MULTISPECTRAL SENSORS IN COMBINATION WITH RECORDING TOOLS FOR CULTURAL HERITAGE DOCUMENTATION

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Figure 1. View of the complex of Djin Blocks along the entrance to the *Siq* (gorge) in Petra Archaeological Park, Jordan, 2010. (José Luis Lerma)

Documentation of cultural monuments and sites often includes a thorough analysis of their condition through time. This paper addresses the benefits of using multispectral imagery such as visible, near-infrared, and thermal infrared imagery in combination with terrestrial laser scanning to assess the state of preservation of a sandstone tomb, the Djin Block No. 9 in Petra Archaeological Park in Jordan. The combination of the different multispectral bands (visible, reflected near-infrared, and thermal infrared) and enhanced combinations of them yielded comprehensive data to analyze with maximum reliability the state of preservation of the monument with state-of-the-art photographic and 3D surveying techniques.

Natural weathering continuously affects the integrity of cultural sites and monuments over time. Together with natural and man-made disasters, pollution, and tourist activities, these combined assaults are steadily altering the condition of the main features of architectural and archaeological objects and sites around the world. A well-known example of a highly weathered and vulnerable site is the Petra Archaeological Park.

For large archaeological sites and architectural complexes, analytical studies should be nondestructive to avoid further deterioration and damage and should be quick and easy to accomplish. Furthermore, they should ideally be carried out by local experts with conventional, state-of-the-art technology. Close-range remote sensing affords such a solution; both aerial and satellite imagery are not appropriate owing to their low spatial resolution and the vertical spatial disposition of inaccessible features such as the carved rock-cut architecture of Petra. On the contrary, close-range terrestrial solutions with multispectral imaging sensors and, if available, laser scanning are ideal for the purpose of a thorough graphic and metric recording of this resource.

Remote sensing includes both active and passive sensors. For the former, terrestrial laser scanning is used herein to determine with maximum reliability the shape of the monument. For the latter, we applied multispectral photography with an off-the-shelf SLR digital camera and gelatin filters to acquire both visible and near-infrared photography, as well as a thermal camera. Passive remote sensing techniques, near-infrared photography, and thermography all register different parts of the electromagnetic spectrum indirectly and convert the radiation onto color (or false-color) imagery. Therefore, the images allow users to view imagery invisible to the human eye, which sees only visible radiation. In particular, the images are used to highlight specific areas with different responses to visible radiation.

This paper focuses on the examination of Djin Block No. 9 owing to its valuable architectural shape isolated from the hill nearby, unique architectural details carved from white Ordovician sandstone (belonging to the Paleozoic), and lastly, the severe damage due to cracks, efflorescence, detachment, loss of material, and scaling. The 3D shape of the monument is perfect to analyze the influence of thermal stress on each side of the monument owing to the four different orientations of the façades, north, east, south, and west. Furthermore, its cube-shaped geometry infers symmetry, which is now lost due to weathering.

Two issues are addressed here. First is the analysis and characterization of the weathering of the Djin Block No. 9 in order to assess the monument's condition, and second is testing the proposed approach of integrating visible, near-infrared, and thermal infrared imagery with terrestrial laser scanning.[1]

Petra Archaeological Park and Djin Blocks

Petra Archaeological Park in Jordan was erected by the Nabataeans in the heart of a mountain range with rough terrain and semiarid landscapes. Petra is full of imposing rock-cut architecture carved within the sandstone cliffs inside the park, and is probably one of the most remarkable ancient cities and wonders of Jordan and the entire Middle East.[2] Petra was listed twice on the World Monuments Watch List, which has brought much attention to the site and has increased tourism activities, adding to the site's risks and management problems.

While most of the monuments inside Petra are carved out of the pink-colored Cambrian sandstone, the Djin Block is one of a few monuments carved out of whitish Ordovician (Disi) sandstone.[3] In addition, the Djin Blocks are among the very few 3D rock-cut carved structures that resemble towers and are spread throughout the site of Nabataean Petra[4] (Fig. 1). Indeed, they stand out mysteriously against Petra's typically two-dimensional monuments. The specific function of these blocks is unknown;[5] however, archaeologists agree that the Djin Blocks had a funerary significance. It is believed that some of them were tombs and while their exact date is not known, they might be one of the earliest Nabataean funerary monuments, dating back to the second or early first century BCE. It is also worth mentioning that the Djin Blocks were often built next to water sources.

In this case study, the Nabataean Djin Block No. 9 (Fig. 2) is in the form of a temple. The block is 5.50 m × 5.50 m × 9.86 m (width, depth, height). The roof is flat and has a carved grave in its center (2 m by 0.6 m and 0.7 m in depth; Fig. 3). Its four sides are all similarly formed, consisting of four main units.[6] The top is a plain entablature unit with rectangular sides. Below it there is a deep rectangular groove in which stone insets were fixed with mortar. The row of inset stones forms a cornice running around the squared block. The row of stones that forms the cornice has a similar Hellenistic profile as is evidenced in most of the monuments in Petra. Each cornice stone has a sharp triangular front end section with a horizontal side pointing upward and a diagonal side facing downward. Below the groove another entablature follows, lying on top of a thin torus and a wider fascia. The latter curves inward into a thinner entablature, which constitutes the second unit. The third unit of the façade is highest in elevation and has two engaged semi-columns that lie in the middle of each of the four façades. On each corner of the façade, a quarter column engaged to a pilaster on both of its sides is carved to form the edges of the block, thus enhancing the overall symmetry that is reflected in the architectural concept. This gives a strong vertical emphasis, which is capped by bold horizontal lines reminiscent of Hellenistic architecture.[7]

The last unit, the base, has steps that add to the majesty of the monument. In fact, the monumental Djin Block No. 9 is the only example in Petra with pure Greco-Roman architectural form.

The Djin Block No. 9 is heavily weathered on the southern side and to a lesser extent on the eastern side, with deteriorated lime mortar joints in which are contained two stone insets. The main weathering mechanisms are water flow down the main elevation, capillary rise at the base, and aeolian attack as confirmed by microscopic examination and XRF analysis.[8]

Remote Sensing Tools and Survey

One of the most important methods to assess the state of a monument is photography. Photographs are easier to interpret and recognize than drawings; they contain information about surface detail and can provide information about the condition of a monument before, during, and after restoration, which is difficult to achieve by graphic documentation techniques alone. However, shadows can cause errors in interpretation as certain information might be lost. Photographic and nonphotographic (graphic) documentation tools can be merged in one process, in which the digital photographic technology is the main base.[9] Photography, however, is still considered one of the most powerful tools in the documentation and assessment of damage.[10] More information can be extracted with digital image processing after filtering or image enhancement. Additionally, both kinds of sources, original input and enhanced imagery, can be draped onto the 3D models to analyze thoroughly the whole object in three dimensions.[11]

Consequently, in order to obtain a correct representation of complex historical structures, it is necessary to plan specific survey and representation techniques. In fact, when dealing with heritage documentation, the correct procedure is to plan and manage different survey techniques, considering the uniqueness of the monument. Thus the research approach presented herein attempts to exploit a combination of these two techniques, near-infrared photography and thermography. Two different cameras were used to acquire the multispectral content, one digital SLR camera for the visible and near-infrared photography and a dedicated video camera for the thermal imagery. In addition, a terrestrial laser scanner was used to build up a 3D model of the monument.

For the visible and near-infrared photography, a Canon 1 Ds Mark III digital camera was used. The acquisition of the near-infrared photography required filters to block all the UV and visible radiation. Herein, a low-cost gelatin filter, the Kodak Wratten 87,[12] was used in front of the camera (Fig. 4).

The acquisition of the visible and the near-infrared images was carried out from the same position and consecutively in order to facilitate the eventual false color composition

Figure 2. View of the Djin Block No. 9 from the southern and eastern sides depicting some of the fragments of the inset cornice in situ, 2010. (José Luis Lerma)

(Fig. 5, bottom left). For that purpose, the visible image (Fig. 5, top left) was separated into the three spectral bands—red, green, and blue—replacing the content of the red band with the near-infrared picture (Fig. 5, top right).

The acquisition of the thermal infrared (TIR) images required several shots to get as much thermal difference as possible over the day. For that purpose, the same side was shot at three different times: early in the morning (around 7:30), midday, and during the afternoon (around 18:00). Nine samples were tracked carefully after rectifying the set of imagery and selecting the same features. In this way it was possible to check the thermal variation of the monument on a specific side (Table 1). Figure 6 depicts the thermal image taken during the afternoon with the nine samples overlaid.

In a way similar to that with the near-infrared (NIR) false color image (Fig. 5, bottom left), another false color image was obtained after combining the thermal image with the

Figure 3. Top view of the Djin Block No. 9 from the northern side depicting the grave, 2010. (José Luis Lerma)

visible image, green and blue bands. Figure 7 shows the results of two additional false image compositions, one with the red, green, and TIR spectral bands (Fig. 7, left), and another with the visible (panchromatic image), NIR, and TIR (Fig. 7, right).

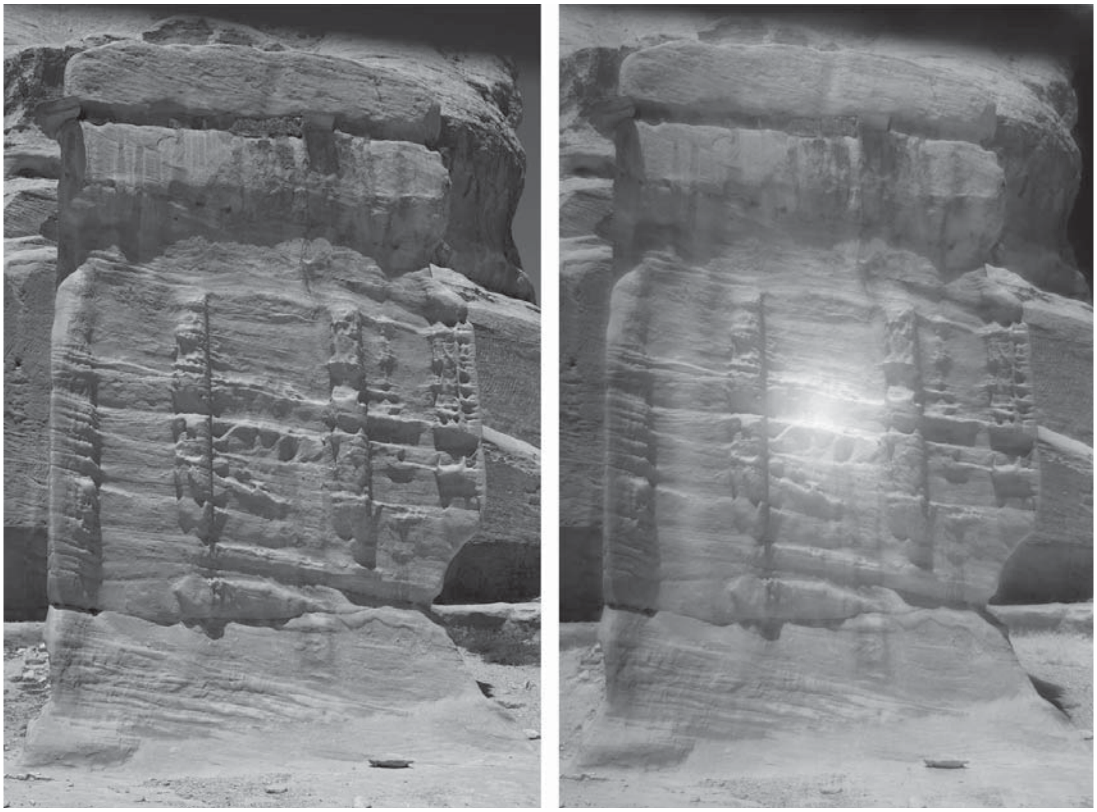
The 3D model developed after the registration of the terrestrial laser scanning point clouds provides the metrics of the state of conservation of the outer surface of the Djin Block (Fig. 8, left). The virtual photorealistic 3D model was used to analyze the monument under different conditions (Fig. 8, right). For instance, small conditions such as flaking and microcracks on the first and second units of the Djin Block No. 9 were visualized better in the virtual 3D model than in situ. Furthermore, the monument can be quickly checked and revisited in the office owing to the high resolution of the data set, as well as the high accuracy (± 3 mm after filtering the point cloud and fitting the mesh).

The level of detail of the 3D model derived from the terrestrial laser scanner can be highly enriched with texture from a digital camera following several photogrammetric steps,[13] even with images taken with noncalibrated cameras.[14] Figure 9 shows the results of draping the visible image (shown at top left in Fig. 5) onto the mesh displayed in Figure 8. Furthermore, draping is independent of the spectral band of the image. The results achieved after draping the visible and thermal imagery onto the digital surface models for the eastern side of the Djin Block is presented in "Integration of 3D Laser Scanning, Photogrammetry and Thermography to Record Architectural Monuments."[15]

Figure 4. Acquisition of the near-infrared photography on site, 2010. (José Luis Lerma)

Results and Assessment

Damage to the Djin Block can be analyzed in 2D either with the three original images—color visible image (Fig. 5, top left), the black-and-white near-infrared (NIR) image (Fig. 5, top right), and the thermal (TIR) image (Fig. 6)—or with the enhanced false color compositions with NIR (Fig. 5, bottom left), with TIR (Fig. 7, left), and even with NIR and TIR (Fig. 7, right). At this point, the amount of additional information provided by the black-and-white near-infrared image is reduced compared to the visible image. In fact, both images can be used to confirm the severe weathering in the cornice, the mortar used to hold the inset stones, the small and large cracks, efflorescence, flakes, and loss of material. The images themselves constitute an easy-to-analyze archive that can be used to monitor the state of conservation over time. Furthermore, they can be used to build up the drawings of the alterations of the monument, metrically if required, either onto the 3D model



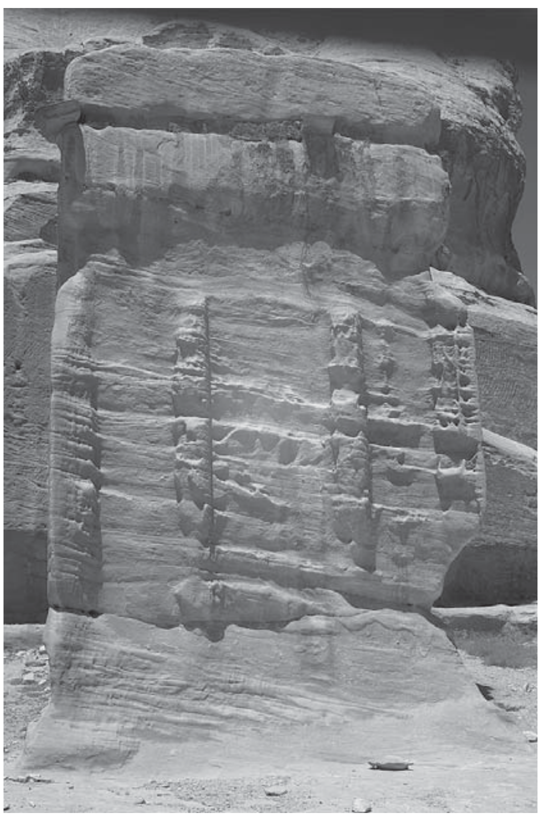


Figure 5. Southern elevation of the Djin Block No. 9. In the top left image the object was digitally photographed under visible light; the top right image depicts the Djin Block using black-and-white near-infrared; and the image at left uses false color composition with the NIR green and red bands, 2010. (GIFLE)

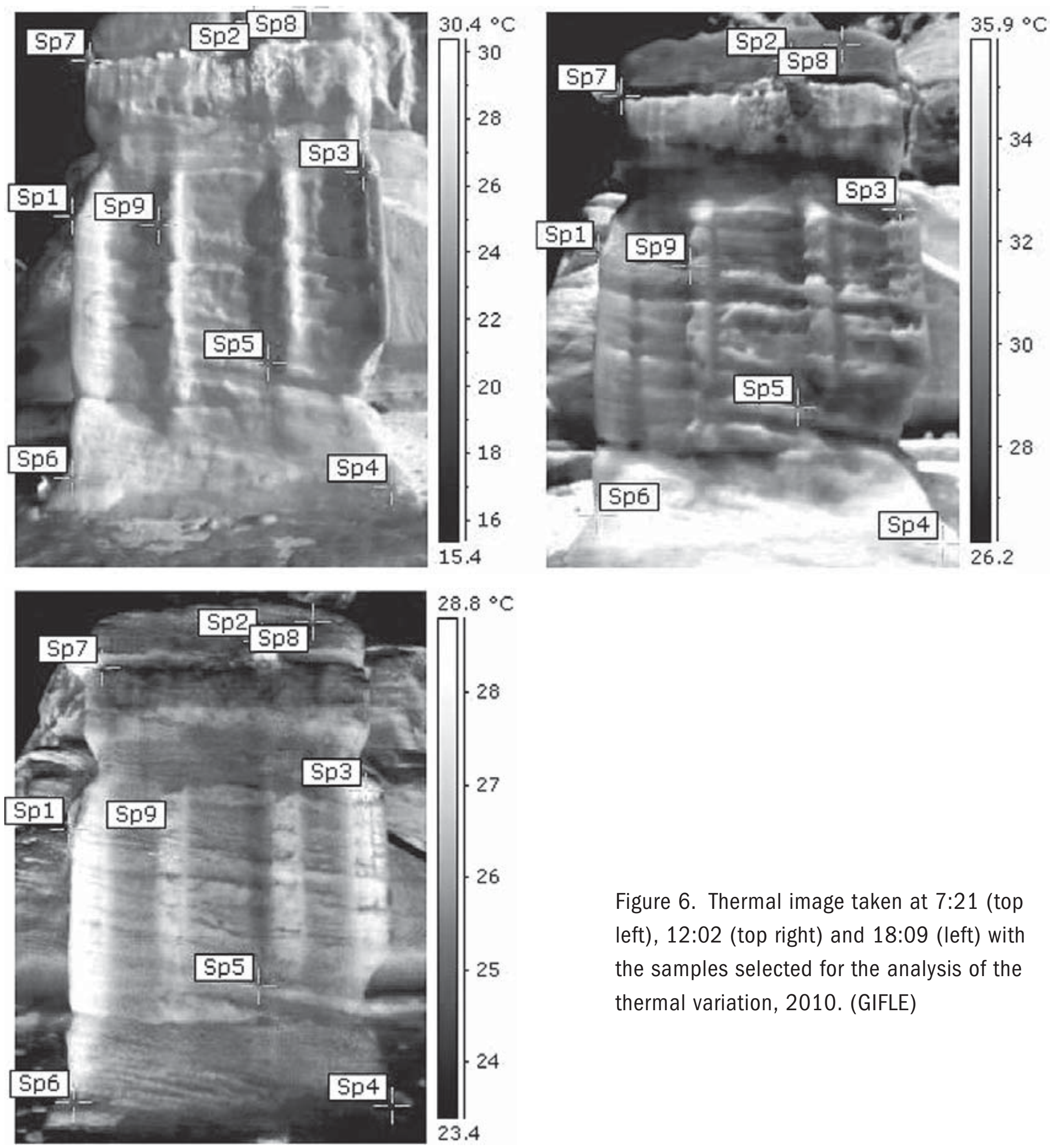


Figure 6. Thermal image taken at 7:21 (top left), 12:02 (top right) and 18:09 (left) with the samples selected for the analysis of the thermal variation, 2010. (GIFLE)

or onto eventual ortho-images (i.e., images corrected of the distortions due to lens distortion, perspectivity, and topography).

The false color composition NIR-green-blue obviously enhances the vegetation in red (namely, the vegetation on the ground around the tomb and below the right insert stone in the cornice, Fig. 5, bottom left). The rest of the false color compositions enhance other features. For instance, red-green-TIR focuses on the water flowing vertically (ochre color) and on the salient areas (hotter areas in bluish), and concavities (cooler areas also bluish). Furthermore, the combination of the three spectral bands, visible-NIR-TIR enhances the water flowing horizontally on the top of the entablature and on the middle of the side (yellowish green), as well as the vegetation (light greenish). Each one emphasizes different alterations.

The thermal images focus the attention on the hotter and cooler areas associated

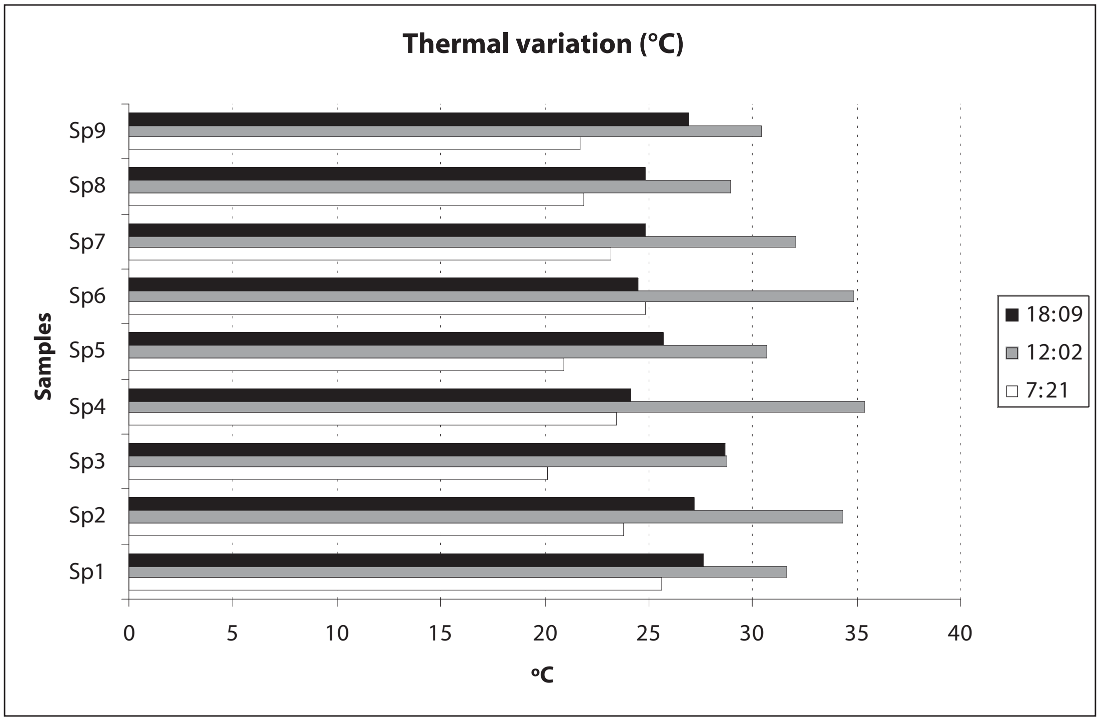


Table 1. Thermal variation of the Southern side at nine sampled areas in April 29, 2009.

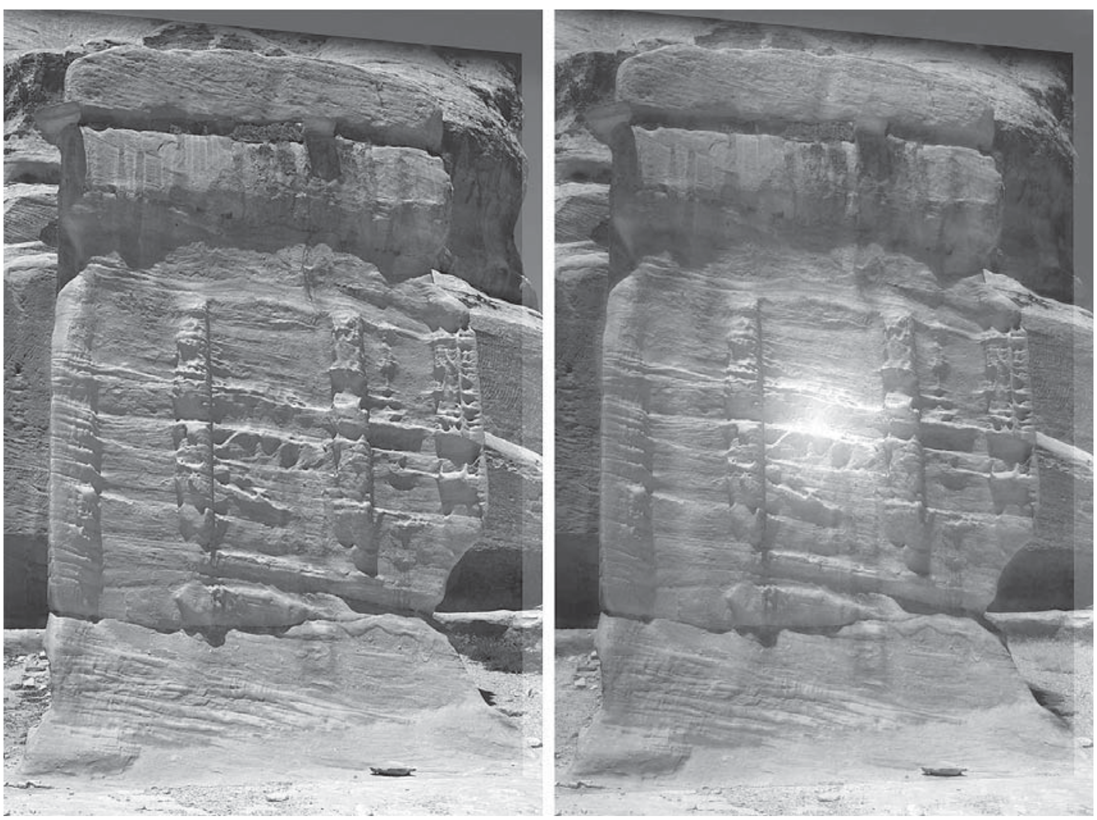


Figure 7. False color compositions of the southern elevation of the Djin Block No. 9. Red, green, and TIR bands are displayed (left); visible, NIR, and TIR bands are shown (right), 2010. (GIFLE)

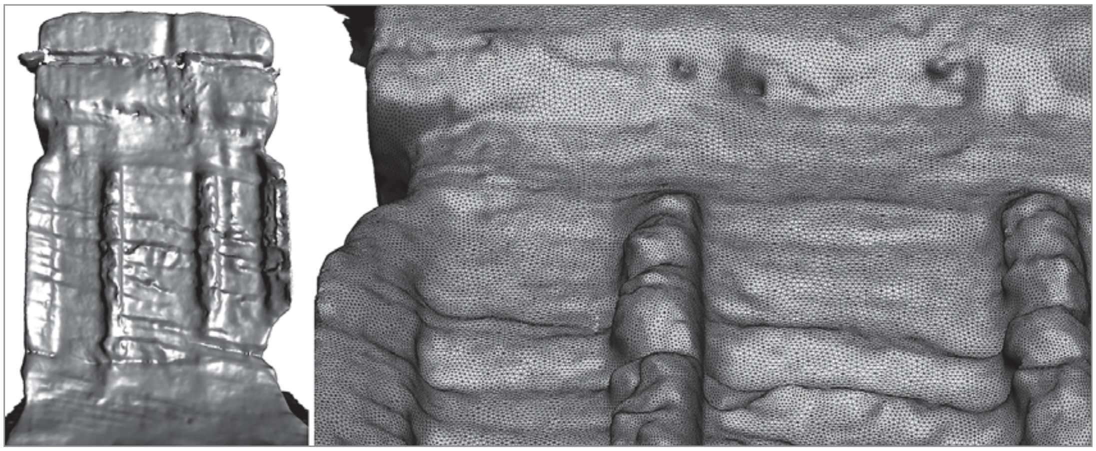


Figure 8. General view and detail of a 3D mesh of the southern elevation, 2010. (GIFLE)

with the thermal properties (conductivity, diffusivity, effusivity, and specific heat); spectral properties (emissivity, absorption, reflection, and transmission); and characteristics such as porosity, volumetric mass, and physiological water content.[16]

The thermal images yield contrast enhanced surface topography due to the temperature variations across the surface of the monument and clearly show the roughness of its surface, the layers of materials, as well as their damages (Fig. 6). In fact, areas with severe loss of material display temperature differences in the range of ±6°C. The first image at 7:21 am (Fig. 6, top left) displayed a stable temperature with a mean value of 22.8°C despite the shadows that affected the image content due to the weathered surface. At the level of the second unit, the bottom end of the rectangular entablature cannot be differentiated from the curve as it is at midday (Fig. 6, top right) and during the afternoon (Fig. 6, bottom left), although the large crack tilted downward from left to right can be clearly defined. In addition, the four semi-columns attached to each surface (vertical features) can be identified in Fig. 6, at top left, as well as the horizontal ones shown in the top right image (the whole concavities and lack of material) and pictured at the bottom left (main and thin layers). The base unit is well contrasted in the afternoon thermal image; the midday picture has saturated shadows, while the image in the morning reveals some vertical stripes with moisture. The architectural details are also enhanced by the thermal imagery since the heating rate of small and sharp edges is different from the mass of the rock. This is an important aspect for the monitoring process since in time one expects to observe edges that have been effaced by weathering. However, this must be left to the future as the process might take some time to occur. This means that revisiting the monument with the thermal camera in the future will prove very useful for this purpose.

In addition, the thermographic analysis allowed us to confirm that the mean temperature range between the morning and the midday data set is about 9.1°C, with a maximum range of 12°C for sampling 4 (Sp 4) at the bottom of the tomb, and a minimum range of 6°C at Sp 1 at the extreme border of the pilaster. The maximum temperature for the

Figure 9. General view and detail of a photorealistic 3D model of the southern elevation, 2010. (GIFLE)

southern part was 35.4°C at Sp 4, while the minimum was 20.1°C in the morning at Sp 3; this minimum temperature is due to the concavity of the point and moisture, apart from the incoming rays of the sun at 7:21. In fact, its maximum temperature is at least 28.8°C, and more interestingly, it is almost stable during the afternoon at 18:09, with a variation of only 0.1°C. Outer parts such as Sp 2 (capital) and Sp 9 (pilaster) also reveal high temperature values during the afternoon.

Controlling the temperature of the monument may be advisable as there are volume changes due to both cyclical thermal variations and the presence of water. The temperature variations can produce dilations and contractions in the material and create deformation and failure. Stones with different mineral textures can also undergo further magnified stresses due to thermal expansion differences. The differences of both dilation coefficients can explain the state of deterioration of the structure.

On the one hand, 2D analysis with multispectral imagery can be conducted quickly with conventional cameras for visible and near-infrared photography, and also quickly with thermal cameras. On the other hand, 3D analysis is more powerful but requires a 3D model. It can be achieved either with photogrammetric image-based solutions or with laser scanning, among other solutions. 3D analysis is not as straightforward as dealing with imagery stand-alone (mainly because it requires specific software and powerful hardware systems) but it opens up many opportunities:

- To examine the monument from different points of view, not only from the perspective view of the photographer.
- To monitor the rate of weathering of the monument in three dimensions through time with high accuracy.
- To build up multimedia products such as fly-through animations, movies, virtual reality, and augmented reality.

Conclusions

The integration of multispectral photography with digital cameras and thermography provides relevant and accurate information to assess the state of preservation of monuments. Visible and near-infrared images can be acquired with conventional equipment. It is preferable to make use of glass IR filters instead of gelatin filters in order to avoid the hot spot effect in the middle of the image. The false color images can enhance the interpretation of materials, deterioration, and damage owing to the juxtaposition of multiple responses of the electromagnetic radiation onto the objects.

For sandstone monuments such as the white Ordovician tomb presented here where most of the stone is the same material, the information gained by the thermal sensor is more relevant than the information obtained from the reflected near-infrared photography. Architectural details (edges) are easily read by thermography, while material information is detectable by near-infrared photography. Damage from microflora or the presence of limonite or hematite veins that can cause structural incongruities and weaknesses are other examples of potential risks observable by thermal analysis.[17] It has also been shown that lichens are detectable even in small infestations with near-infrared photography. Furthermore, out of the thermal imagery, thermal variations can be quantified to determine the microscopic stress inside the minerals which water (moisture) is present in its three different stages: ice, liquid, and gas.

Regarding the 3D model in comparison to other conventional 2D techniques, the following can be summarized:

- First, the 3D model is a correct and complete documentation of objects. With a realistic 3D model, its exploration could let the user obtain detailed data of various degrees; from the 3D model, it is possible to realize a section with a horizontal and vertical plane in the different zones of interest and extract immediate measurements, which are essential for the analyses of cultural heritage structures.
- Second, a 3D model covers most of the needs for historic sites. It can be directly used for 3D visualization and point-to-point measurements and can be stored for subsequent use.
- Third, the accuracy of the laser scanner allows subtle detection of provenance.
- Fourth, it allows an easier communication between the documentation specialist and the “client” compared to other survey products. This is a very important issue in historic conservation and preservation.
- Fifth, images can be mapped onto the model to get a virtual copy of the real object.

Three-dimensional models allow users to deliver comprehensive analysis not only in two dimensions but in three dimensions, or even in four dimensions if the acquisition is carried out at different times. 3D point clouds can be quickly acquired by terrestrial laser scanning techniques but require still expensive hardware and software. Image-based photogrammetry might be an economical alternative approach. Regardless of which of the two techniques is used, the photorealistic 3D model yields maximum information as it is based on real and existing data.

The three approaches based on photographic records for the monuments of Petra[18] are still valid with state-of-the-art technology (hardware and software): first, manual editing with popular image software; second, multispectral photography; and third, advanced classification and feature extraction. This research moves forward the integration of metric data and multispectral imagery, opening up comprehensive ways to analyze and disseminate weathering behavior of cultural heritage.

Acknowledgments

The authors would like to express their thanks for the support provided by the *Agencia Española de Cooperación Internacional para el Desarrollo* (AECID) to the project A/025999/09 and the Spanish Ministry of Science and Innovation to the project HAR2010–18620. Additional support to the Jordanian team from *Società Italiana per Condotte d'Acqua S.p.A.* is very much appreciated.

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