Virtual Reality Model of the Northern Sluice of the Ancient Dam in Marib/Yemen
by Combination of Digital Photogrammetry and Terrestrial Laser Scanning for Archaeological Applications

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In this paper the potential of digital photogrammetry and terrestrial laser scanning in combination is demonstrated in the recording and 3D CAD construction of the northern sluice of the ancient dam in Marib/Yemen, which is located approx. 150 kilometre east of the capital city Sana’a, close to the inner Arabic desert. The Yemeni government proposed for initiation of the building into the list of the UNESCO world cultural heritage. This described project work is a co-operation between the Commission for Archaeology of Non-European Cultures (KAAK) Bonn of the German Archaeological Institute (DAI) and the department Geomatics of the HafenCity University Hamburg. The object recording was carried out in January 2006 with the digital SLR camera Fujifilm FinePix S2 pro and the terrestrial laser scanner Trimble GS100 during the archaeological excavations. The northern sluice was reconstructed and visualized as a computer-based 3D CAD model for archaeological investigations (as-built-documentation of the excavations) and for future tourism advertising and publication purposes.
1. Introduction

Yemen offers extensive archaeological potential, but many important archaeological sites are still unexplored to a large extent, as for example those of the antique Sabean capital city Marib. In the context of the main research field “antique water management” the remains of the antique dam of Marib have been comprehensively excavated, analysed and restored by the German Archaeological Institute since 2002 ([1], [2]), despite recent political events such as a kidnapping in December 2005. The project is financed by the German Federal Ministry for Economic Cooperation and Development and the Deutsche Gesellschaft für Technische Zusammenarbeit (GTZ) GmbH. The organisation of the project is performed by the Commission for Archaeology of Non-European Cultures (KAAK) Bonn of the German Archaeological Institute (DAI).

The three-dimensional data acquisition and digital construction of a potential world cultural heritage site needs complex data volumes, since complete geometry as well as surface characteristics of the recording objects are specifically required, in order to be able to generate as realistic as possible a virtual model. Therefore, a combination of digital photogrammetry and laser scanning was used for the recording of the northern sluice (Figure 1), in order to use the specific advantages of each respective recording system and to be able to judge the effectiveness of the evaluation procedures in cultural heritage applications. As a result of the recording a three-dimensional visualized and/or animated model of the northern sluice is available, which additionally can be offered as the base for a subsequent 3D geo-information system (GIS). How one can use a three-dimensional, visualized model as an optimal base for a 3D GIS was realized for the Geoglyphs of Nasca Palpa in Peru, which were mapped by photogrammetric methods and represented afterwards in a 3D GIS [3].

Photogrammetry and laser scanning are important instruments for the documentation of cultural monuments. The required precision from the archaeology is about ±10cm for object points, since archaeology is mainly focussed on interpretation and visualization of historic buildings. Combined photogrammetric and laser scanning data processing was already accomplished at HafenCity University for the project West Tower ensemble in Duderstadt (Lower Saxony, Germany) with the program PHIDIAS [4]. Due to the combined graphic display of digital, orientated images and geo-referenced 3D point clouds of a laser scanner the data processing using PHIDIAS has proven to be very efficient. As an example for another cultural heritage application the voluminous geometrical documentation and visualization of the temple ruin Athribis of the lion goddess Rept in northern Egypt is summarized in [5].
Figure 1: Overview image of the northern and southern sluice of the ancient dam in Marib/Yemen. (Photo: Google Earth)
2. The recorded object – northern sluice of the ancient dam in Marib/Yemen

The former Sabaeer capital city Marib is located approx. 150 km east of the Yemeni capital Sana’a in the transient area of the Yemeni highland to the inner Arab desert Ramlat as-Sab‘atayn.

In the year 548 A.D. the ancient community established the large dam of Marib, a masterpiece of engineering architecture at that time. Thus, the inhabitants of southern Arabia could use the periodically occurring monsoon rain as tide irrigation for agriculture. Typically twice per year the violent rains were captured by the dam and led into a comprehensive irrigation system. The water masses were reserved by an earth dam with a so-called stone ticking, which was built at a narrowed location of the Wadi Dhana. Hence, the task of the dam consisted of catching and supporting the incident water off flow. However, no water reservoir was to be created, but the groundwater level of the area should slowly have increased. At the northern and southern end of the dam water gates (sluices) existed (Figure 1), with which the supplies of water could be regulated for the cultivated areas via the main channels [1]. The northern sluice of the old dam (Figure 2), which was recorded in this project, is located at the foot of the adjacent mountain range. The main walls of the building bordered a basin, in which the arriving water masses were supported and later flowed into an artificial canal system. From this the water flow was well distributed via twelve smaller canals into the oasis land. The overflow wall served as flood discharge.

On the one hand the water from the mountains could be accumulated with this water management system, in order to prevent inundations on the oases. On the other hand despite increasing sedimentation in the area causing a rise in levels for the cultivated lands irrigation was guaranteed. Consequently, the irrigation level continuously rose after each flooding [3]. Nevertheless, in order to be able to supply the agriculture surfaces with sufficient water, the buildings had to be raised to achieve a higher level than the irrigation level. From the places in the northern sluice, in which the stone boarding is missing,
it is clearly recognizable that the wall of the catchment’s basin of the water off flow was increased due to the sedimentation and the rising level of the water. It was foreseen by constant rising of the sediment layers that the dam could not sustain the masses and the pressure any longer. Consequently, after a short period of use a break of the dam finally occurred between 575 and 600 A.D., which was no longer be repaired. Thereafter, water management stopped and lead to the depopulation of the once thriving oasis [2].

3. Systems used for object recording

The recording of the dam was performed with a commercial digital SLR camera Fujifilm FinePix S2 pro and the terrestrial laser scanning system Trimble GS100. The S2 possesses a CCD chip with a sensor of 23.3 mm × 15.6 mm, which offers a maximum interpolated resolution of 4256 × of 2848 pixel, which yields a file size of approx. 35 MB per image in TIFF. At this resolution 28 photos can be stored on one Compact Flash Card with 1 GB storage capacity. The camera was used with a Nikkor lens with the focal length of 28 mm.

The 3D laser scanning system GS100 is manufactured by Trimble S.A., France and consists of a laser scanner, accessories (Figure 3) and appropriate software for data acquisition and post processing. The optimal scanning range is between 2–100 m. The panoramic view scanner (field of view 360° horizontal, 60° vertically) offers an uninterrupted panoramic capture of a scene of 2 m × 2 m × 2 m up to 200 m × 200 m × 60 m indoors or outdoors. The resolution of the scanner is 0.002 gon (Hz/V). The laser point has a size of 3 mm in 50 m distance, whereby the standard deviation of a single distance measurement is 6 mm. The distance measurements are performed by pulsed time-of-flight laser ranging using a green laser (532 nm, laser class II or III). The system is able to measure up to 5000 points per second.

Figure 3 shows the 3D laser scanning system Trimble GS100 (weight 13.5 kg) with accessories, consisting of a rugged flight case and a notebook for controlling the unit during data acquisition. The usage of an efficient power generator is recommended for field work, when mains power cannot be obtained.

Investigations into the accuracy behaviour of the terrestrial laser scanning system Trimble GS100 are described in [7].

4. Photogrammetric object recording and laser scanning

The object recording was performed with a team of four people from the HafenCity University Hamburg within a three week campaign from December 29th 2005 to January 17th 2006. First, a local 3D network and control points for photogrammetry and laser scanning were measured with the Leica tacheometer TCRP 1201. From a previous diploma thesis of the department Geomatics fixed points were already available for the transformation into the UTM coordinate system [8]. Due to reduced transportation facilities,
sufficient tripods could not be brought for the geodetic net measurement. The network had to be measured without forced centering on tripods, which slightly reduced the precision. In addition, the zenith angle measurement was significantly affected by the high refraction. But with respect to the later applications in archaeology the precision losses are quite justifiable.

The photogrammetric recording was carried out with the SLR camera Fuji S2 in multi image triangulation mode. In order to obtain a good camera configuration around the object, a 5 m high ladder was used for additional camera stations (Figure 4a). In total, 458 images of the entire dam were recorded, although for the subsequent evaluation only 138 were used. 53 circular targets, which were generated in AutoCAD, were used as photogrammetric control points, whose coordinates were determined geodetically in a 3D network.

Using the laser scanner Trimble GS100 (Figure 4b) the 3D geometry of the northern sluice could be scanned and additionally intensity values of the laser beam and the RGB values of the internal video camera were stored for each 3D point. Thereby, the initialization of the scanner as well as the definition of the respective scanning station was performed using the scanning program PointScape V2.0. After scanner initialization the scanning area was specified in real time via the displayed video frame from the scanner’s internal camera. This process was particularly recommendable, in order to avoid unnecessary data volumes from the environmental area of the dam. For the complete object scanning 19 scanner stations in total were needed. Moreover, all visible control points and registration points, which were equipped with spheres, were scanned additionally from each scanner station. All control points were determined in the geodetic network.
measurement. These points were used later for the registration and geo-
referencing of the scans in the UTM coordinate system.

5. Data processing

5.1. Geodetic 3D network adjustment

The program system Panda (GeoTec, Laatzen, Germany) offers computation
and adjustment of geodetic 3D networks including the computation of relevant
network specific parameters for the analysis, optimization and evaluation of 3D
nets. The three-dimensional network adjustment delivers control point
coordinates for the subsequent geo-referencing of the recorded
photogrammetric images and the point clouds from laser scanning. In the three-
dimensional net adjustment a standard deviation for the horizontal and vertical
angle measurement of approx. 3 mgon and for the distance measurements a
standard deviation of approx. 3 mm was achieved. For the adjusted UTM
coordinates of the network stations a maximum standard deviation of 1 mm
was determined. For the control point measurements the largest residual in
planimetry amounts to 10 mm, while the average residual was approx. 2 mm.
Due to the more inaccurate zenith angle measurements the height coordinates
showed higher residuals, i.e. the largest residual for a photogrammetric control
point was 6 mm, while the average value was 3.5 mm.

5.2. Registration and geo-referencing of scans

The manual registration and geo-referencing of the three-dimensional
point clouds of each laser scanner station was accomplished with the
software RealWorks Survey 5.0 (RWS). The 19 scanner stations were
registered using at least three of the 22 control and tie points (spheres).
The precision of the registration amounted to maximally ±11.7 mm (RMS) per station. Subsequently, the entire registered point cloud could be geo-referenced into the UTM system with a precision of 1 cm for the transformation using four control points in total. This achieved precision easily fulfils the requirements for object construction in archaeological applications.

Subsequently, the entire point cloud (28 million points) (Figure 5) was cleaned up, i.e. all redundant points, which did not belong to the object like scaffolding or workmen, were deleted. Thus, the point cloud could be reduced to 21 million points in total. For the object construction the parts/areas in the point cloud, which were required for data processing, were segmented and exported as ASCII file, in order to be able to be processed in PHIDIAS.

5.3. Image orientation and camera calibration

The bundle block adjustment for image orientation including simultaneous camera calibration was accomplished with the program PHIDIAS, which is an MDL application of the CAD system MicroStation. Moreover, PHIDIAS offers the combined evaluation of orientated images with geo-referenced 3D point clouds of a laser scanner.

Before the final 3D object construction the orientation of 138 digital images and a camera calibration were accomplished in PHIDIAS. Figure 6 shows the principle of the photogrammetric measurements of the control and tie points. On average 27 image points were measured per image, while each object point was measured in ten images. Thus, a good connection of the multiple images within the triangulation block as well as a reliable point determination could be ensured. Systematic errors like the high lens distortion were compensated for in the camera calibration for the further evaluation. The average measuring precision of image points was sx = 7.7 µm and sy = 7.0 µm, which corresponds to a measuring precision of ca. 1 1/2 pixel.
The precision of object points after adjustment was ± 8 mm. This obtained precision in image space was slightly worse than compared to precisions of other projects reached so far in digital architectural photogrammetry [9], since the definition of object points was not always completely clear with this antique building.

5.4. Object construction in PHIDIAS

Due to the combined representation of photogrammetric images and laser scanner data in PHIDIAS a 3D digitization of the object can be carried out then directly in a digital, orientated image using CAD elements such as points, lines, polygons or surfaces. Therefore, the point clouds of each facade generated in RWS were imported in PHIDIAS (Figure 7). Thereby, an orientated image supplies the XY object point coordinates, while the laser scanning point cloud delivers the Z-coordinate of the respective point. This procedure is called monoplotting. Thus, the 3D information of the point cloud is supplemented with the details of an image.

With the help of the point cloud an auxiliary plane can now be specified, so that the ray of each image point is cut with this plane and thus three-dimensional coordinates of this point can be measured in the image, and computed respectively. The auxiliary plane is defined by three points of the point cloud, which may not be on a straight line. Subsequently, the entire point cloud can be faded out, in order to ensure better distinction in the image and faster computing times. On this level the object with assistance of points, lines or polygons was then reconstructed (Figure 8a). The geometrical elements were stored as CAD objects in a DXF or a DWG format, so that a following data processing could be performed in AutoCAD, which was more familiar for the first author than MicroStation. Special
object characteristics like e.g. specific stones (Figure 8b) were measured in detail, which was particularly time-consuming.

Due to the object characteristics in the transition area of the water gate and wall it was also necessary for the modelling to generate a cylinder into the point cloud. After the construction of all object parts a complete 3D volume model of the northern sluice was available in AutoCAD, which is depicted in a rendered representation in Figure 9. A detailed description of the construction of the ancient dam is summarized in [10].
5.5. Visualisation

Firstly, for the interactive representation a visualization of the northern sluice was provided with AECViz, while in the second step the object was visualized as a video sequence with photo-realistic textures using Highlight pro. AECViz software is produced by Tornado Technologies Inc., Canada and produces simple visualization. However, the advantage of this program is the interactive representation of the object, i.e. the user can independently rotate the model, zoom in and out to receive a comprehensive impression of the object. With the import of DXF- or DWG files all in AutoCAD defined layer structures can be transferred to AECViz. However, the characteristics and colours of each individual layer can still be changed afterwards. Moreover, the solar radiation and the lighting conditions can be determined according to given countries and places. Finally, an EXE file can be generated, which can be executed on any windows-based computer (Figure 10).

Additionally, the building was visualized photo-realistically as a virtual reality model in a video sequence using the program Highlight pro V3. The software is divided into the two sub-programs Graph and Animate. In Graph a 3DS file can be first imported, which can be provided in AutoCAD from DXF or DWG formats. Since in Graph the processing of the file is based on triangles, all possible triangles in the model were generated during the import. The layer structure from AutoCAD can be transferred as well, however only 16 layers can be processed at once, so that the number of layers should be minimized to this number in AutoCAD prior to export. In order to simplify the definition of the layers, the user should arrange, that all object parts, which receive the same texture mapping later, should be placed on the same layer. Thus, the number of layers as well as the processing in Animate can be reduced. For
the texture mapping the photogrammetric images were used. After texture mapping was performed for all layers, a completely visualized model of the northern sluice was available (Figure 11 top). In addition, a fly through was generated as a video sequence of 69 seconds with Highlight pro, which consists of 2070 single video frames with a format of 800 × 600 pixel. Two images of this sequence are represented in Figure 11 (centre and bottom).

6. Time and cost aspects
On the basis of time and cost management the project could be judged with regards to economy and efficiency. In Figure 12 it can be seen that the photogrammetric evaluation and the object construction account for approx. 50% of the entire project. According to project experiences for instance a ratio of 1:10 can usually be assigned for object recording in relation to data processing for object modelling and construction. However, a ratio of 1:6 could be achieved for object recording and construction in this project due to the combined evaluation of photogrammetric and laser scanning data.

The expenditure of human labour for this project amounted to 459 hours in total. This corresponds to theoretical costs of approx. €30,000, which were deduced using appropriate current hourly wages for measuring assistant, technician and engineer. However, these are theoretical costs, but it can be finally stated that the expenditure and the costs of this project do not appear to correspond to real market conditions and to be economical for pure visualization applications. However, the exact and detailed evaluation of the ancient building represents high value as inventory documentation and thus for further archaeological investigations.
Figure 11: Perspective scenes of the virtual model of the dam in Marib/Yemen generated by Highlight pro V3.
7. Conclusions and outlook

The northern sluice of the antique dam in Marib/Yemen was completely recorded, modelled, reconstructed, visualized and successfully animated in three dimensions using a combination of digital photogrammetry and laser scanning. The use of a digital SLR camera Fuji S2 as well as the terrestrial laser scanner GS100 from Trimble allowed an evaluation precision of approx. 1–2 cm, which thus fulfils the requirements of the archaeology of a maximum of ±10 cm for visualisation and publication purposes (inventory documentation) of the virtual model. The combined evaluation was performed with the MicroStation Plugin PHIDIAS from Phocad, Aachen, Germany. Due to the experiences of the authors in similar projects with different software, it can be stated that the PHIDIAS software permitted a very efficient evaluation for stone-by-stone mapping of the dam and the expenditure of time could be regarded as reduced due to the combined use of photogrammetric and laser scanner data. Since in archaeology, architectural photogrammetry and cultural heritage very high accuracies are not demanded, the use of digital SLR cameras proves particularly efficient. In comparison to metric cameras these cameras are characterised by small initial costs and ease of use and maintenance. Nevertheless, they offer a high accuracy potential of 1–2 cm for applications in architectural photogrammetry.

The use of a laser scanner is only recommended, if already appropriate equipment and the pertinent software are present, since the construction of antique buildings can also be realized only by architectural photogrammetry. Thus, the use of a laser scanner should be gauged before the start of the project due to saving of time, but as well due to the high initial costs. It could be shown in this project that the hybrid measuring and evaluation procedure offer a meaningful possibility of reconstructing and of visualizing the future world cultural heritage site as a virtual reality model, in order to inform about the object and to awaken public interest. In addition this provided and visualized 3D model offers an optimal base for the structure of a three-dimensional geo information system (GIS), which shall be realized in future work. In this way interested users can move interactively in the model and can attain further information about history, accretion or art-historical aspects of the dam.

Figure 12: Expenditure of human labour for project ancient dam Marib/Yemen in percent.
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