ELSEVIER

Developing a documentation system for desert palaces in Jordan using 3D laser scanning and digital photogrammetry

Sharaf Al-kheder [a,*], Yahya Al-shawabkeh [a], Norbert Haala [b]

[a] The Hashemite University, PO Box 150459, Zarqa 13115, Jordan
[b] Institute for Photogrammetry (ifp), University of Stuttgart, Geschwister-Scholl-Strasse 24D, D-70174 Stuttgart, Germany

ARTICLE INFO

ABSTRACT

Desert palaces in Jordan are unique pieces of art scattered in the desert as standing symbols of ancient civilizations. Due to their location, these palaces witness different environmental conditions which affect their status and sustainability. This raises the need to have a 3D documentation system reporting all spatial information for each palace, which can be used later for monitoring purposes. Digital photogrammetry is a generally accepted technique for the collection of 3D representations of the environment. For this reason, this image-based technique has been extensively used to produce high quality 3D models of heritage sites and historical buildings for documentation and presentation purposes. Additionally, terrestrial laser scanners are used, which directly measure 3D surface coordinates based on the run-time of reflected light pulses. These systems feature high data acquisition rates, good accuracy and high spatial data density. Despite the potential of each single approach, in our opinion, maximum benefit is to be expected by a combination of data from both digital cameras and terrestrial laser scanners. By these means the efficiency of data collection as well as the geometric accuracy and visual quality of the collected textured 3D models can be optimized. Within the paper, a 3D documentation system for Umayyad desert palaces in the Jordan desert will be presented using digital photogrammetry and laser scanning. The approach is demonstrated by generating high realistic 3D textured models for Amra and Kharanah palaces.

© 2008 Elsevier Ltd. All rights reserved.

1. Previous work and research goal

The generation of 3D models of historical buildings is an important task while aiming at a continuous monitoring of the related spatial information at different time epochs. Such photo-realistic models have to provide high geometric accuracy and detail at an effective data size. Traditionally, close range photogrammetry is used during the required data collection of heritage sites (Gruen et al., 2002; Debevec, 1996). Within the past two decades, the efficiency of this image-based technique has been increased considerably by the development of digital workflows. Furthermore, 3D data collection based on laser scanning has become an additional standard tool for the generation of high quality 3D models of cultural heritage sites and historical buildings (Alshawabkeh, 2006; Boehler and Marbs, 2002). This technique allows for the quick and reliable measurement of millions of 3D points based on the run-time of reflected light pulses, which is then used to

effectively generate a dense representation of the respective surface geometry.

Despite the transformation of these approaches from research work to generally accepted techniques, there are still some limitations, which have an effect on the quality of the final 3D model (Shin et al., 2007; El-Hakim, 2007). Even though current laser scanners produce dense information along homogeneous surfaces, the resolution of this data can still be insufficient if breaklines such as cracks have to be collected and analyzed. In contrast, digital photogrammetry is more accurate if such outlines have to be measured, while on the other hand, image-based modeling alone is difficult or even impractical for surface parts, which contain irregular and unmarked geometric details. Additionally, photogrammetry requires long and tedious work, especially if a considerable number of points have to be captured manually. In addition to geometric data collection, texture mapping is particularly important for the area of cultural heritage to have complete documentation. Photo-realistic texturing can for example provide information on the object's condition, such as decay of the material, which is usually not present in the 3D model. Additionally, color image information is also indispensable for features like frescos and mosaics. Texture mapping is also considered a prerequisite for

* Corresponding author. Tel.: +962 53903333x4730.
E-mail addresses: salkhede@hu.edu.jo, sharafalkeder@hotmail.com (S. Al-kheder), yahya.alshawabkeh@hu.edu.jo (Y. Al-shawabkeh), norbert.haala@ifp.uni-stuttgart.de (N. Haala).

visualization and animation purposes. Thus, some commercial 3D laser systems additionally provide model-registered color texture using a camera, which is integrated in the system. However, these images are frequently not sufficient for high quality texturing as required for documentation. Usually, the ideal conditions for taking the images may not coincide with those for laser scanning (Alshawabkeh, 2006; El-Hakim et al., 2002). So it is therefore more useful to acquire geometry and texture by two independent processes and allow for image collection at optimal position and time for texturing. If the characteristics of spatial data as acquired from imaging and laser scanning systems are considered, the combination of both techniques by integrated data processing will be beneficial for accurate and complete description of the object space. The disadvantages of one approach can be compensated for by the advantages of the other technique.

In archaeology and especially in projects dealing with historical building survey, laser scanning and other digital technologies" capacity of representing the entire 3D nature of archaeological objects has initially provoked – and still continues to cause – overwhelming enthusiasm (Weferling et al., 2001; Riedel et al., 2006). A large number of projects focusing on using such spatial technologies for 3D modeling of heritage sites can be seen in the literature. Among these is the work of Lambers et al. (2007) for the 3D modeling of the site ground plan and stone architecture at Pinchango Alto, Peru, based on a combination of image and range data. Their work emphasizes the importance of using such integrated technologies in 3D documentation of heritage areas. The generated 3D textured models in their work suffer from a large number of occlusions in both point clouds and images, which causes difficulties during surface reconstruction and texture mapping. Our work focuses on solving such occlusion problems efficiently. Along these lines is the project carried out to record stone 11 of the Castlerigg stone circle in Cumbria through two different non-contact techniques: laser scanning and ground-based remote sensing (Díaz-Andreu et al., 2006). Researchers in this project encourage the usage of such technologies, based on the digitization of 3D surfaces, due to their ability to produce models with high accuracy without being in direct contact with the object. 3D laser scanning also presents a future direction for researchers to enhance the quality of their 3D models. This is clear in the work of Losier et al. (2007) who are planning to use 3D laser scanning as a substitute for generating 3D models from GPS positions taken at the top and the bottom of the excavation units' boundaries. Another example of current documentation projects is the work of Henze et al. (2005). Their interdisciplinary research project for the sustainable restoration of the late Gothic St. Petri cathedral of Bautzen used combined of geodesy and photogrammetry methods, supported by several laser scans from different positions, to create a form-correct and deformation-true documentation of the facades. Due to the extensive use of laser scanning in documentation, some researchers (e.g. Barber et al., 2003) call for articulated work to define specifications for such usage. This includes defining standard deliverables relevant to cultural heritage subjects.

Our work presented in this paper introduces a methodology for the 3D high quality digital preservation of selected desert palaces in Jordan, using laser scanning and digital photogrammetry. The 3D digital documentation of such palaces is of considerable interest for heritage management professionals besides its importance for conservation, education, virtual visits and as a monitoring system. A complete description of the work carried out at these palaces is presented, including the acquisition of laser scan and image data, co-registration of point clouds, 3D modeling and texture mapping. The acquisition of the relevant image and laser scanning data besides data pre-processing, which is mainly required for a perfect alignment of laser and image data for high quality mapping as well as our approach for texture mapping, is presented in Section 3. Only

the exterior facades of the buildings have been covered in the paper. This work will be expanded in the future to cover the rest of these palaces in Jordan to form a complete documentation system.

2. Desert palaces in Jordan

2.1. Umayyad palaces

Umayyad is the first Arab Muslim dynasty of caliphs (religious and secular leaders) founded by Muawiyah I in 661 and lasting until 750. The buildings erected by the Umayyad dynasty constitute the earliest Islamic monuments reflecting the dynasty's adaptation of the Hellenistic and Sassanian cultural traditions in their region (Bosworth, 1996). The most famous Umayyad architecture is a number of desert palaces, constructed of stone and/or brick that have been interpreted as princely residences, scattered in the region containing areas of Jordan, Syria, Lebanon and Palestine. The purpose such palaces served is not completely known, however existing theories indicate that they might have served a variety of defensive, recreational, agricultural and/or commercial agendas (Creswell, 1989; Finster and Schmidt, 2005; Genequand, 2005). Examples of the most famous desert palaces in the region include: in Jordan (Kharanah, Amra, Azraq, Hallabat, Qastal, Mushatta, Tuba and Muaqqar); Syria (Qasr Al-hayr East, Qasr Al-hayr West and Palmyra); Lebanon (Anjar); and in Palestine (Khirbat Al-mafjar). Fig. 1 presents a detailed GIS map (the topography layer is ©HU GIS lab and other GIS layers are created by the authors) showing the distribution of the most famous desert palaces in the region. Desert palaces in Jordan (Fig. 1) are located in the desert to the east of Amman (capital of Jordan) on the ancient trade routes. These palaces are easily accessible by following the northern route from Amman to Azraq city. The architecture of these complexes, a square floor plan of stone construction with corner bastions and semi-circular towers, has the influence of construction techniques drawn from Egypt, Mesopotamia and elsewhere throughout the region (Ettinghausen and Grabar, 1987).

A number of desert castles are adjacent to an international highway that connects Jordan to Saudi Arabia and Iraq. For this reason these palaces witness different environmental conditions which affect their status. The most fatal threat to the monuments results from the vibration of heavy trucks and lorries traveling along the highway (Euromedheritage, 2008). The effect is clearly visible through the serious longitudinal cracks in the walls, as can be seen in Fig. 2. A comprehensive study is needed to assess the current threats and the conservation needs of the palaces to ensure their sustainability.

2.2. Amra and Kharanah desert palaces

This section provides a detailed description of the two most famous desert palaces documented in this paper, Amra and Kharanah, in terms of geographic location, functions, architectural style and conservation status.

Amra palace, a UNESCO World Heritage site located about 85 km to the east of Amman, was built by the Umayyad Caliph al-Walid between 712 and 715 AD probably for use as a vacation residence or rest stop (Bianchin et al., 2007). Most of the Amra buildings, originally protected by a small square fortress and a watchtower on a nearby hill, are still standing and can be visited (Meloy, 1996). Fig. 3 shows a number of pictures of the Amra exterior from different view points.

Fig. 4. shows a detailed plan of the Amra main edifice (Abela and Alliata, 2001; Arida, 2003), which is composed of three long halls with vaulted ceilings resting on transverse arches: the audience hall, the baths and the hydraulic system (Al-Asad and Bisheh, 2000; Creswell, 1989; Ettinghausen and Grabar, 1987; Hillenbrand, 2000).
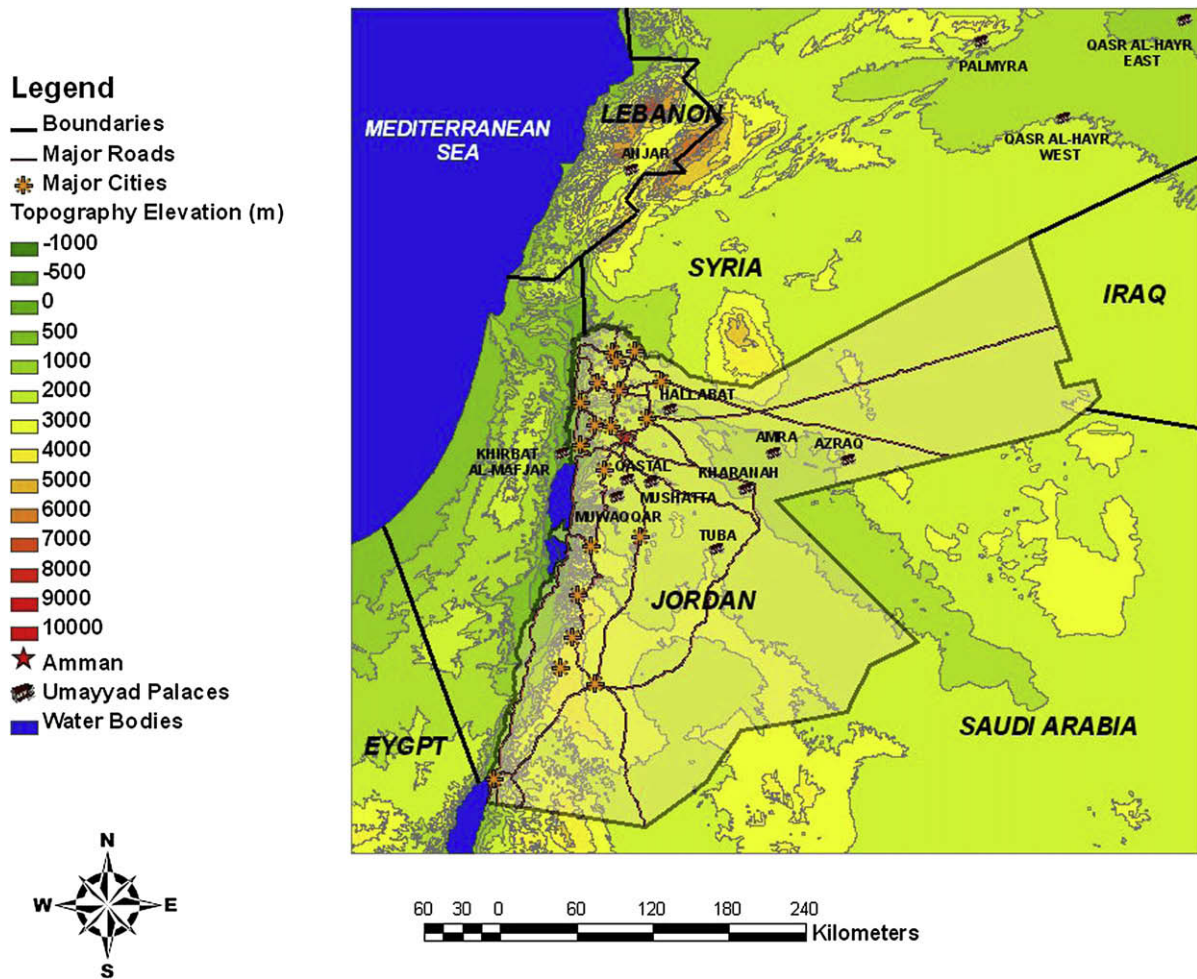
Fig. 1. Detailed GIS map of the study area showing the distribution of the desert palaces.

The audience hall is rectangular with a throne alcove in the middle of the south side. The bath complex comprises three rooms corresponding to the frigidarium, tepidarium and calidarium, i.e. the cold, warm and hot rooms respectively. The hydraulic structure includes an elevated water-tank, a masonry-lined deep well, and the apparatus for drawing water from the well into the water-tank. The real attraction at Amra is the extensive frescoes that depict a variety of subjects including hunting scenes, athletic activity, mythological images, and astronomical representations. In term of conservation status, Amra is the best preserved among desert palaces. It was added to the UNESCO World Heritage list in 1985

which has proven vital to the conservation and preservation efforts of this beautiful building complex (Bianchin et al., 2007).

Kharanah palace, located about 65 km east of Amman and 18 km west of Amra, which dates from the early Umayyad period (inscriptional evidence confirms a date prior to 710 AD) is one of the best preserved Umayyad sites in the Jordanian steppe (Urice, 1987). Fig. 5 shows the Kharanah exterior (aerial view is from Atlas Travel and Tourist Agency (TTA) website, 2008) while Fig. 6 shows a plan of its architecture. As it is strategically located on a rise some 15 m above its neighboring wadi, Kharanah might have served a variety of defensive, recreational, agricultural and/or commercial

Fig. 2. Serious longitudinal cracks extended through the Amra palace walls (World Cultural Heritage Site).

south view   southwest view   northwest view

Fig. 3. Amra palace exterior from different view points.

agendas (Creswell, 1989). Kharanah is a two-storey rectangular palace with thick stone walls interrupted by rounded interval and corner towers (Euromedheritage, 2008). A three-quarter-round buttress supports each of its four corners and two quarter-round towers line the entrance in the middle of the south side whereas half-round buttresses occupy the middle of the three remaining sides (Urice, 1987). Kharanah's slits are narrow, of a constant width, and probably too high off the floor for providing light and ventilation. While today Kharanah is extremely well preserved, contemporary restoration efforts have masked some of the original features altering the spirit and initial intent of several of the rooms (Creswell, 1989).

3. Methodological work

3.1. Field investigation

Also due to the current threats, the conservation of the desert palaces as a significant part of Jordan's heritage is very important. As a first step, a documentation system is required in order to record and monitor all of their external and internal features. An adequate documentation system needs to be effective at both levels: information gathering and data representation. This section presents the 3D documentation work carried out at Amra and Kharanah based on laser scanning and digital photogrammetry. The collection of the data, which has been used for our investigations, was performed in cooperation with the Institute for Photogrammetry, Stuttgart University. Similar to other research groups our work aims for 3D model generation by the integration of multiple techniques in order to capture all geometrical details and to represent these features with high-resolution triangular meshes for accurate documentation

and photo-realistic visualization (El-Hakim et al., 2004a,b, 2008; Remondino and Zhang, 2006; Kersten et al., 2004). The main equipment used for in situ documentation in our work are a 3D laser scanner and a digital camera.

3.2. Technology and equipment used

For 3D laser scanning the GS100 system manufactured by Mensi SA, France, is used. This scanner features a field of view of 360° in the horizontal direction and 60° in the vertical direction, enabling the collection of full panoramic views. The distance measurement is realized by the time of flight measurement principle based on a green laser at 532 nm. The scanning range of the system allows distance measurements between 2 and 100 m. The scanner's spot size is 3 mm at a distance of 50 m; the standard deviation of the distance measurement is 6 mm for a single shot. The laser scanning system is able to measure 5000 points per second. During data collection, a calibrated video snapshot of 768×576 pixel resolution is additionally captured, which is automatically mapped to the corresponding point measurements. The top row of Fig. 7 shows images which were collected by this integrated camera during the collection of the 3D point clouds.

Because it is not possible to completely cover such complex 3D structures from a single station without occlusions, different viewpoints are required. As is visible in the top row of Fig. 7, the different acquisition time and positions of the images collected by the camera integrated in the laser scanner results in considerable differences in brightness and color. This will definitely disturb the appearance of the textured 3D model. For this reason, additional images were collected simultaneously by a Nikon D2x camera, which provides a resolution of 4288×2848 pixels with a focal
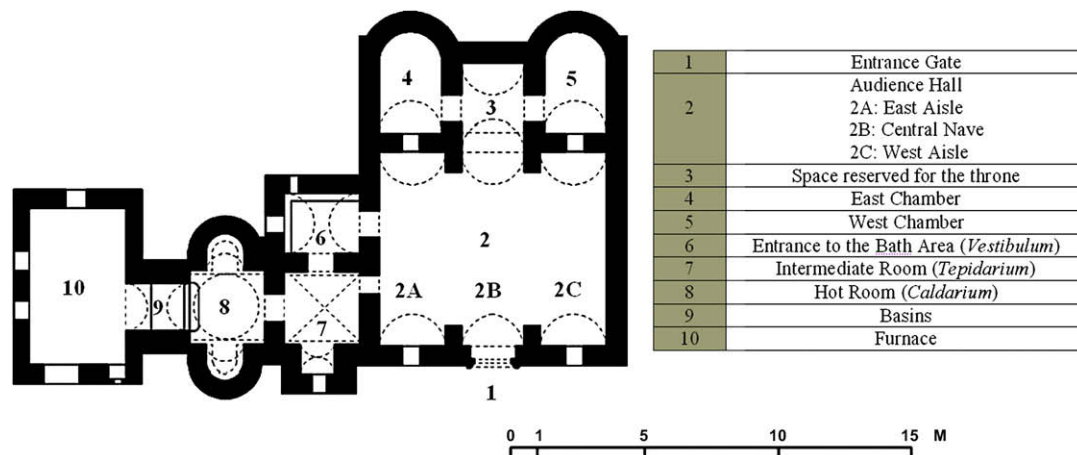

1	Entrance Gate
2	Audience Hall 2A: East Aisle 2B: Central Nave 2C: West Aisle
3	Space reserved for the throne
4	East Chamber
5	West Chamber
6	Entrance to the Bath Area (*Vestibulum*)
7	Intermediate Room (*Tepidarium*)
8	Hot Room (*Caldarium*)
9	Basins
10	Furnace

0   1   5   10   15 M

Fig. 4. A detailed top plan of the Amra main edifice (Abela and Alliata, 2001; Arida, 2003).

aerial (northwest view)

south view

south east view

northwest view

Fig. 5. Kharanah exterior from different view points.

length of 20 mm. These images, depicted in the bottom row of Fig. 7, were collected at almost the same time, and thus are much more suitable for texture mapping of the 3D models generated using a laser scanner.

3.3. Processing of collected data and 3D modeling

In order to provide complete 3D coverage for the palace facades, eight different scanner viewpoints were used during data collection. The selection of appropriate viewpoint positions is very important for a successful survey of such monuments since the number of potential sensor stations is usually restricted by the complexity of the structure. The collected scans contain sufficient overlapping regions to allow for subsequent integration, however, due to the flat desert environment, no scans could be collected from elevated viewpoints.

The different processing steps to generate the required 3D models were realized using the PolyWorks software from Innov-Metric. For the registration of the different scans corresponding points in overlapping areas were used. This is demonstrated exemplarily in Fig. 8, which shows the registration of two scans collected for Amra palace. After registration, the Polyworks software constructs a non-redundant surface representation, where each part of the measured object is only described once. The resulting combination of scans for 3D model generation is given in Fig. 9. The model of Amra (bottom) has an average resolution of 2 cm on the object surface with more than six million triangles, whereas the final model of Kharanah (top) has around four million triangles.

3.4. High quality texture mapping for constructed 3D models

The purpose of texture processing is to integrate the 3D measurements from the laser scanner with 2D image information taken with the camera. In order to warp the independently collected images onto the corresponding object surfaces using perspective or affine transformation projection, different approaches are available (Kada et al., 2003; Remondino and
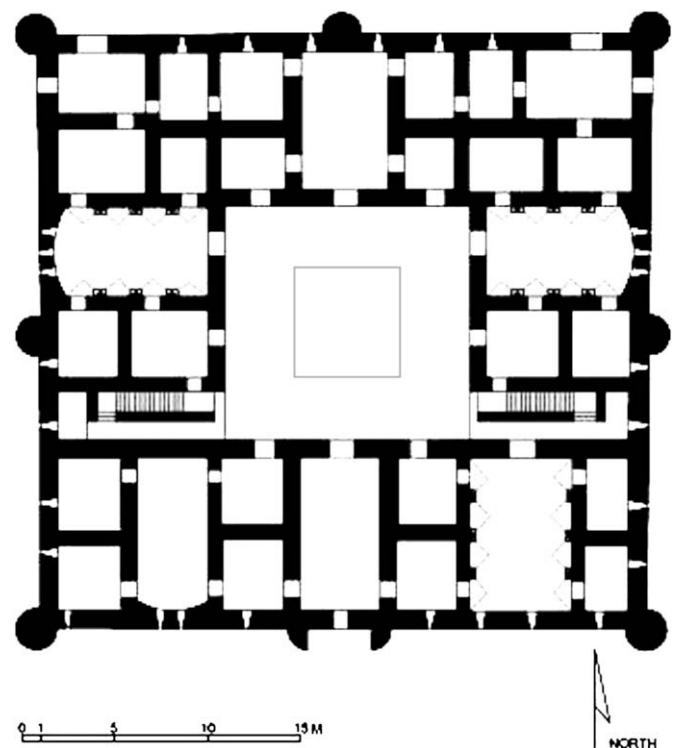

0 1   5   10   15 M

NORTH

Fig. 6. Plan of Kharanah (upper floor, Arida, 2003).

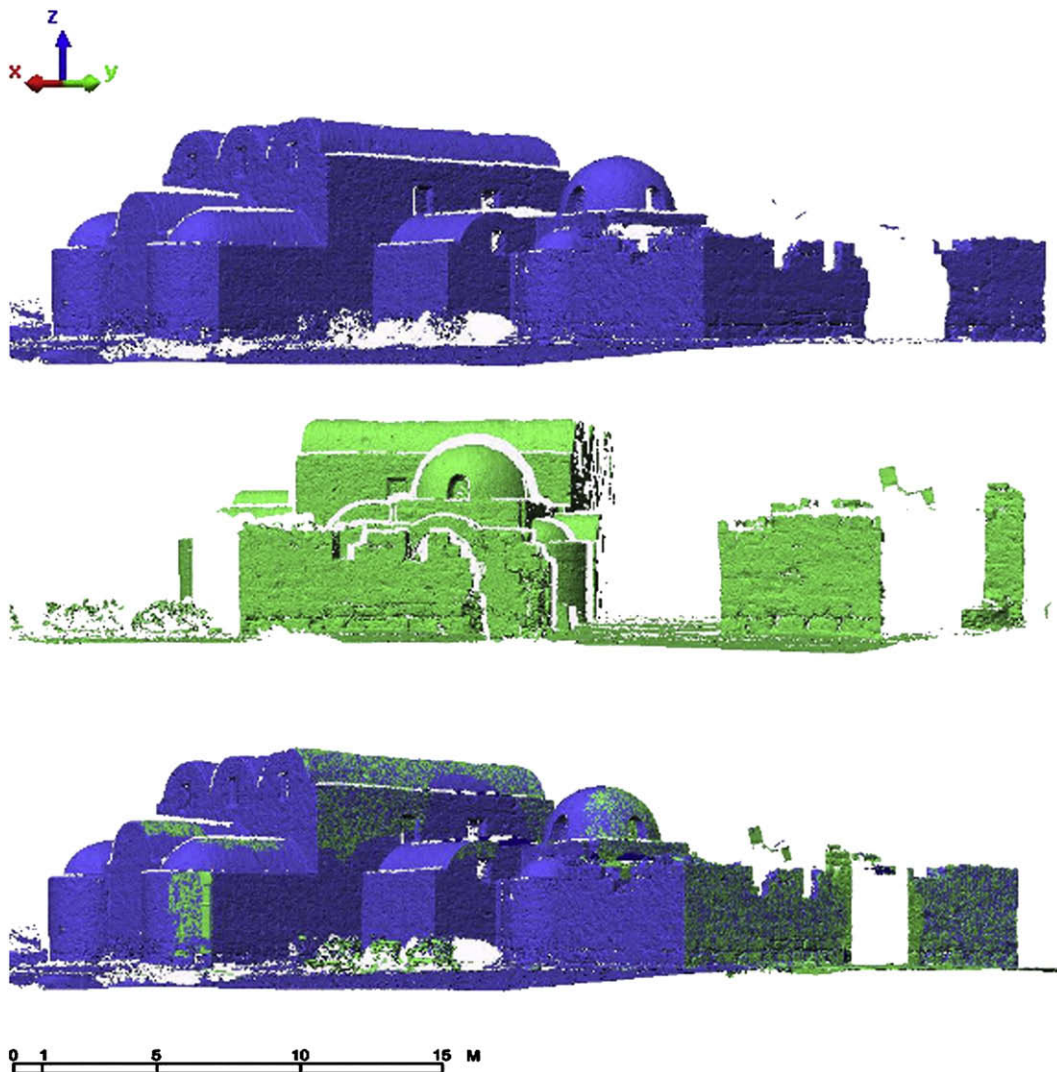**Fig. 7.** Top row, Mensi laser scanner images (768 × 576); bottom row, images collected using Nikon D2x camera (4288 × 2848).

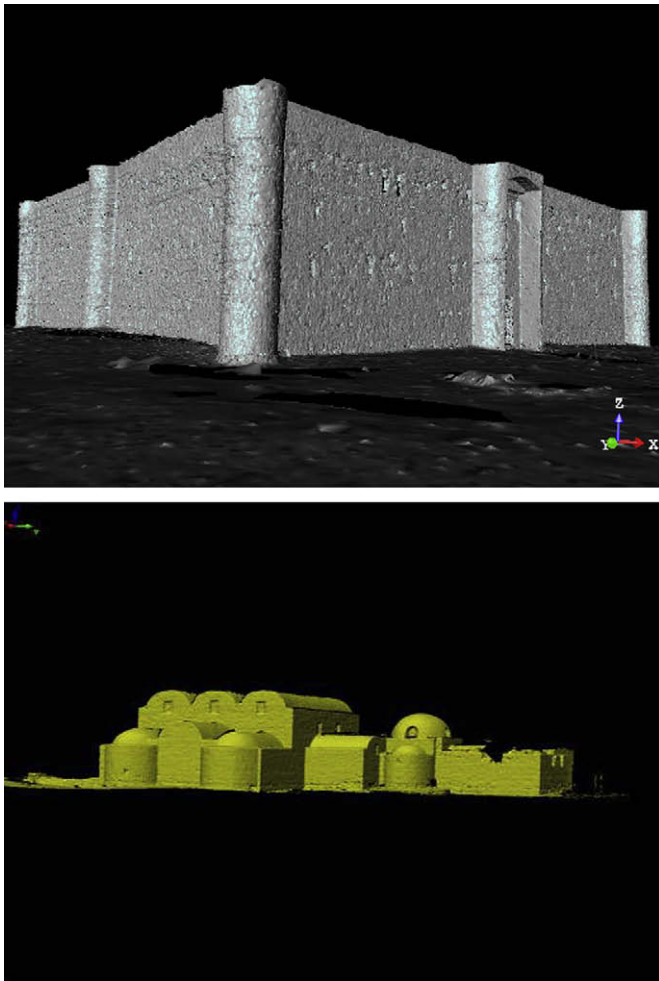**Fig. 8.** An example of two scans registration at Amra

Fig. 9. 3D Model of Kharanah (top) and Amra palace (bottom).

Fig. 10. Visibility occlusions and double projection problem.

If the image is warped naively over the geometry, each 3D point is just transformed to a corresponding pixel in the color image. By these means texture gets mapped onto all occluded polygons on the path of the projected ray. So the geometry that is occluded in the image will receive incorrect texture coordinates instead of remaining in shadow. Fig. 10 shows this problem and defines the three types of occlusion problem as they are known in computer graphics applications: ambient, self and view frustum occlusions.

The occlusion problem can be avoided by manual texture extraction and mapping, however, this task is very tedious and can take up to several days for good results. Fully and semi-automatic texture extraction and placement of the real scene have been presented in different works (Grammatikopulos et al., 2004; Sequeira et al., 2000) but with more complex processing. Those approaches use automatic techniques for occlusion detection, such as the z buffer algorithm (Cutmull, 1974). An effective automatic approach to the problem of high-resolution photo-realistic texture mapping onto 3D complex models generated from range images is presented by Alshawabkeh and Haala (2005). This approach allows taking the images at different times from laser scanning and at whatever locations will be best for texturing. This method of texture mapping is based on the selection of a combination of optimal image patches for each triangle of a 3D model. According to the best possible geometric and radiometric conditions, the locations of the image triangles are computed from object faces via co-linearity equations. The procedure consists of

Niederoest, 2004; Visnovcova (Niederoest) et al., 2001). However, such approaches can only be applied for simple objects with a restricted number of surfaces with no occlusions. Otherwise, if a direct projection transformation is applied without considering occlusions, the mapping between object geometry and image will be incorrect.
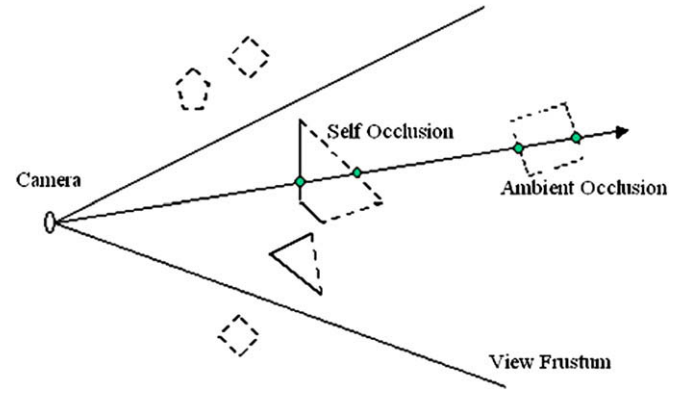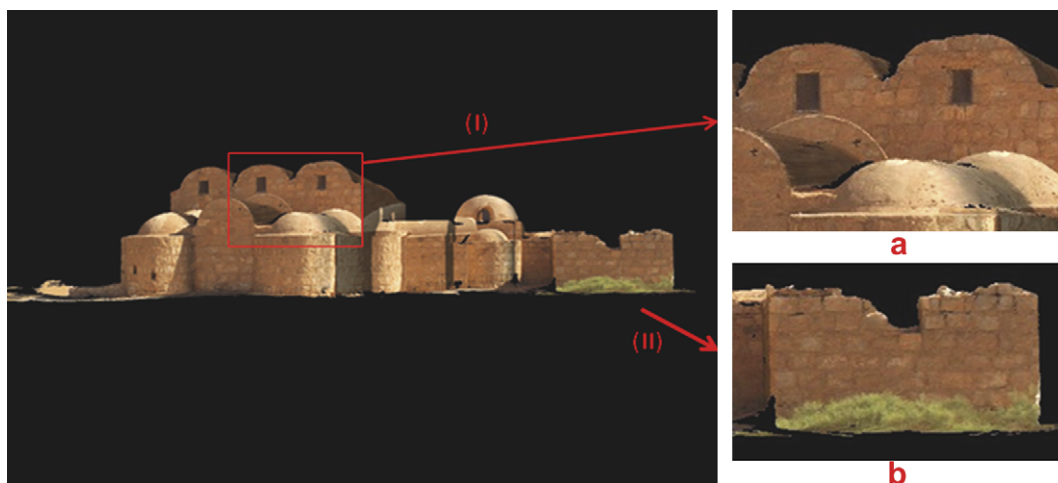

Fig. 11. Problems related to texture mapping: double projection problem (top right image, a-I) using the master image and the erroneous projection of the artifacts such as ground grass (bottom right image, b-II); master image is on the left in Fig. 7.
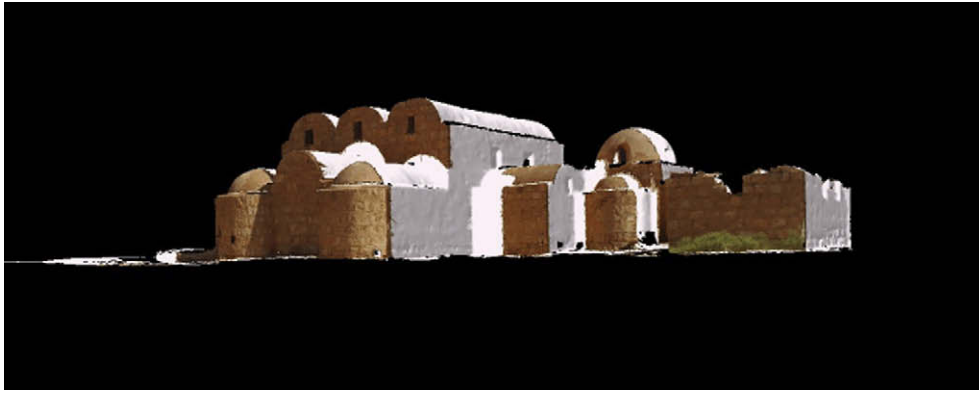
Fig. 12. 3D textured model using the master image, the occluded parts which do not appear in the master image have zero texture values. These parts will be textured from the other images.

three main steps: pre-processing, which includes camera calibration, color corrections and data co-registration; visible surface computing; and texture warping.

3.4.1. Camera calibration

Distortion free images and a high quality registration process are crucial factors for getting a realistic looking model. This requires an accurate determination of the camera's interior and exterior orientation parameters. For our investigations, the interior orientation parameters were computed using a calibration computed by the Australis software. These parameters were used to create zero distortion images as an intermediate step. Corresponding coordinates between image and laser scanner were measured using the Photomodeler software, which was also applied to calculate the camera position and orientation in the coordinate system of the geometric model.

3.4.2. Color correction

Different illumination conditions prevent color continuity at the borders of each image, leading to observable discontinuities in color and brightness. For high realistic 3D texture mapping the artifacts caused by illumination changes during image collection have to be removed. For this purpose we used ENVI 4.1 software to perform a histogram equalization enhancement for all three channels in the texture images.

3.4.3. Summary of the overall procedure

During texture mapping every point on the surface of the object (in x, y, z coordinates) is mapped to some point (in u, v coordinates) on the texture image. If no special care is taken, erroneous pixel values are extracted for the occluded parts of the scene as can be seen in Fig. 11. To avoid such artifacts, occlusion detection is realized. In our approach (Alshawabkeh, 2006), invalid pixels that belong to the shadow polygons are identified and marked as depicted in Fig. 12. The occluded parts are then used as input for the second selected texture image, i.e. the process for checking visibility and texturing is repeated automatically until the model is textured from all the available images. One advantage of using multi-image photo-texturing approach is the flexibility to avoid any moving or stable artifacts such as tourists, trees or other occluding objects. As an example, the master image in Fig. 11 shows ground grass which is projected together with the correct image texture to the 3D model. This erroneous projection can be handled easily using another image taken from a different angle.

For this procedure, both a triangulated 3D mesh describing the object surface as well as calibrated color images along with their exterior orientation parameters are required. Additionally two threshold values have to be set: the object space threshold (T1) represents the maximum length of the triangle edge in the scene space (sampling interval), and the image space threshold (T2) represents the maximum number of pixels of triangle edge
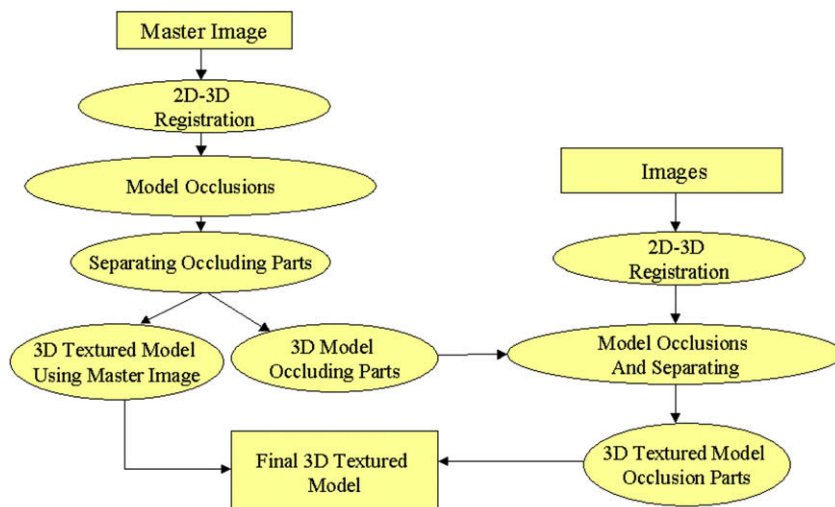

Fig. 13. The overall procedure for texture mapping.

Fig. 14. Final 3D textured model of Amra palace.

projected onto the image. The overall procedure for texture mapping as depicted in Fig. 13 can be summarized as follows (Alshawabkeh, 2006):

(1) Select the most appropriate image that depicts most parts of the object (master image).
(2) Given the exterior orientation parameters, the texture coordinates associated with each polygon vertex can be located using the co-linearity equations.
(3) Check for frustum occlusion to exclude texturing the coordinates that are not within the range of the image. Store the other texture coordinates in a matrix with the Z value of the corresponding vertex.
(4) In image space define the searching area using the threshold (T1), search and sort all the triangles within the specified area, then select the nearest triangle dependent on the Z value and the (T2), give an ID for such polygons as an occluded polygon.
(5) The occluded polygon vertices will take zero textured values.
(6) The un-textured parts will be used as input for the second selected textured images.
(7) The process for visibility will be repeated automatically until the model is textured from all angles/sides using all available images.
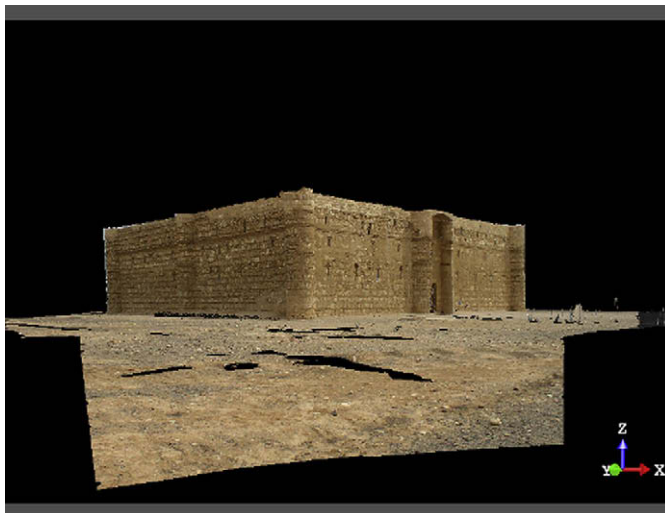
In our approach, C++ and VRML modeling language are used. The approach has been demonstrated for texture mapping the Amra and Kharanah palaces, as is depicted in Figs. 14 and 15.

4. Conclusions and future work

The work introduced in this paper presents the initial phases of establishing a documentation system for desert palaces in Jordan using 3D laser scanning, digital photogrammetry and GIS technologies. The documentation of such important heritage is vital in order to provide a complete monitoring, protection and maintenance plan. Besides its importance for conservation, education, virtual visits and as a monitoring system the 3D digital documentation of such palaces is of considerable interest for heritage management professionals. A complete description of the work carried out at selected palaces, Amra and Kharanah, is presented, which includes steps like the acquisition of laser scan and image data, co-registration of point clouds, 3D modeling and multi-image texture mapping of the palaces' exterior facades. Certain issues, as related to 3D modeling and texture mapping, such as visibility occlusions and double projection problems are discussed in the paper to enhance the generated 3D textured model. This work will be expanded in the future to cover the remaining palaces in Jordan to form a complete documentation system. The proposed system design as integrated with GIS, which will be the base for the 3D documentation system to be developed, is anticipated to be linked with the internet through WebGIS to provide updated information about the palaces' system to different users. All the extracted information from the constructed 3D models, such as palace structural condition and maintenance activities, can be stored in a GIS database for spatial modeling and follow-up purposes. Other spatial information, related to the palace system, such as road infrastructure, landmarks, hotels and other services will be entered as layers in GIS for comprehensive landscape modeling. This system upon completion will be a necessary tool for all boards in the field of heritage management and urban planning, for assessment, maintenance, and monitoring of such palaces.

References

Abela, J., Alliata, E., 2001. QuseirAmra, Franciscan friars of the Holy Land and Malta. http://198.62.75.5/www1/ofm/sbf/escurs/Giord/03GiordEn.html (accessed 10 July 2008).
Al-Asad, M., Bisheh, G., 2000. Palatial residences. In: The Umayyads the Rise of Islamic Art. Amman and Vienna: Ministry of Tourism, Department of Antiquities, Amman, Jordan and Museum With No Frontiers. Austria, Vienna, pp. 50–51.

Fig. 15. Final 3D textured model of Kharanah palace.

Alshawabkeh, Y., Haala, N., 2005. Automatic multi-image photo texturing of complex 3D scenes. Proceedingsof the CIPA 2005 XX International Symposium XXXIV-5/C34, Torino, Italy, pp. 68-73.

Alshawabkeh, Y., 2006. Integration of laser scanner and photogrammetry for heritage documentation. PhD thesis, Institut für Photogrammetrie der Universität Stuttgart, Germany.

Arida, S., 2003. Nasser Rabbat/Aga Khan Program for Islamic Architecture, MIT, http://ArchNet.org (accessed 10 July 2008).

Atlas Travel and Tourist Agency (TTA) website, 2008. http://www.atlastours.net/jordan/desertcastles.html (accessed 10 July 2008).

Barber, D.M., Mills, J.P., Bryan, P.G., 2003. Towards a standard specification for terrestrial laser scanning. International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences XXXIV-5/C15, 619–624.

Bianchin, S., Umberto, C., Monica, F., Pietro, A., 2007. Painting technique and state of conservation of wall paintings at Qusayr Amra Amman – Jordan. Journal of Cultural Heritage 8 (3), 289–293.

Boehler, W., Marbs, A., 2002. 3D scanning instruments, in: Boehler, W. (Ed.), Proceedings of the CIPA WG 6 International Workshop on Scanning for Cultural Heritage Recording, Ziti, Thessaloniki, pp. 9–18.

Bosworth, C.E., 1996. The Umayyad Caliphs. In: The New Islamic Dynasties. Columbia UP, NY, pp. 3–5.

Creswell, K.A.C., 1989. A Short Account of Early Muslim Architecture. revised. In: Allan, JamesAldershot, W. (Eds.). Scolar Press, pp. 179–200. and 96-105.

Cutmull, E., 1974. A subdivision algorithm for computer display of curved surfaces. PhD thesis, University of Utah, USA.

Debevec, E., 1996. Modeling and rendering architecture from photographs. PhD thesis, University of California at Berkeley, USA.

Díaz-Andreu, M., Brooke, C., Rainsbury, M., Rosser, N., 2006. The spiral that vanished: the application of non-contact recording techniques to an elusive rock art motif at Castlerigg stone circle in Cumbria. Journal of Archaeological Science 33, 1580–1587.

El-Hakim, S., Beraldin, J., Picard, M., 2002. Detailed 3D reconstruction of monuments using multiple techniques. Proceedings of the International Workshop on Scanning for Cultural Heritage Recording – Complementing or Replacing Photogrammetry, Corfu, Greece, pp. 58–64.

El-Hakim, S., Beraldin, J., Picard, M., Godin, G., 2004a . Detailed 3D reconstruction of large-scale heritage sites with integrated techniques. IEEE Computer Graphics and Applications 24 (3), 21–29.

El-Hakim, S., Gonzo, L., Girardi, S., Picard, M., Whiting, E., 2004b. Photo-realistic 3D reconstruction of castles with multiple-source image-based techniques. XXth ISPRS Congress34(5), Istanbul, Turkey, pp. 120-125.

El-Hakim, S., Gonzo, I., Voltolini, F., Girardi, S., Rizz, A., Remondino, F., Whiting, E., 2007. Detailed 3D modeling of Castles. International Journal of Architectural Computing 5 (2), 199–220.

El-Hakim, S., Remondino, F., Voltolini, F., 2008. 3D modeling of castles. GIM International 22(3), http://www.gim-international.com/issues/articles/id1073-D_Modelling_of_Castles.html (accessed 7 July 2008).

Ettinghausen, R., Grabar, O., 1987. The Umayyads and their art. In: The Art and Architecture of Islam 650–1250. Yale University Press, New Haven, pp. 26-74.

Euromedheritage website, 2008. http://www.euromedheritage.net/adopt/adopt_gallery/qasr_kharaneh.htm (accessed 10 July 2008).

Finster, B., Schmidt, J., 2005. The origin of 'desert castles': Qasr Bani Muqatil, near Karbala, Iraq. Antiquity 79 (304), 339–349.

Genequand, D., 2005. From 'desert castle' to medieval town: Qasr al-Hayr al-Sharqi (Syria). Antiquity 79 (304), 350–361.

Grammatikopulos, L., Kalisperakis, I., Karras, G., Kokkinos, T., Petsa, E., 2004. Automatic multi-image phototexturing of 3D surface models obtained with laser scanning. CIPA International Workshop on "Vision Techniques Applied to the Rehabilitation of City Centres", Lisbon. 25–27 October.

Gruen, A., Remondino, F., Zhang, L., 2002. Reconstruction of the Great Buddha of Bamiyan, Afghanistan. International Archives of Photogrammetry and Remote Sensing XXXIV-5, Corfu, Greece, pp. 363–368.

Henze, F., Wulf-Rheidt, U., Schneider, D., Bienert, A., 2005. Photogrammetric and geodetic documentation methods at St. Petri Cathedral, Bautzen. Proceedings of the CIPA 2005 XX International Symposium, Torino, Italy, pp. 366-371.

Hillenbrand, R., 2000. The Palace in Islamic Architecture: Form, Function and Meaning. Edinburgh University Press, Edinburgh, pp. 443-446.

Kada, M., Roettger, S., Weiss, K., Ertl, T., Fritsch, D., 2003. Real-time visualisation of urban landscapes using open-source software. Proceedings of the 24th Asian Conference on Remote Sensing & International Symposium on Remote Sensing (ACRS 2003 ISRS), Busan, Korea.

Kersten, T., Pardo, C., Lindstaedt, M., 2004. 3D acquisition, modeling and visualization of north German castles by digital architectural photogrammetry. XXth ISPRS Congress34(5), Istanbul, Turkey, pp. 126-131.

Lambers, K., Eisenbeiss, H., Sauerbier, M., Kupferschmidt, D., Gaisecker, T., Sotoodeh, S., Hanusch, T., 2007. Combining photogrammetry and laser scanning for the recording and modeling of the Late Intermediate Period site of Pinchango Alto, Palpa, Peru. Journal of Archaeological Science 34, 1702–1712.

Losier, L.-M., Pouliot, J., Fortin, M., 2007. 3D geometrical modeling of excavation units at the archaeological site of Tell 'Acharneh (Syria). Journal of Archaeological Science 34, 272–288.

Meloy, J.L., 1996. Islamic civilization. In: Fagan, B. (Ed.), The Oxford Companion to Archaeology. Oxford University Press, Oxford, UK, pp. 355–357.

Remondino, F., Niederoest, J., 2004. Generation of high-resolution mosaic for photo-realistic texture-mapping of cultural heritage 3D models, in: K. Cain, Y. Chrysanthou, F. Niccolucci, N. Silberman (Eds.), Proceedings of the 5th International Symposium on Virtual Reality, Archaeology and Cultural Heritage (VAST). Brussels, Belgium, pp. 85–92.

Remondino, F., Zhang, L., 2006. Surface reconstruction algorithms for detailed close-range object modeling. The International Archives of the Photogrammetry, Remote Sensing & Spatial Information Science (IAPRS&SIS) XXXVI-3, Bonn, Germany, pp. 117-121.

Riedel, A., Heine, K., Henze, F., 2006. VonHandaufmaß bis Hightech II. Informationssysteme in der historischen Bauforschung. Verlag Philipp von Zabern, Mainz am Rhein.

Sequeira, V., Ng, K., Wolfart, E., Gonçalves, J., Hogg, D., 2000. Automated reconstruction of 3D models from real environments. ISPRS Journal of Photogrammetry and Remote Sensing 54, 1–22.

Shin, S., Habib, A., Ghanma, M., Kim, C., Kim, M., 2007. Algorithms for multi-sensor and multi-primitive photogrammetric triangulation. ETRI Journal 29 (4), 411–420.

Urice, S.K., 1987. Qasr Kharanah in the Transjordan. American Schools of Oriental Research. North Carolina, Durham, pp. 108.

Visnovcova (Niederoest), J., Zhang, L., Gruen, A., 2001. Generating a 3D model of a Bayon tower using non-metric imagery. Proceedingsof the International Workshop "Recreating the Past – Visualization and Animation of Cultural Heritage". Ayutthaya, Thailand and IAPRS, Vol. XXXIV, Part 5/W1, pp. 30–39.

Weferling, U., Heine, K., Wulf, U., 2001. Von Handaufmaß bis Hightech I. Aufnahmeverfahren in der historischen Bauforschung. Verlag Philipp von Zabern, Mainz am Rhein.