

INTEGRATION OF 3D LASER SCANNING, PHOTOGRAMMETRY AND THERMOGRAPHY TO RECORD ARCHITECTURAL MONUMENTS

M. Cabrelles^a, S. Galcerá^a, S. Navarro^a, J. L. Lerma^{a,*}, T. Akasheh^b, N. Haddad^c

^a Photogrammetry & Laser Scanning Research Group (GIFLE), Universidad Politécnica de Valencia, Camino de Vera, s/n. 46022 Valencia, Spain – (micablo, sergalus, sannata, jllerma)^a@upvnet.upv.es

^b CulTech for Archaeology and Conservation, Amman, Jordan - takasheh@index.com.jo

^c Dept. of Conservation Science, Queen Rania's Institute of Tourism and Heritage, The Hashemite University, Amman, Jordan - naifh@hu.edu.jo

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ABSTRACT:

In this paper we present a methodology to record accurately and exhaustively a World Heritage Monument by means of terrestrial laser scanning (TLS), close range photogrammetry and thermal imagery. On the one hand, TLS will provide 3D point clouds as well as rough photo models that can substantially improve the draping of texture with external imagery. On the other hand, thermal imagery will provide further information about the actual state of conservation of the monument. As a case study, we present the complete documentation of a tomb, Djin Block No. 9. This monument is one of the park's archaeological monuments in Petra (Jordan), declared a World Heritage Site in 1985. Today, corrosion of the clay water management systems surrounding Djin Blocks has contributed to the weathering of the monuments, and erosion from wind, water and salt threatens to destroy these monuments despite efforts to preserve them for future generations. This study aims to contribute both metric and non-metric data in order to record the actual state of the tomb at present, before archaeologists, architects and further specialists start any kinds of intervention activities. Furthermore, the 3D photo-models will be used to visualize and disseminate the monument virtually through the Internet.

1. INTRODUCTION

Documentation of huge and complex cultural heritage sites is a challenge not only because of sophisticated technology, but also the planning, processing and data deliveries of cost-effective solutions. Furthermore, the non-stop deterioration processes on monuments makes the documentation activity an important fundamental step in order to record the state of the site at a particular time, facilitating the decision making that should be followed by experts to for a comprehensive conservation plan. What would seem to be a simple documentation activity on a single architectural monument is just a tiny part of the exhaustive requirements that a World Heritage Site might require. We present herein the complete documentation of a tomb, the Djin Block No. 9 (Figure 1), one of the park's archaeological monuments in Petra (Jordan).

Terrestrial laser scanning is increasing its range of applications in architecture and archaeology. This tool can be used standalone or in combination of other surveying techniques for multiple purposes (English Heritage, 2007). One effective solution is its integration with photogrammetry (Al-kheder et al, 2009; Biosca et al, 2007) either to improve the resolution of the 3D model, the accuracy of the objects, the definition of

geometries or the colour enhancement. Additionally, both techniques can be used to complement each other, e.g. when there is lack of information in occluded areas.

The addition of thermographic data in cultural heritage applications is not as common as the combination of photogrammetry and laser scanning, despite its benefits (Lerma et al 2007, 2008).

2. CASE STUDY: DJIN BLOCK N° 9

2.1 The Djin Block N° 9

Djin Blocks are three-dimensional stone-carved funerary structures that resemble towers and are spread throughout the site of Nabataean Petra on white Ordovician sandstone. All the Djin Blocks are on the list of the park's archaeological monuments of Petra, which has been a world heritage site since 1985. Petra was listed twice on the World Monuments Watch List of the One Hundred Most Endangered Sites.

Our study is centered in on monument no. 9 (Figure 1), one of the three Djin Blocks that are found just before the main entrance to the Siq (a narrow and deep gorge). It is about 9.8 m high, with a square horizontal plan with each vertical each

* Corresponding author.

facade measuring about 5.5 m wide. The four facades are similarly carved, while the roof is flat and hollowed out, probably serving as a grave. A row of inset stones forms a cornice running all around the block from all facades.

Today, corrosion of the clay water management systems surrounding the Djin Blocks has contributed to the weathering of the monuments, and additional erosion from wind, water and salt threatens to destroy these monuments before archaeologists and specialists can begin to understand or appreciate them. There has been data collection, preservation and dissemination of various specific monuments of Petra. For example previous studies on the conservation status of Djin Block No. 9 show that the main factor of erosion is due to the joint action of wind and water.

Block No. 9 follows the 'Adopt a Mediterranean Heritage Program', an innovative initiative within the framework of the Euromed Heritage program aimed to facilitate the contact between cultural promoters of endangered Mediterranean heritage and international investors. A recent study (Akasheh et al. 2005) has focused on this tomb because it stands out in two ways from other monuments. First while most of the monuments inside Petra are carved out of the peach coloured middle and upper part of the Cambrian (also known in Jordan as Um Ishrin) sandstone, the Djin Block is one of a few that are carved out of whitish Ordovician (Disi) sandstone. Second, it is the largest of a series of three dimensional blocks, where unlike most monuments that have two dimensionally carved facades, has four facades pointing roughly towards the four geographic directions. Fitzner and Heinrichs (2005) have indicated that the Eastern and Southern facades are the hardest hit by weathering attrition. Paradise (2005) has studied Djin Block No. 5 and tried to correlate the extent of weathering with the insulation of the surfaces. He concludes that the more the insulation the higher the temperature of the surface and therefore the greater the weathering damage. This is contested by Heinrichs' (2008) elaborate work which arrived at the conclusion that temperature effects do not seem to play a major role as opposed to that due to rainfall, water flow down the facades, moisture, salt content and eolian wind abrasion. The work of Akasheh et al. (2005) seems to confirm this statement. Furthermore the mortar which was used to attach inset stones in a groove that runs around the four facades has played a major role by interacting with downward flowing water to exacerbate the situation.



Figure 1. Djin Block N° 9 (in the centre) and Djin Block N° 8 (on the right)

2.2 Planning and data acquisition

Projects involving different sets of survey devices require careful planning in order to yield appropriate documentation with minimal effort. The 3x3 CIPA rules for simple photogrammetric documentation of architecture were considered to guarantee full photographic coverage, redundancy, control, stable geometry and organization (Waldhäusl and Ogleby, 1994). Additional guidelines were followed to ensure full coverage, resolution and accuracy on terrestrial laser scanning (Lerma et al, 2008).

Four different surveying sensors were used for the data acquisition on site:

- Leica T1800 reflectorless total station. Measures distances and angles without prisms up to 200 m; standard deviation of about 2-4 mm.
- TLS medium-range time-of-flight MENSIS GS100; panoramic field of view of 360° (horizontal) and 60° (vertical), 5000 points per second. The standard deviation of a single distance measurement is 6 mm at 100 m. This scanner incorporates an internal colour calibrated video camera that has a maximum resolution of 768 x 576 pixels.
- Canon EOS-1Ds Mark III digital camera, with a CMOS of complete photogram, resolution of 21 megapixels, focal length of 15-30 mm.
- FLIR ThermoCAM B4 camera to acquire the thermal infrared imagery. It works in the spectral electromagnetic domain of 7.5-13µm, has a high thermal sensitivity of 0.10°C and produces clear noise-free infrared images with a resolution of 320x240 pixels. For the purpose of measurement, its wide angle lens (field of view 41° x 31°) was used.

A total of eight natural control points were measured with the reflectorless total station to relate the geometry among the different sensors. Regarding laser scanning, a total of seven scans from five different positions were acquired to ensure good coverage of the monument as well as sufficient overlap among the different scans from the different scan sites. Images from the scanner were in colour but at low resolution, and show important radiometric differences due to changing lighting conditions during the data acquisition. Figure 2 displays the points with their intensity values; Figure 3 shows the coloured point clouds of the scanner after registration.

A minimum of fifteen external RAW images were acquired with a Canon EOS-1Ds Mark III digital camera from different positions to improve the quality of the colour, and to yield texture to both the 3D photorealistic model and the orthophotos. The use of external imagery has additional advantages: fast data acquisition, RAW digital development, flexibility of shooting, and eventually less chance of changing the light conditions.

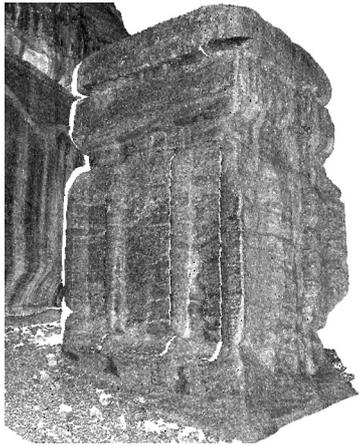


Figure 2. Intensity-based point cloud from the scanner. View of one single scan



Figure 3. Point clouds coloured from the scanner, view after registration

Thermal images were also taken from various surrounding sites at different times of the day to get maximum thermal contrast on the monument itself. Figure 4 displays an instance of the image acquisition process on site, meanwhile Figure 5 shows a sample of the visible and thermal imagery without processing. Additionally, detail thermal images were taken on part of the monument affected by weathering effects.



Figure 4. Data acquisition with visible and thermal sensors

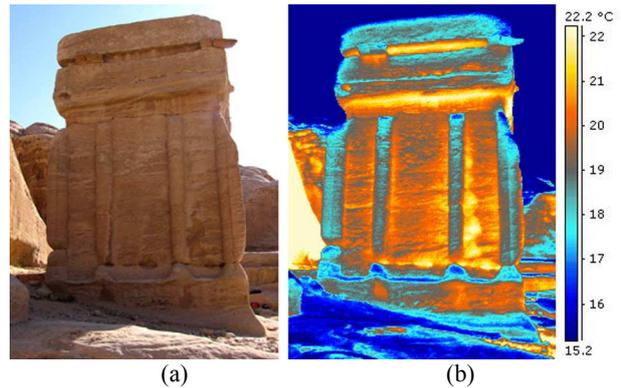


Figure 5. Djin Block No. 9 Western façade (a) Visible image; (b) Thermal image taken at 08:36

3. METHODOLOGY AND RESULTS

3.1 Point cloud processing and meshing

The point cloud processing phase began by referencing all the raw data captured from each scanner position to a single object coordinate system. The residuals of the registration process were better than 4 mm in XYZ coordinates. Additionally, some filtering was carried out in order to eliminate noise in the point clouds on the surfaces of the Djin Block.

Meshing involves data triangulation to build a unique surface over the object. The 3D triangulation mesh results lacked topological errors. Moreover, tiny holes due to hidden areas were filled. The final 3D model of the Djin Block No. 9 consisted of 780,000 triangles. Figure 6 shows the mesh of the 3D model in two modes, wireframe, and with lights on.

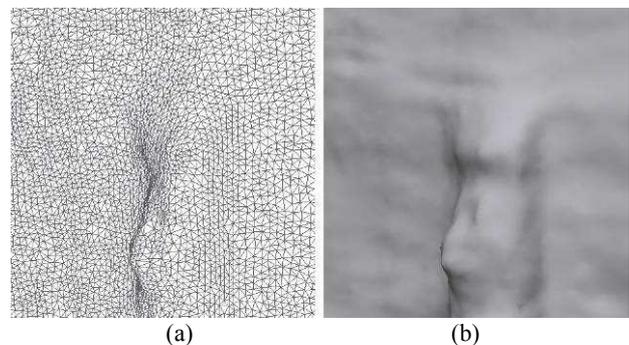


Figure 6. Detail of the 3D model: a) Wireframe; b) With lights on.

3.2 Image orientation

The appearance of the 3D model can be improved by draping virtual (unreal) texture or real textures captured by a visible or multispectral camera. For the purpose of fitting with maximum reliability the real texture coming from the real imagery to the 3D model, all the images were positioned and oriented in the object space following two particular solutions based on the well-known collinearity equations, bundle adjustment and single image resection. The former was used to adjust the high-resolution visible images; the latter to add the thermal information to the 3D models.

Bundle adjustment was performed to determine the exterior orientation parameters of the twelve visible images used to model the tomb. Figure 7 displays the planimetric distribution of the visible images around the Djin Block No. 9. The three top camera positions were taken up from the mountain next to the tomb to be able to document its five sides, including the top.

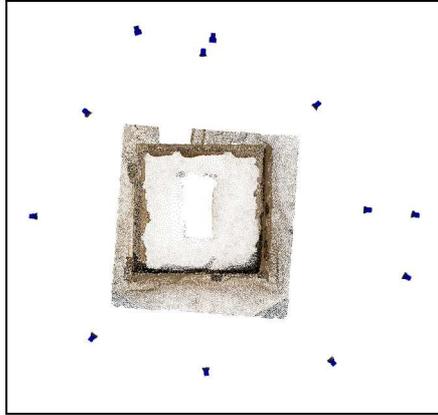


Figure 7. Top view of the visible camera positions surrounding the tomb

Tables 1 and 2 show some of the results achieved after the bundle adjustment solution. The first displays the accuracy of the achieved spatial orientation parameters, and the second the ground residuals.

EOP	ω (g)	φ (g)	χ (g)	X_L (m)	Y_L (m)	Z_L (m)
082	0.0055	0.0031	0.0045	0.001	0.000	0.001
070	0.0066	0.0040	0.0063	0.001	0.001	0.001
088	0.0058	0.0037	0.0051	0.000	0.001	0.001
067	0.0265	0.0108	0.0239	0.001	0.001	0.001
241	0.0233	0.0097	0.0280	0.001	0.001	0.001
247	0.0157	0.0070	0.0184	0.001	0.001	0.001
199	0.0274	0.0093	0.0299	0.001	0.001	0.001
214	0.0081	0.0056	0.0053	0.001	0.001	0.001
232	0.0105	0.0057	0.0053	0.002	0.001	0.001
265	0.0522	0.0134	0.0617	0.001	0.001	0.001
259	0.0156	0.0081	0.0183	0.001	0.001	0.001
253	0.0368	0.0134	0.0447	0.002	0.001	0.001

Table 1. Standard deviations achieved on the six exterior orientation parameters (EOP)

Point	X (m)	Y (m)	Z (m)
5001	0.001	-0.006	-0.015
5002	0.003	-0.004	0.009
5003	0.001	-0.011	-0.012
5004	-0.007	0.006	0.007
5005	-0.002	0.001	0.017
5006	-0.005	0.014	-0.006

Table 2. Ground control point residuals

Instead of bundle adjustment, the thermal image followed a different orientation approach: image space resection of a single image for non-metric cameras as proposed by Navarro et al (2009). Following that approach, space resection would start

with the DLT, afterwards collinearity, next collinearity plus principal distance as additional parameter, and finally collinearity plus the first radial distortion parameter as an additional parameter.

Once the 3D model is achieved and the images are oriented in space, the next step is texturing. Therefore, the next section will discuss the results after the draping of the textures of the imagery onto the 3D models.

3.3 Photorealistic texturing

Besides the piecewise geometric transformations of the imagery to fit the whole 3D model following the collinearity equations, some radiometric transformations were carried out to remove the slight changes of lighting and reflections during image capture. Following this procedure, a homogeneous photorealistic model in 3D can be built up to guarantee maximum reliability in the visualisation of the state of the monument (Fig. 8).

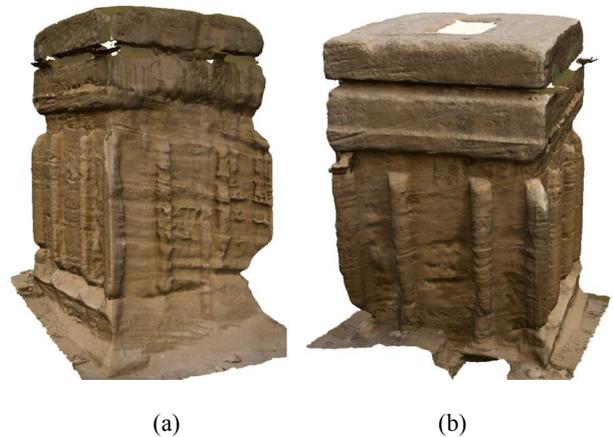


Figure 8. Overall photorealistic model of the Djin Block No. 9 (a) western and southern sides; (b) northern and western sides

In a similar way as was used applied to build the photorealistic model, the thermal imagery was also draped onto the 3D model yielding 3D thermorealistic models (Fig. 9).

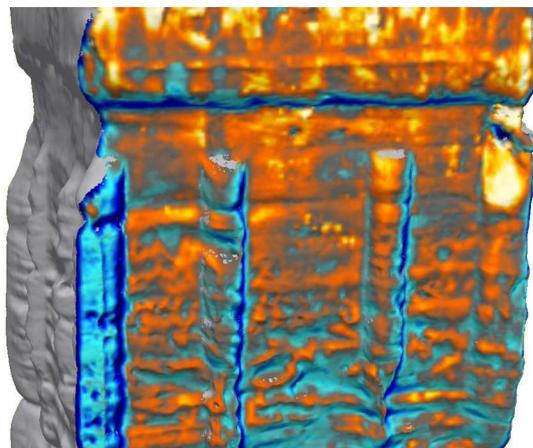


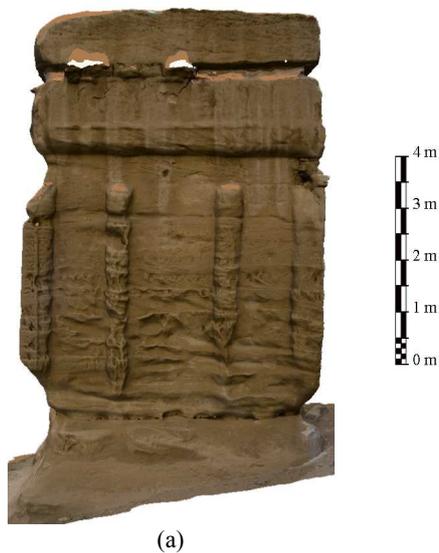
Figure 9. Detail of the thermorealistic model of the Djin Block No. 9. Eastern side

The thermorealistic model over the 3D model allows an analysis of the monument from a different points of view due to the combination of 3D information and thermal infrared data.

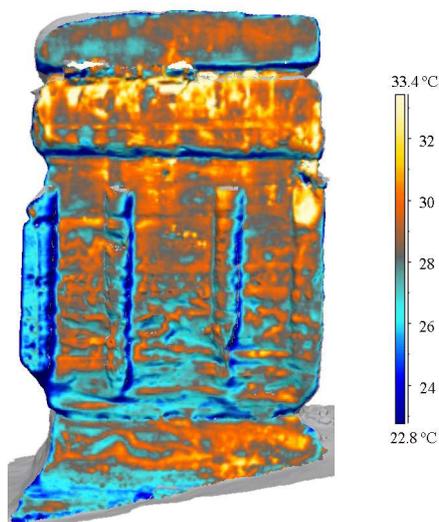
4. ANALYSING THE STATE OF THE TOMB

The four lateral sides of the tomb and its top cover (entrance) were exhaustively analysed in 3D due to the high quality of the two photomodels (one photorealistic and the other thermorealistic). Furthermore, rigorous plots of each side were provided after projecting each side onto its orthogonal plane for systematic analyses. Figure 10 displays an example of the orthophoto products (orthoimages) generated for mapping, one visible and one thermal. These data are ready to be imported into and managed by different databases, GIS or image repositories.

There exist differences in the state of the conservation of each side. For example, the eastern and southern sides are more eroded due to the higher exposition to climatic effects such as sun, raining and wind. The medium-grained sandstone is mainly the water capillarity effect (after entering the tomb through the open top cover) and, last but not least, wind.



(a)



(b)

Figure 10. Eastern side orthographic views of the Djin Block No. 9: (a) Visible orthoimage; (b) Thermal orthoimage at 08:15

In general, the coldest areas (around 23 °C) point out areas in shadows when the images were taken. Areas around 26 °C in the lower middle part of tomb represent either extreme loss of material (lower middle part), borders or materials different composition of minerals (top). Areas around 30 °C show either minimum erosion or moisture. Hottest areas around 33 °C (in white) represent detachments or porous materials.

Moreover, the thermal information provides an effective way to display the sequential layers of rock as well as the rich ornamentation chisel the sandstone (cf. the central part of Fig. 10b). This last statement is even enhanced after analysing the 3D thermorealistic model (cf. central part of Fig. 9). This kind of information is negligible on the visible image as well as on the photorealistic model.

5. CONCLUSIONS

This paper presents a photogrammetric procedure to integrate effectively visible and thermal imagery as well as laser scanning data. The quality of the 3D photomodels for the two versions, the photorealistic with visible pictures and the thermorealistic with the thermal images, draped on top of the simplified 3D model from laser scanning allows not only correct visualisations of the monuments, but also unique and high-resolution analyses in the laboratory/office.

Images combined from the visible and thermal infrared parts of the electromagnetic spectrum are very effective for determining features, alterations or damage, otherwise very difficult to characterise by traditional means. Furthermore, the integration of the imagery to yield 3D photomodels allows comprehensive analyses far beyond traditional 2D imagery. This study also demonstrates the benefit of using thermography to detect otherwise invisible patterns of no longer existing attachments onto the eastern facade.

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