Virtual 3D Model of the Antique Temple Construction in Sirwah (Republic of Yemen) for Archaeological Object Documentation by Terrestrial Laser Scanning and Digital Photogrammetry

Thomas P. Kersten[1] – Maren Lindstaedt – Klaus Mechelke –
Marcel Götting – René Heiden

HafenCity University Hamburg, Department Geomatics, Hebebrandstrasse 1, D-22297 Hamburg
[1]thomas.kersten@hcu-hamburg.de

Abstract

This paper presents the combined use of digital photogrammetry and terrestrial laser scanning for 3D data acquisition and modelling of the Almaqah temple in Sirwah (Republic of Yemen). This ancient building is located 120km east of Sana'a and approximately 40km west of Marib. This project is a co-operation between the German Archaeological Institute (DAI), Sana'a Branch of the Orient department and the department Geomatics of the HafenCity University Hamburg. The recording phase of the project was carried out in February 2007 with a Fujifilm Fine Pix S2 pro digital SLR camera and a Trimble GS101 terrestrial laser scanner during archaeological excavations. The temple was modelled as base data for archaeologists and other research disciplines using triangle meshing. Different possibilities for texture mapping the model were identified and discussed.

Keywords

archaeology, documentation, 3D modelling, photogrammetry, terrestrial laser scanning

1. Introduction

In the past the recording of complex objects was frequently undertaken using photogrammetric multiple image procedures and geodetic measuring methods. In recent years further high performance technology has become available in the form of terrestrial laser scanning. Depending upon the requested final product these scanners can be used as stand alone systems or in combination with other sensors such as digital cameras. As a result of the laser scanner's characteristic ability for measuring an extremely high number of points within a short time period, it is a genuine alternative to conventional recording methods for many modern applications, particularly in order to procure 3D data for the modelling of a diverse range of objects. If the object to be recorded is of archaeological importance, the generation of an interactive, virtual 3D model offers many advantages regarding interpretation and the possibility of integrating a variety of different information sources within a spatially referenced system. Furthermore, the interactivity of a virtual model offers users the possibility of measuring and collecting the important information itself from the represented virtual object. The level of information that can be derived from the virtual model is limited to the level of detail which was used for recording and modelling. Only the performance of the hard- and software create restrictions since they define the possibilities for the representation and storage of information.

The project presented here was carried out by the HafenCity University Hamburg in co-operation with the Orient Department (outpost Sana'a) of the German Archaeological Institute. Co-operation between the two project partners has been ongoing for several years, e.g. the recording and 3D modelling of the large dam in Marib/Yemen (Kersten 2007). The Almaqah temple in Sirwah, which is located 120km east of the Yemeni capital Sana'a, was recorded by terrestrial laser scanning and digital architectural photogrammetry, although it was not clearly defined before acquisition whether the data evaluation should be conducted using the combination of the two data records or only one of the two data sets. The accuracy requirement was defined by the archaeologists as 3cm precision for a point, since the generated 3D model should not only be used for visualization purposes, but also for later analyses by structural engineers, stress analysts, architects and archaeologists. The use of terrestrial laser scanning and digital photogrammetry

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in archaeology has already been successfully presented by several authors (El Hakim *et al.* 2004; Fux *et al.* 2008; Kersten *et al.* 2009). Furthermore the virtual model is planned as base data for a 3D geo-information system, which will be implemented in the future. Such a system has already been realised by the DAI in co-operation with the ETH Zurich for the geoglyphs of Nasca/Palpa in Peru, which were mapped by means of photogrammetric methods and which were subsequently made available in a 3D GIS (Lambers 2004).

2. The recorded object – Almaqah temple construction in Sirwah

The sabaean town of Sirwah is located 40km south-west from Marib in Yemen. With an approximate trapezoidal shape the town covers an area of approximately 220m x 230m. *Fig. 1* shows an aerial photo of the complex town area of Sirwah, with the Almaqah temple located in the red circle. The temple is considered to be one of the masterpieces of sabaean architecture. It forms the central element of the town area and is integrated into the town wall. The main building was established in the mid 7th century BC, but was converted several times and extended in the following centuries. Embedded into the town wall the temple wall is over 8m high and is still in a very good condition today. The centre of the yard is dominated by the inscription stones Karib'il Watars, which rise on a bricked base, which was probably originally built with alabaster plates. The 6.80m long, one-above-the-other lying stones contain the longest known sabaean inscription on

both sides. The north-south expanse of the temple construction is about 40m, while the east-west range is approximately 30m. The height of the outside wall measures at most 9m above ground and the tower, in the southeast part of the temple, at 10m is the highest object within the construction. The restoration of the temple construction has already taken several years and resulted in today's complete excavation.

3. Systems used for data acquisition

The combined data acquisition of the Almaqah temple was carried out using a Fujifilm Fine Pix S2 pro digital SLR camera with a 28mm Nikkor lens (using a super CCD chip with an area of 23.3mm x 15.6mm and 4256 x of 2848 pixels) and a Mensi GS101 the terrestrial laser scanner from Trimble. The laser scanning system, consisting of scanner, software and accessories, scans with the pulsed time-of-flight method. For an optimal measuring distance of 2–100m the measuring accuracy of a single distance is 6mm. With an angular resolution setting of 0.0018° a grid width of 3x3mm at 100 m distance can be realized. The panorama view scanner (360° horizontal, 60° vertically) is able to scan 5000 points/second at its maximum. The geodetic network measurement and determination of the control points were carried out with a Leica TCRP 1201 R300 total station.

Fig. 1. Aerial image of the sabaean town area of Sirwah (Gerlach 2003) with the Almaqah temple in the circle (left), Almaqah temple in February 2007 (right).

4. Photogrammetric object recording and laser scanning

The object recording was conducted in a four week measuring campaign in February 2007, with each week consisting of six working days in the field due to the limited time available for recording. The team consisted of one scientific staff member and two diploma students from the HafenCity University Hamburg.

For network measurements, which were collected at the beginning of the project, fixed points, which were determined in an earlier GPS campaign in the UTM system, were used. Within this geodetic network the necessary control points were then determined for photogrammetry and laser scanning. For the photogrammetric recording 285 control points (*Fig. 8* shows the signal used) were attached to the object. In total 450 photographs were taken with the Fuji S2 pro on two days, which corresponds to a data volume of 16GB. In order to ensure optimal geometrical configuration, the photographs were taken not only from the ground, but also from a ladder and/or from the tower of the temple. Also since details, e.g. the inscription stones, needed to be recorded and evaluated, very different distances between object and camera position are used resulting in large differences in photo scales, which resulted in complex data evaluation.

The object recording with the laser scanner Mensi GS101 required the whole field campaign; however, the scanning was interrupted several times for a number of days. The scanning started with large objects such as the outer wall and later the recording of smaller objects like the inscription stones and bronze chambers was carried out. In total 41 scanner stations were needed and 45 million points were scanned, which corresponds to a data volume of 2.7GB. For the registration and geo-referencing of each scan station several white spheres, which were determined in the same way the photogrammetric control points, i.e. using the total station, were scanned from each scan station. Since the scanner's maximum operating temperature of 40° Celsius was always reached by mid-morning, work was only possible using a sun umbrella as heat protection.

5. Data processing

5.1. Registration and geo-referencing of point clouds

For the registration and/or geo-referencing of the point clouds the program RealWorks Survey 5.1 from Trimble was used. Due to the large data volume of 45 million points the scans from several stations were not registered into one scanner coordinate system; rather each scan station was directly geo-referenced into the UTM system using the scanned white spheres. Only the seven scan stations of the bronze chambers were an exception, since here sufficient geodetically determined spheres were not available for each scan; therefore a registration of all stations was conducted

Fig. 3. Entire point cloud of the Almaqah temple after geo-referencing.

Fig. 2. Object recording with the terrestrial laser scanner MENSI GS101.

before geo-referencing. In total an accuracy of 9mm, on average, for all object points was obtained, which fulfilled the requirements of the archaeologists for 3D modelling. For further data processing the point cloud (*Fig. 3*) was reduced to a point sampling distance of 15mm, which still corresponds to 22 million points. Therefore, the point cloud was segmented into seven parts to be modelled and exported in ASCII format including RGB values with the XYZ values.

5.2. Photogrammetric data acquisition

Although 450 images were taken in total, only 260 pictures of the interesting object parts were selected, distributed on two photogrammetric image blocks. The image orientations of these two photo blocks with 130 pictures each and the camera calibration of the Fuji S2 were determined simultaneously in a bundle block adjustment using PHIDIAS, which is an MDL application (MicroStation development LANGUAGE) for the CAD system MicroStation. A good connection within the photo blocks was ensured by the high number of measured points per image (14 and/or 21), whereby each object point was measured in seven or eight images, on average. All systematic errors (mainly caused by lens distortion) were compensated by simultaneous camera calibration, which was confirmed by comparison of the two very similar calibrations. The average measuring precision of the image points was 3–4µm, which corresponds to approximately half a pixel. The precision of the objects points was 3–4mm, which was still better than the accuracy values demanded by the archaeologists.

5.3. 3D modelling of the temple

Thus for modelling of the temple both the point cloud generated by laser scanning and the oriented photogrammetric images were available. In this project phase it was decided, for reasons of timing, to carry out the modelling using only meshing of the point cloud and to use the images primarily for geometric checking and for texture mapping of the generated model. Although the possibility of combined evaluation of scan data and oriented images was given using PHIDIAS, this option was rejected due to the complexity of the object. Instead, the software Raindrop Geomagic V9 was used for the triangle meshing of the scan data. For import of the point

clouds generated by RealWorks Survey the digits of coordinates were shortened, since Geomagic was primarily designed for industrial applications and the UTM coordinates cannot be used without problems. The work procedures described in the following were executed for all seven sub parts of the entire point cloud.

Firstly remaining outliers were eliminated using a filter function. Then the 3D triangulation was executed. For most of the model entire sub parts were not modelled at once. Rather different triangle sizes were used for different sub parts depending upon the point density. Finally the smaller remaining holes in the model were filled. For this the software Geomagic offers several options from which the curvature-based filling was chosen in order to adapt the missing triangles in the best possible way to the surrounding object form. During triangle meshing a RGB colour value, which is interpolated from the three points of the triangle, is assigned to each produced triangle. Thus, the produced virtual model is already quite descriptive, but nevertheless, for realistic visualization purposes, texture mapping with digital high resolution images was preferred. After meshing some polygons were smoothed if necessary due to registration inaccuracies within the overlapping areas of the scans, which resulted in slightly rough surfaces in these areas. Since the data volume was 12 million triangles after modelling, in some selected parts the number of triangles was reduced significantly. E.g. this was the case with the outer wall, which exhibits a completely smooth surface for the very finely formed stones, and thus the accuracy of the model was not affected by the reduction in the number of triangles. The result of the modelling is illustrated in *Fig. 4*. In order to prove that the form of the model had not deteriorated from this data reduction, the two models
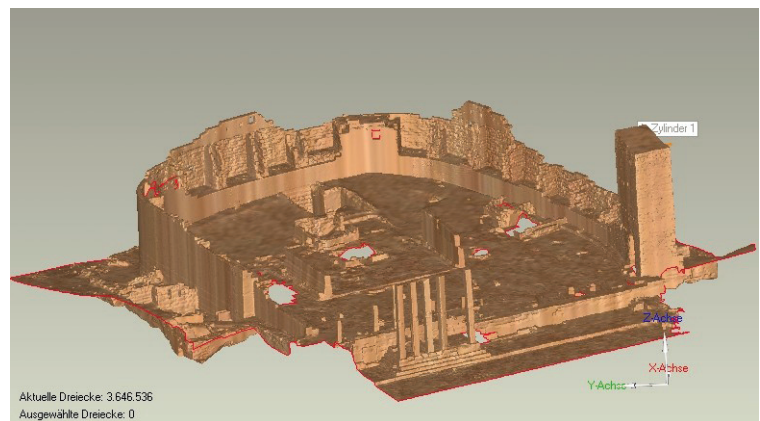

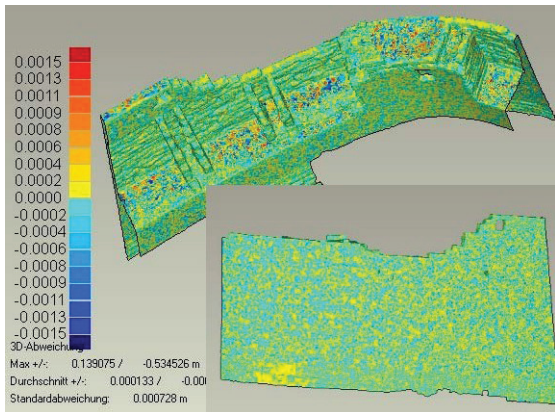*Fig. 4. Entire virtual model of the Almaqah temple after meshing in Geomagic.*

Fig. 5. Differences between original and reduced model of the Almaqah temple.

(before and after the reduction) were compared to each another. The result is shown in *Fig. 5*, where the deviations are depicted with a range of no more than 2 millimetres. Thus, the number of triangles could be reduced to approximately one third of the total amount.

Finally, the virtual model was checked by some measurements from photogrammetry. The average distance differences between model and photo-grammetric measurements were 13mm, where also the maximum deviation of 27mm fulfils the require-ments of the archaeologists. A detailed description of the modelling is summarized by Götting and Heiden (Götting and Heiden 2007). Further investigations examined how greater data reductions might affect

the accuracy of the model. For these the original data set of the model with 3.5 million triangles was used as a reference. The data reduction was carried out in seven steps up to a minimum of 5% compared to the original number of triangles (*Fig. 6*). For these computations the option of the maximum curvature priority was always selected. The results showed that five of six distances compared in all stages including 10% of all differences being within 2.5cm of the original data set (*Table 1*). The only distance with a larger deviation, the distance 4, is not clear defined due to rounded edges on the stone. However, it is possible to determine clearly defined distances in the significantly reduced model with an accuracy of better than 5cm. This proves that the use of curvature-based reduction can reduce planes (particularly smooth ones) very significantly, while corners and edges are retained, and thus also the original geometry of the model is uncompromised.

5.4. Texture mapping of the model

Finally, parts of the model were textured with the available high resolution imagery. For this test two different software packages were selected and the results were compared with each other. Due to the huge model size only the tower and an inscription stone were textured in detail in order to examine the potential of the different programs used. The data evaluation was carried out on the one hand in Geomagic studio V9 and on the other hand with the program QTSculptor (demo version) from Polygon Technology GmbH. However, the results of both software packages were not perfectly satisfying. Both programs realized
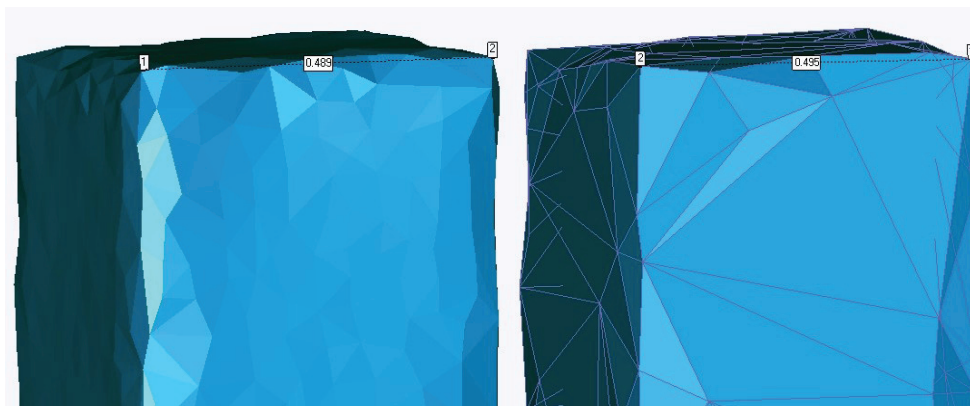

Fig. 6. Original data set (left) and the reduced data set (10%).

		Data set reduced to x percentage						
		80%	60%	50%	25%	20%	10%	5%
	1	0.2	0.4	1.1	0.9	1.0	0.5	0.4
	2	-0.1	0.0	-0.5	0.2	-0.1	-0.5	-0.2
Distance	3	0.3	0.1	-0.1	-0.7	-0.8	-0.7	4.5
	4	-4.7	0.8	-7.0	-5.7	-6.1	-4.5	-6.7
	5	-1.5	-2.1	-0.9	0.1	0.0	0.2	2.1
	6	0.3	0.1	0.0	1.3	0.9	1.4	-1.0

Table 1. Differences between original and reduced data set [cm].

the registration of the image and model with control points; however this did not always function properly, particularly not when a higher number of control points were used. The largest problems were discovered using Geomagic; the registration succeeded only randomly. However a reason for this could not be found. The option of using image orientations is not provided in either of these two programs. Nevertheless, the option exists to import camera calibration parameters in QTSculptor, in order to compensate for lens distortions. A further problem occurred within the overlapping

Fig. 7. Radiometric differences in the textured model.

Fig. 8. Tower and inscription stone, both textured in Geomagic.

area of two images. There either both textures were mixed, which led to blurring/haze within this area, or an edge was clearly depicted in the model without radiometric adjustment of the two images (*Fig. 7*).

Furthermore, quality evaluation of the accuracies of registration is not quantifiably with a visual check being the only available option in QTSculptor. The textured tower and the inscription stone are represented in *Fig. 8*.

6. Preparation for GIS integration

Several different technical disciplines such as restoration, conservation, archaeology and architecture can work with virtual models exported into VRML format to map, to classify, to divide into their essential elements, to measure and to prepare for scientific analysis. Using a software package such as aSPECT3D (from ArcTron, Germany) the temple can be viewed interactively from all sides, so that arbitrary distances can also be measured in the model (*Fig. 9 right*). Thus the model serves as a valuable source of information for civil engineers, architects, stress analysts and archaeologists to replace the labour intensive manual hand sketches from the field traditionally required for many applications. Moreover, once the model is generated as the base data for archaeologists, it can be used to map finds from the excavation fieldwork directly in the model and to provide all available related attributes and information (*Fig. 9 left*) for later
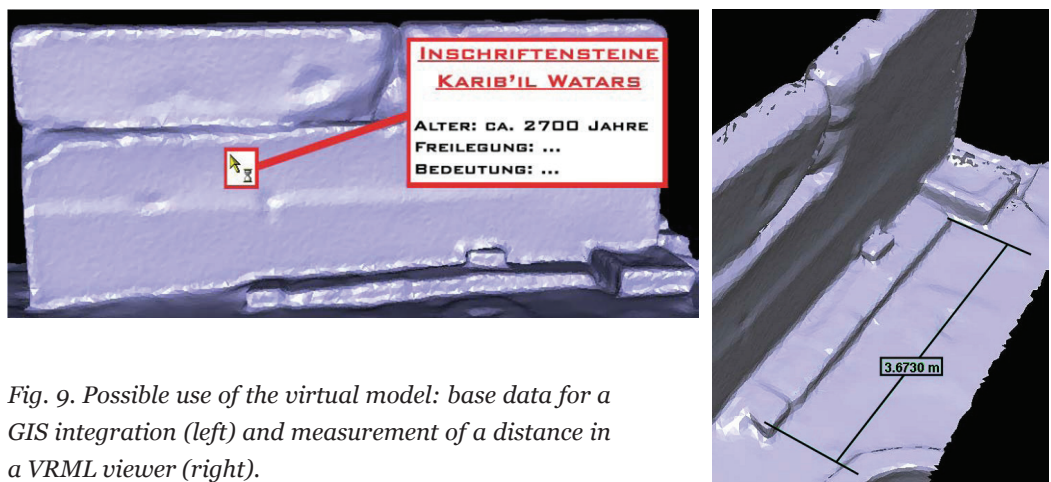

Fig. 9. Possible use of the virtual model: base data for a GIS integration (left) and measurement of a distance in a VRML viewer (right).

integration of 3D data, textures and archaeological information into a database connected to a GIS (Sauerbier *et al.* 2008).

7. Conclusion and outlook

In this project work 3D object recording of the Almaqah temple in Sirwah/Yemen by means of terrestrial laser scanning was demonstrated. The Trimble GS101 used in this project fulfilled the accuracy requirements of 3cm given by the archaeologists as proven by checks made against photogrammetric data. Thus, the model can serve as base data in the field for different research disciplines. The modelling by triangle meshing of the point cloud results in a very complete representation of the temple; the evaluation of the photogrammetric data was not necessary for the construction of the model. Nevertheless, this method of modelling by meshing is less time-consuming than photogrammetric data evaluation and reconstruction in CAD; however this model has a similar degree of detail as achievable using stone-by-stone mapping in CAD. Nevertheless, a significant problem is still the volume of data. The laser scanner offers the possibility of scanning high data rates, but the evaluation and subsequent processing of these huge data volumes on a standard computer is still limited by typical computer performance. The virtual model, which was generated in this project, has a file size of 120 MB as VRML format, which already makes the interactive handling on a standard PC difficult. Complete texture mapping of the temple to this degree of detail would make interaction with the model impossible.

The investigations in texture mapping of the model, described above, are still not completely satisfying solutions because the use of image orientations was not possible in either of the evaluated software packages and the texture mapping could only be carried out through intensive manual interaction. Therefore only a few selected parts of the model could so far be textured as examples. As the next step automatic texture mapping of the different reduced 3D models of the Almaqah temple is planned by using image orientation parameters and the related camera calibration data with the software 3D IMAGE from the Technical University in Braunschweig (Abdelhafiz 2009). For these reasons, in future project's priority should be given to whether photogrammetric recording and/or evaluation is

requested, or whether images should be taken only for the texture mapping of the object. If a huge model has to be generated with high accuracy as base data for future analyses etc., texture mapping with today's state of the art hard- and software is still a difficult task. However, if visualization is the focus of the final product, the model should be simplified from the beginning in such a way that the use of this model is possible for any applications on standard PCs.

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