 3D modeling software. External images taken with a CCD camera were used for the texture mapping. The final 3D model contains approximately 5 million triangles. Nearly the same results were obtained by using the corresponding functions of the Breuckmann system, except texture mapping.

3D documentation and visualization of cultural heritage objects is an expanding application area. This paper covers essential steps of the 3D object modeling pipeline from point cloud acquisition to 3D visualization, and presents the gained experiences. The next chapter gives information about the working principle and specifications of the sensor and the scanning campaign in Antalya. The third chapter explains the processing workflow and addresses the capabilities of the used hardware and software.

2. DATA ACQUISITION

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 one of the cameras with 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 et al., 2000; Beraldin, 2004; Blais, 2004).

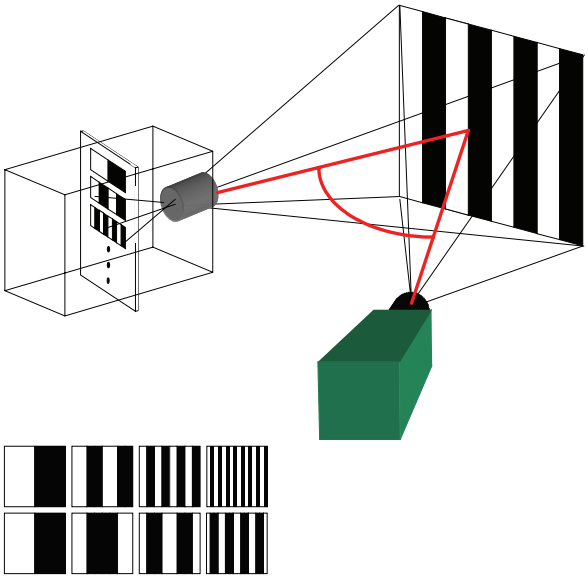
The coded structured light technique, also called topometric technique, is based on a unique codification of each light token projected onto object. When a token is detected in the image, the correspondence is directly solved by the de-codification. It requires a complex light projection system. There exist many codification methods (Batlle et al., 1998; Salvi et al., 2004; Dipanda and Woo, 2005).

The time-multiplexing, also called temporal codification, with a combined Gray code and phase shifting is the mostly employed technique. The optoTOP-HE sensor uses the same technique. A sequence of Gray coded binary fringe patterns is projected onto the object. This divides the object into a number of 2^n sections, where n is the number of pattern sequences (Fig. 3a). 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.

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

[1] http://www.photogrammetry.ethz.ch/research/herakles/

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. 3b and 3c).



(a)

(b)

(c)

Figure 3. (a) Setup of a topometrical 3D-scanner with the natural binary codification, (b) natural binary code, (c) Gray binary code

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. An alternative method to phase shifting, so called line shift has been proposed. For the details of the phase shift and line shift techniques we refer to Gühring (2001).

2.2 The Scanner : Breuckmann optoTOP-HE

The optoTOP-HE system (Fig. 4), as a high definition topometrical 3D-scanner, allows the 3-dimensional digitization of art objects and paintings with high resolution and accuracy. Optionally, the texture and/or colour of the object can be recorded, offering a one-to-one correspondence of 3D-coordinate and colour information.

Figure 4. The optoTOP-HE sensor

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, 1993, 2003). The time for a single scan takes about 1 second for a 1.4 MPixel camera and a few seconds for high definition cameras with 4-8 MPixel. Different scans can be directly aligned by means of the 3D geometry of the digitized object without using any additional markers.

The sensor of the optoTOP-HE system can be scaled for a wide range of Field of Views (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. For the high definition digitization of the Weary Herakles a sensor with a 1.4 MPixel camera and a FOV of about 480x360 millimeter has been used, resulting in a lateral resolution of approximately 360 micron and a depth resolution of about 20 micron. More details are given in Table 1.

Table 1. Technical specifications of the optoTOP-HE system

Field of View (FOV)	480x360 mm
Depth of View	320 mm
Acquisition time	< 1 sec
Weight	2-3 kg
Digitization	1280x1024 = 1.25M points
Base length	600 mm
Triangulation angle	30^0
Lateral resolution	~360 micron
Depth resolution	~20 micron
Feature accuracy	1/15000 (~45 micron)

The corresponding software supports the most important strategies for the alignment and registration of point clouds. It also offers a bundle of postprocessing functions, e.g. for the generation of a combined polygon mesh (merging), calculation of cross-sections, data reduction/compression, filtering and hole filling. The recorded 3D data may be visualized in shaded form, optionally with overlapping texture or colour information, and stored in standardized file formats, e.g. STL, PLY, WRL, DXF.

(a)

(b)

Figure 5. (a) Preparation, (b) first 4 fringe projections of a scan

2.3 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. The average point spacing is 0.5 millimeter.

The optoTOP-HE is an instantaneous 3D digitization system, which means that the acquisition of one point cloud is done in nearly less than one second. However, orienting the scanner and planning the scan overlay needs careful preparation (Fig. 5), especially for this kind of object with many concave and hidden parts. Due to the sensitivity of the sensor to ambient light special attention was paid to environment lighting conditions. Two ceiling halogen lambs looking at the statue were turned off.

3. POSTPROCESSING WORKFLOW

The following processing steps were carried out from the raw point clouds to 3D visualization. Different software packages were used at each step.

- Registration (LS3D)
  - + Pairwise registration
  - + Global registration
- Point cloud editing (Geomagic Studio)
  - + Cropping the area of interest
  - + Noise reduction
  - + Down-sampling
- Surface triangulation and editing (Geomagic Studio)
- Texture mapping (Weaver)
- Visualization (PolyWorks IMView)

3.1 Point Cloud Registration

3.1.1 Pairwise Registration with Least Squares 3D Surface Matching: The pairwise registration was done by use of an in-house developed method, called Least Squares 3D Surface Matching (LS3D) (Gruen and Akca, 2005).

The LS3D estimates the transformation parameters between two or more fully 3D surfaces, using the Generalized Gauss-Markoff model, minimizing the sum of squares of the Euclidean distances between the surfaces. This formulation gives the opportunity of matching arbitrarily oriented 3D surfaces simultaneously, without using explicit tie points. The geometric relationship between the conjugate surfaces is defined as a 7-parameter 3D similarity transformation. This parameter space can be extended or reduced, as the situation demands it. The unknown transformation parameters are treated as stochastic quantities using proper a priori weights.

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).

Totally 234 consecutive matching processes were performed using the LS3D matching method. In all cases the solution was found. No divergence or failure case occurred. The average of the sigma naught values is 81 micron.

3.1.2 Global registration: The first scan was selected as the reference, which defines the datum of the common coordinate system. Since multiple overlaps exist among the point clouds, there is need for a global registration, which distributes the residuals evenly among all the scans, and also considers the closure condition, i.e. the matching of the last scan to the first one. For this purpose we used the block adjustment by independent models solution (Ackermann et al., 1973), which was formerly proposed for global registration of laser scanner point clouds, but for the case of retro-reflective targets as tie points (Scaioni and Forlani, 2003).

In the LS3D matching processes, the final correspondences were saved to separate files. The number of tie points was thinned out by selecting every 24th correspondence. Then all these files were given as input to the block adjustment by independent models software BAM7, which is an in-house software based on a 7-parameter 3D similarity transformation. It was run in the rigid body transformation mode by fixing the scale factor to unity. The block adjustment concluded with 47 micron *a posteriori* sigma naught value in 4 iterations.

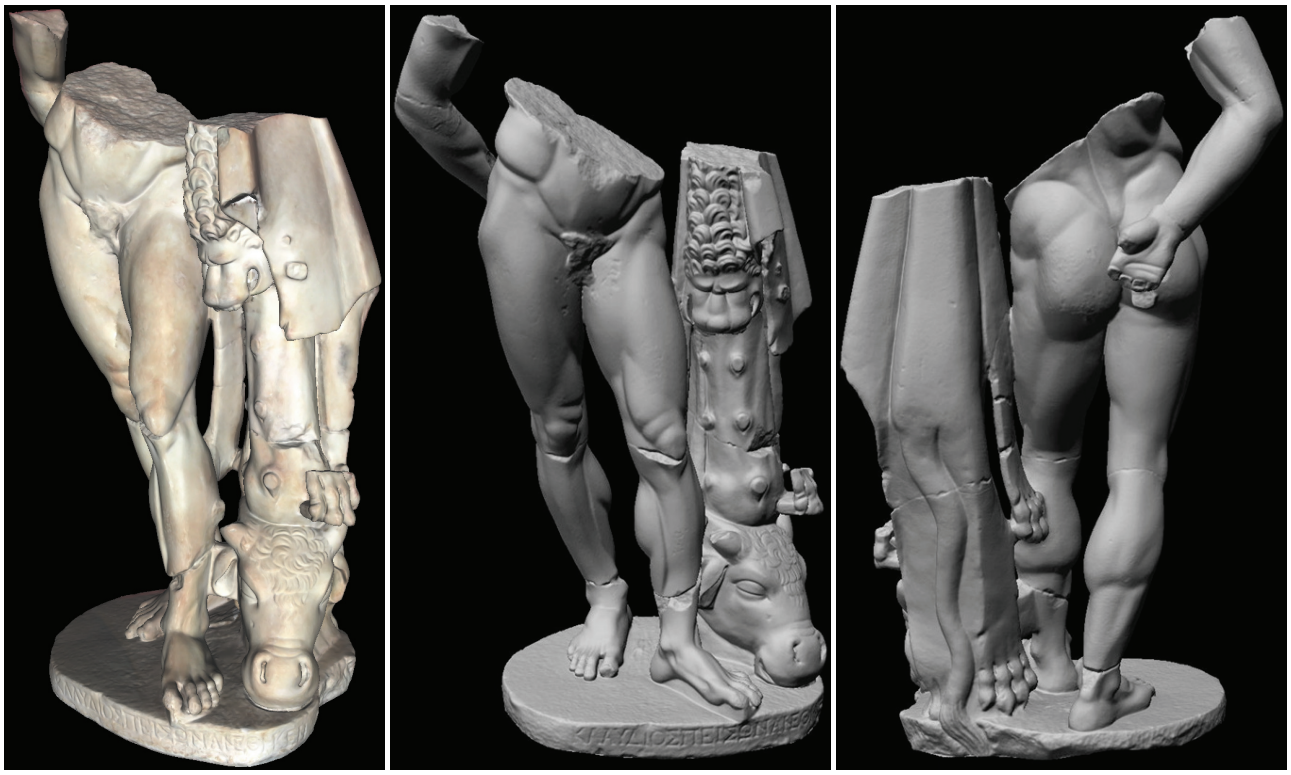
Very similar results were obtained by using the corresponding functions of the OPTOCAT software of the Breuckmann scanner.

3.2 Point Cloud Editing

After the registration all scan files were merged as one XYZ file, discarding the scanner detected blunders. This file totally contains 36.2 M points. The file was imported to Geomagic Studio 6 (Raindrop Geomagic). All the editing procedures were carried out in Geomagic Studio. The data set was further cropped to include only the area of interest, i.e. deleting the background wall or other non relevant parts, concluding with 33.9 M points. A low level noise reduction was applied using the “Reduce Noise” function of Geomagic Studio.

As a first attempt the surface mesh generation was tried at the original data resolution. The operation could not be performed, since the memory request of the software exceeded the physical memory limit of 2 GB of the computer. Therefore, the number of points was reduced to 9.0 million by applying the “Curvature Sampling” function of Geomagic Studio. This operation eliminates points in flat regions but preserves points in high-curvature regions to maintain detail.

Figure 6. Picture of the statue and its back-projected 3D model



(a) (b) (c)

Figure 7. (a) Frontal view of the texture mapped model, (b) frontal view and (c) back view of the grey shaded model

3.3 Surface Triangulation and Editing

Surface triangulation was done by setting the number of target triangles to 5 million. 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 wrapped surface. They were interactively filled with the "Fill Holes" option of the software. The final model contains 5.2 M triangles. We have achieved a high level of realism, which can make a one-to-one scale production of the statue possible, if required (Fig. 6).

The main portion of the editing effort is for the hole filling. It is a tedious work, and takes the longest time among all the steps of the project.

3.4 Texture Mapping and Visualization

Seperately 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 algorithmic details of the software can be found in Callieri et al. (2002). The VCLab's Tool is a bundle of modules, which comprise the fundamental steps of the 3D modeling (Callieri et al., 2003).

The visualization of the final model was done with the IMView module of PolyWorks. It gives a better shading than Geomagic Studio. The textured model was visualized with the viewer of the VCLab's Tool (Fig. 7).

3.5 Capabilities of the Used Hardware and Software

The optoTOP-HE sensor as a coded light projection system meets the project requirements satisfactorily. It has some distinctive advantages over the triangulation-based laser systems (Table 2). The use of incoherent light reduces speckle noise and provides better surface smoothness (Blais, 2004). Furthermore it does not penetrate into the object surface, unlike laser light whose penetration property is well known, e.g. for marble (Godin et al., 2001). All these reasons make the system a suitable choice for Cultural Heritage applications.

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 size is another aspect. Geomagic Studio crushed several times while filling the holes interactively.

Table 2. Triangulation-based systems: laser versus coded light

	Laser	Coded light
Weight and price	identical	identical
Scanning speed		faster
Sensitivity to ambient light	less	
Speckle noise		less
Penetration into object surface		no
Imaging for texture mapping		yes
Depth of View	larger	

4. CONCLUSIONS

Active sensors, e.g. laser scanners and structured light systems 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 the Weary Herakles statue, where a close-range coded structured light system was used for digitization.

The system has acquired high quality point cloud data of the statue. The results of the processing (accuracy of about 50 micron) 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 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.

Active sensing with structured light systems is a mature technology and allows high resolution documentation of cultural heritage objects.

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