Documentation of Weathered Architectural Heritage with Visible, Near Infrared, Thermal and Laser Scanning Data

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Abstract

Documentation of cultural heritage requires simple, quick and easy to use multi-sensor approaches to determine the state of conservation of monuments and sites. The documentation of a highly weathered architectural heritage such as the Obelisk Tomb is a good example to test the performance integrating multispectral imagery and laser scanning data. The Obelisk Tomb is the first important façade that a visitor sees while entering to the archaeological site of Petra in Jordan. The rich architectural formations carry Egyptian, Hellenistic and Nabataean influences. The damage that was inflicted on this unique monument led us to study it applying a number of modern digital techniques including 3D scanning, multispectral photography with visible and near infrared images, and thermography. All the multiband content is initially registered onto different multispectral bands. The multispectral information is enhanced and eventually draped onto the 3D laser scanning model in order to improve documentation and analysis of the state of conservation. Our results integrating the multispectral data, thermography and terrestrial laser scanning clearly enhance the power of diagnosis over the Obelisk Tomb with state-of-the-art optical equipment and image processing software. Furthermore, the capacity to examine, analyse and detect the existing damages is enhanced by the false colour processing of the input photographic data. Weathering effects are highlighted onto the 3D model and shed some light on the causes of the damages.

KEY WORDS: Thermal analysis, Multispectral photography, Laser scanning, Photogrammetry, Cultural heritage recording
1. Introduction

Since cultural heritage is a unique expression of human achievement, and as this cultural heritage is continuously at risk due to physical, natural, environmental and anthropogenic factors, documentation is one of the main ways available to give understanding, meaning, definition and recognition of the values of the cultural heritage. The importance of documentation may be undertaken as a support to various action and activities including protection, restoration, conservation, preservation, identification, monitoring, interpretation, public awareness, management of historic buildings and sites and cultural landscapes (Haddad and Akasheh, 2005; Haddad, 2007), in addition to creating a register of stolen movable objects. Article 16 of the Venice Charter (1964) state that, in all works of preservation or excavation; there should always be precise documentation in the form of analytical and critical reports, illustrated with drawings and photographs. Every stage of the work, including technical and formal features identified during the course of the work, should be included. This record should be placed in the archives of a public institution and made available to research workers. It is recommended that the report be published. Thus documenting the Cultural Heritage not only describes the context in which the materials were found, and their relationship in space and time to geological deposits and large architectural features, but also as monitoring of the remains of past human activities.

The surveying methods of documentation for cultural heritage can be categorized by tools and techniques (Dallas, 2007): first, manual survey techniques for base recording and condition assessment (hand survey, sketch diagrams); second, instrument survey tools considering total stations, laser scanning and global navigation satellite systems (GNSS); third, image-based documentation methods, including pictorial imagery, rectified photography, multispectral imaging, thermography and photogrammetry; and forth, data management, including computer-aided design and drafting (CAD), computer modelling, databases and geographic information systems (GIS). A review of these techniques can be found in Eppich and Chabbi (2007), Böhler (2006).

In comparison with other issues of the cultural heritage conservation and preservation, the impact of modern technology during the last 20 years is obvious with new documentation techniques and tools. Modern technology has changed matters in documentation of cultural heritage radically and promises to continue to bring rapid changes. Photographic and non-photographic (graphic) documentation tools are merging in one process, in which the digital image technology is the main base. Taking into consideration that
documentation frequently requires integrating data from different sources, the impact of the new technologies in historic documentation can be realised in three aspects: data quality, flexibility and accuracy of the graphic and photographic documentation (Haddad, 2011). However, the more complex the structure, the more care and specialized data are necessary. A photorealistic 3D model can let users explore the data in a variety of degrees, depending on the level of inquiry and the performance of the approach (Bornaz and Rinaudo, 2004; Remondino and El-Hakim, 2006; Lerma et al., 2011c).

On the other hand, when dealing with documentation, it is important to represent in geometric base materials, colours, decorations, physical and chemical decay and other phenomena. Though, the correct procedure is to plan and manage different survey techniques, considering the particularity of the monument in relation to the ability to benefit from modern digital techniques and the success in acting as a historical record of human activities. In the mean time, by using an accurate planning and some defined procedures, it is possible to reduce the time necessary for the batch processing. However, the method which should be applied in each case depends on various factors such as cost and time, location facts, size extent, content (qualitative as well as quantitative), accuracy class, approach (direct or indirect), style of presenting the results, interpretation, and last but not least, monitoring (Haddad, 2007, 2011).

In practice, the familiarity of the user (expert) with one of the methods is often the deciding factor instead of the optimal approach for the intended purpose. However, the support of different specific skills is often required; hence it is crucial to choose the correct tools for a multidisciplinary analysis. For instance, a digital orthophoto allows users to point out and manage information about many elements on the documented object on different layers which is a very important issue in historic conservation and preservation (Haddad, 2011). In fact, layers such as architectural elements, shape relationships, construction techniques, material and texture, historical phases, colour values, decorative elements, decay conditions, etc. can be considered and integrated together.

Digital photogrammetry and laser scanning techniques, in recent years have undergone an important technological progress. Both approaches bring new perspectives and can satisfy most requirements in cultural heritage documentation. Both of them can be used standalone or in combination with other surveying techniques for multiple purposes (Rüther et al., 2003; Georgopoulos and Ioannidis, 2006). The advantages and disadvantages of close range photogrammetry and TLS methods are well-known (Kern, 2001; Boehler and Marbs 2004). Nevertheless, both techniques can be used together
to complement each other, for instance when dealing with occluded areas, when there is lack of texture or when the study area is complex and large (Remondino and Campana, 2007; Lerma et al. 2010b).

The application of remote sensing to record cultural heritage either with multispectral photography or with multispectral sensors is still a challenge and not an extended practice despite its benefits either to automate mapping (Lerma 2001, 2005) or to identify damages and features on the monuments (Akasheh, 2000; Alba et al. 2011; Lerma et al. 2011a). False colour composition extending the visible electromagnetic spectrum (to ultraviolet (UV) and near infrared (NIR) for instance) also helps to enhance the damage and the material variations. Akasheh (2000) showed that it is possible to locate plant infestations no matter how small and even if they are not easily apparent to the naked eye. In addition, UV allowed the detection of limonite veins and infestations even when mixed with dust, clays and other sandstone types. The inclusion of thermal infrared (TIR) adds even more possibilities on stone monuments such as analysing indirectly both the stone temperature variations and the different morphologic features on the surface depending on the time of the measurement (Akasheh et al. 2010, Lerma et al., 2010a). In addition, the TIR can be used to detect moisture, voids, drainage systems, delaminations and further anomalies (Clark et al. 2003; Lerma et al., 2011b; Tavukçuoğlu et al., 2005).

This paper concentrates on the effective integration of multispectral imagery, photogrammetry, laser scanning and thermography to record a highly valuable stone monument at the entrance of the Petra archaeological site in Jordan, the Obelisk Tomb. The rest of the paper is organised as follows. Section 2 describes in detail the main features of the Obelisk Tomb. Section 3 presents the different approaches used to record in 2D and in 3D the complex site with a thermal video camera, an on-the-shelf single-lens-reflect (SLR) digital camera (with and without a NIR filter) and a time-of-flight terrestrial laser scanner. Some image processing tools are used to create false colour images that reveal more easily damages and alterations. For that purpose, different bands coming from multiple image sensors are used. The resulting images render some interesting results that are presented in this section. The technique of draping either the obtained band combinations of false colour images or the field photos onto the 3D model opens up the rendering to enhance the visualisation of the weathering effects and their damages. Section 4 opens up a discussion of the results presented in the previous section. Finally, Section 5 concludes with a summary of the research.
2. The Obelisk Tomb

The Obelisk Tomb and Bab As-Siq Triclinium (1st century BC - 1st century AD) is the first major monument encountered when entering Wadi Musa on the way to the 1.2 km long Siq, the main gorge entrance to the ancient city of Petra. This complex facing NW is dominating the left side of the road, a few meters down from the Djin blocks. The Obelisk Tomb (also known as 'Nefesh' Tomb) is stacked on top of the Bab as-Siq Triclinium (Fig. 1). The Obelisk Tomb is named after the four obelisks that decorate the top of the entrance of the tomb guarding the rockhewn cave tomb entrance and was used for burials. The lower storey, the Bab as-Siq Triclinium is decorated in a more classical style and was apparently used for funeral banquets as many such chambers in Petra used for memorial feasts in honour of the dead, a practice that was also common among the Greek and Romans. Through this variety and richness of the decorative and symbolic architectural elements, this complex reflects perfectly the spirit of the late Hellenistic architecture, where architects moved among different cultures create high artistic architectural formations, especially the Baroque nature of the rock-cut sandstone façades. Certainly these different historical architectural treatments at the same monument were not only decorative but they indicate how this family wanted to be seen for the eternity. It is possible, therefore, that this architectural formation may have come from that direction.

The Obelisk Tomb has several graves housed in it. The Tomb section is characteristic; mostly the floor is clear to the bedrock, the interior consisting of an approximately square chamber (5.80 m x 5.90 m, h. 4m) with a broad recess in the back wall in a form of rectangular arcosolium (2.9 m x 1.7 m, h. 3.1 m) starting 0.2 m above the floor, and decorated with 2 carved pillars (w. 0.49 m) crowned by a segmental arch, and two Loculi, with the approximate dimensions of 2.5 m x 1.25 m, h. 2.3 m, starting 0.12 m above the floor level, and carved on each side of the wall. There is a grave (2 m x 0.5 m) in the floor towards the front of the chamber, parallel to the left side wall. The façade wall has a slightly raised band on both sides of the doorway and two splayed windows which emerge as slits on either side of the entrance doorway. The doorway width is about 1.35 m and is approached by four steps of 0.4 m width.

The façade (w. 16 m, h. 12.25 m) is remarkable (Fig 2); it is approached by a staircase on the left (Fig 1a), passing a cistern (2 m x 2.1 m). Across the top part of the Tomb façade there are four obelisks cut free from the rock behind magisterial obelisks, 'pyramids' (Nefesh), with the top part of each weathered away. The left obelisk, which is the longest one, has approximately 7 m height.
These obelisks are clearly influenced by the Ptolemaic Egyptian stylistic prototype approach. Between the centre pair in the plain rock faced behind the level of the four obelisks, there is a classical niche carved with a statue in deep bas-relief, with two pillars and anta-type capitals, entablature and a Doric frieze. This bas-relief is quite weathered and has lost its head. However, the four obelisks and bas-relief are properly symbolic representations of the five people buried in the tomb.

The lower part is plain, with a central classical order doorway. It is very weathered with little detail visible clearly. The two doorway pillars had anta-type capitals and the entablature had a Doric frieze. In general, the façade is too weathered for any tooling to be realized.

In the Obelisk Tomb the frontal surfaces of all four obelisks are generally in a good condition except for the rightmost one, which is affected by Eolian weathering. A few alveolus or honeycombs can be observed on this surface (Figure 2). North western winds hitting the frontal surface seem to be responsible for this. The other three Obelisks are only slightly affected by this process. This is evidenced by the small
cavity on the third obelisk from the left and the fact that all the frontal surfaces exhibit a certain roughness not common in freshly carved surfaces. The frontal side walls that flank the obelisks are harder hit on the front than the obelisks. More serious is the heavy erosion of the top of the obelisks. This problem appears to be due to down flowing water in combination with wind. The signs of water down flow are obvious on the left sides of the middle two obelisks. The impact of water and wind left these sides seriously honeycombed, with the tops being hardest hit. Thus the middle two obelisks have already lost their pointed tops. The top of the rightmost obelisk shows serious loss of material with granular disintegration as a result and is of the shortest height. While only a small portion of the top of the tallest left most obelisk has been lost, its top is in a relatively good condition but horizontal cracks and left side alveoli at the top threaten a similar fate to this top as for the other obelisks. It seems that as the north westerly wind hits the back surface of the façade eddy currents are created with result that the left surfaces and the top of the obelisks are hardest hit. The back surface shows some alveolar weathering (very high on the right side) with water down flow. The niche in the center has retained its rectangular shape but the statue in its center suffers from granular disintegration with material loss. The right sides of the obelisks are in a better condition than the left, and are very similar in appearance and roughness as the frontal surfaces.

The horizontal surface (entablature) forming the base for the obelisks and topping the lower chamber below has lost some of its edges (double cornice) by water flow. Where complete loss of the cornice occurs, the effect of this flow is very high on the surface below. Water down flow along the surface below the cornice is very clear on both sides. The base of the leftmost obelisk is adversely affected by this process, since an angular crack, whose vertical inclined edge reaches right to the bottom of the obelisk and whose horizontal edge reaches the side protective wall and right though to the bedrock. The same figure shows serious loss of material at the doorway and its sides caused by capillary rise from the horizontal base in front of the entrance. The situation is made worse by the fact that a rectangular cistern and round hole have been dug in this surface and water collection during the rainy season poses an obvious threat so much that big voids are left on both sides of the entrance.

3. 3D Documentation and Multispectral Recording of Weathering

In order to obtain a correct representation of the existing condition over a large historical complex structure, it is necessary to plan, to introduce and to accept some specific surveys and representation
techniques with support of different skills. Hence, it is crucial to choose the correct tools for a multidisciplinary analysis.

A general pipeline of architectural documentation is presented in Fig. 3. It is divided in five parts: a) architectural documentation as a discipline; b) field work with data acquisition; c) processing with surveying and imaging equipment; d) processing to deliver multispectral photorealistic 3D models; and e) results.

Basically, the 3D documentation with multispectral recording can be summarized as follows (Fig. 3):

1.- Data acquisition from multiples sensors, namely, terrestrial laser scanner, digital camera and thermal camera.
2.- Warping of imagery to register multispectral bands. Out of the multispectral bands, all the false colours with three bands will be determined. In addition, digital image processing will be used to enhance image features.
3.- Generation of the 3D model from the laser scanning point clouds. It is supposed that the 3D model is eventually free of errors and ready to be used after registration, filtering, decimation, smoothing and hole filling.

Figure 3. 2D/3D documentation with multispectral recording
4.- Photorealistic 3D modelling generation for each of the different sets of images (visible, near infrared (NIR), thermal infrared (TIR) and false colour).

5.- Thermographic analysis from the multiple thermograms in order to monitor the behaviour of the monument over time.

The approach presented herein takes advantage of different surveying techniques based on imagery coming from different sensors (digital cameras and thermal cameras) and terrestrial laser scanning. The pipeline follows, on the one hand, photogrammetric processing to fix image-to-image and image-to-object geometry, on the other, multispectral processing. Therefore, both geometry and radiometry continuity need to be as accurately adjusted as possible to yield seamless photorealistic 3D mosaics for visible and false colour images.

Next sections review part of the afore-mentioned steps, particularised for the documentation project carried out in the Petra Archaeological Park on the Obelisk Tomb in different campaigns from 2008 till 2010.

3.1 Data Acquisition:

Several scan stations in front of the Obelisk Tomb were selected to achieve an overall coverage of the two monuments with minimum effort on site. A time-of-flight Mensi GSI 100 laser scanner was used to acquire a total of four point clouds, three of them with a resolution of 10 mm and one at 5 mm. The average resolution was 3 mm approximately for the whole façade. Fig. 4a displays the data set with the registered point clouds.

As regards imagery, a full-frame Canon 1Ds Mark III digital camera (with a resolution of 5616 x 3744 pixels) and a Canon EF 50 mm f/1.4 USM lens was used to acquire the visible (Fig. 4b) and near infrared (NIR) images in RAW file format (Fig. 4c). The acquisition of the NIR imagery required a chase for an opaque Kodak Wratten 87 infrared gelatin filter, despite other infrared bandpass glass filters might have been used.

For the thermal infrared images, a medium resolution FLIR Systems ThermaCAM B4 camera was used because it has a high thermal sensitivity as low as 0.10ºC and produces clear noise-free infrared images (7.5-13 µm) with a resolution of 320 x 240 pixels. Multiple thermal images were taken at different times of the day in order to determine thermal variations among different features on the façade (Lerma et al., 2011a, 2011b). An example of one the pictures taken is depicted in Fig. 4d. The camera-object distance was approximately 50 m, due to the topography of the site and a dry riverbed passing across the bottom part of the Bab as-Siq Triclinium. In addition, close-up
Figure 4. Input data: (a) Registered 3D point cloud; (b) Visible Image; (c) NIR image; (d) Thermal image
thermal images of the Obelisk were taken from the floor around the front of the chamber targeting the façade and obelisks.

3.2 Warping and Image Processing

NIR bands are very common in satellite imagery (Spot, Landsat, etc.) and have long been used in vegetation analysis and mineral identification from space. The application of this technique to archaeology, especially to paintings, landscapes, cropmarks and buried structures (Verhoeven, 2008), has come more recently, partly because the cameras involved were very expensive, and because the architectural and archaeological community took some time to appreciate the value of this technique. Moreover, NIR paper films were subject to rapid deterioration with heat and had to be kept in cold environments. On the contrary, conservators and restorers of paintings either in museums and exhibitions or in churches (namely murals on walls and vaults) have long been used NIR reflectography to track the false drawings and the original traces from the master painters. It is possible owing to the reflexion of the NIR wavelength onto the deeper paint layers.

Nowadays, with digital cameras, new changes exist to get visible extended wavelength radiations, in particular the NIR wavelengths (Verhoeven, 2008). In fact ordinary digital cameras can be modified to enhance their sensitivity in the UV and NIR region, due to the response of the CCD or CMOS solid state sensors approximately from 350 nm up to 1200 nm. Nevertheless, higher response in the NIR (and even short wage IR) is achieved with InGaAs sensor imagers. A review of imaging the invisible with NIR photography can be found in Verhoeven (2008).

It is well-known that most of the off-the-shelf digital cameras incorporate IR cut-off filters to block NIR due to the high sensitivity of the camera sensors. However, there is still a chance to register that part of the electromagnetic spectrum with long exposure times (to get a well-balanced image). For instance, the image displayed in Fig. 4c required an exposure time of 210 s at f/16. As the camera used was not monochrome and registered the three channels (through a Bayer colour filter mosaic), the original input image was enhanced with histogram stretching (Fig. 5a); Fig. 5b is the corresponding black-and-white NIR image.

The acquisition of images outside the visible electromagnetic spectrum such as the NIR and the TIR presented herein, allows users to display false colour imagery. False colour images bring together the image content provided by the different spectral bands. A similar experience of yielding false colour images with visible and NIR images, visible and TIR images, and last but not least visible, NIR and TIR images can be found in Lerma et al. (2010a) for the Djin Block No. 9.
False colour near infrared imagery can be used to highlight features such as vegetation. Fig. 6 shows the combination of NIR, Green, and Blue bands after merging the visible and the NIR images. By contrast, vegetation is not always as easily noticeable in visible images. Since vegetation growth is one of the means of biological weathering, NIR is an important tool for conservation of stone monuments. Contrast enhancement leads to Fig. 7 where the pitted surfaces (due to alveolar weathering (circles)) appear in two or more colours, while smoother surfaces appear in one colour even if smooth granular disintegration weathering is present.

3.3 3D modelling by terrestrial laser scanning and texturing of the multispectral data

3D modelling from point clouds coming from different sources is not an issue, despite there are many alternatives to process the data in the
right way. Details on a comprehensive terrestrial laser scanning pipeline can be found in Bornaz and Rinaudo (2004) and Statopoulou et al. (2010). Fig. 8 shows the 3D model of the Obelisk Tomb. It is possible to verify the loss of materials, quantify holes, cracks, flaking, rounding of the edges, etc. and even quantify the volumetric loss of material considering that most of the surfaces on the façade were flat.

With the advent of digital modern techniques for 3D acquisition, it has become possible to drape images onto the 3D models. This allows users the examination of the weathering effects from different points of view in the office. It can be carried out with only one non-calibrated (conventional) camera (Navarro et al., 2009) or preferably with multiples images (Cabrelles et al., 2009), independently of the electromagnetic range, visible, NIR or TIR (Brumana et al. 2005). Without any doubt, it is by far one of the most realistic and accurate approaches to present large complex monuments such as the Obelisk Tomb and the Bab As-Siq Triclinium.

The methodology carried out to deliver the photorealistic 3D models can be found in Lerma et al. (2010b), and particularized for the monuments reported herein in Lerma et al. (2011c). Figure 9 displays the complex reconstruction of the Obelisk Tomb from three different points after resampling the texture patches from three visible
images. This kind of presentation enhances the virtual visualisation of the monument and the chances to analyse the state of conservation. In fact, the perspective views presented in Fig. 9 are recreated from ideal spatial positions, only achievable with other high-end devices such as unmanned aerial vehicles (UAVs), balloons or forklift trucks.

The NIR and the false colour images require the same photogrammetric processing than the visible images to deliver photorealistic 3D models. However, if the images are shot from the same stations, there is no need to reorient them: only a substitution of bands or spectral channels yields the output product with multispectral information. FOTOGIFLE photogrammetric software developed at the Universitat Politècnica de València was used to integrate the imagery and the 3D models in order to yield the photorealistic texturing in 3D. Another alternative is to consider a bi-camera through a photogrammetric network as presented in Alta et al. (2011).
Figure 10 displays both the colorized false colour as well as a detail of the standard false colour. More examples can be found e.g. in Rizzi et al. 2006. The advantage of visualizing the multispectral images in 3D is straight whether the interactive handling is possible (as for example on VRML/X3D browsers) or not (for example on movies). All these kinds of false colour compositions allow researchers to enhance features hard to be found in normal colour images. Therefore, false colour compositions are relevant to help interpretation of the monuments.
The lack of photographic content in the latter perspective views in false colour (Fig. 10) compared to the visible ones (Fig. 9) is due to the fact that the photorealistic visualisation is delivered from one and three images, respectively. With more imagery, more chance to have an overall reconstruct without omissions. Last but not least, whether stereopair or multiple-imagery were acquired on site for the details, they might be used not only for texturing but for modelling purposes, specially either in occluded areas not reach by the laser scanner or in areas requiring higher degree of resolution/accuracy.

3.4 Thermal Analysis

Passive thermography has been used in many applications related to cultural heritage (Danese et al. 2010; Ludwig et al., 2004; Rosina and Robison, 2002; Rosina et al., 1998). Several thermal studies with thermal cameras have been previously conducted on a close monument to the Obelisk Tomb, the Djin Block No. 9 (Cabrelles et al. 2009; Lerma et al., 2010a, 2011a). Another study revealed flaking on the Cambrian sandstone, severe lack of material on areas affected by direct insulation, and last but not least, a correlation between temperature
values and areas with high calcium content, especially at the bottom of the south eastern side (Akasheh et al., 2005).

The thermal images enhance some architectural details such as the borders of the obelisks, arcosolium, doorways, pillars, pilasters and columns. This is not surprising since the edges tend to warm up and cool faster than the bulk of the rock mass. Some spots were selected to analyze the variation of temperature during the day as well as the thermal stress (Fig. 11). Figure 12 shows the temperature variation for seven samples at different times during a day: in the morning at 8:35, after midday at 13:25, and two in the afternoon, one at 16:25 and another at 18:28. Due to the northwest orientation of the front, the first shot was on shadow and the last three under sunny conditions, although the second one at 13:25 hardly started to be hit by the light. Fig. 11 displays the presence of shadows on the monument at 18:28. Table 1 shows the variations of temperature for these spots considering 8:35 as starting value.

Figure 11. Spots measured on the Obelisk Tomb

Figure 12. Temperature variations on the Obelisk Tomb
The measured spots are lowest in the morning and highest in temperature at 4:25 pm. From the lowest till the highest there is a steady increment. The maximum temperature values (determined after interpolation) are around 16:00. After that time, the temperature values clearly decrease despite the fact that the sunlight is still affecting the monument. Spots 3 and 6 have the highest temperature values. As regards temperature differences, Spot 6 gets the maximum between 8:35 and 16:25, 12.9 ºC, due to its western orientation (outside the Obelisk and with no carvings), followed by Spots 7 and 10 both at the upper parts of the obelisks, with 11.6 ºC and 11.4 ºC respectively. Clearly the temperature behaviour at the obelisks is similar and with close absolute and relative (delta) temperature values. Spots 8 and 9 yield the minimum deltas during the day owing to their placement in the centre and on the bulk of the rock, most of the time on shadow; the latter spot is the only one that behaves anomaly with the measurements at 18:30 (all the temperature values go down except for this spot). Its anomaly can be explained because that area in particular is most of the times on shadow, except late in the afternoon. Furthermore, it can be stated that the minimum thermal stress is suffered by the bulk of the rock, being its minimum on Spot 8, followed by Spots 3 and 9.

The left-hand side surfaces of the monument have large alveolar holes owing to the Eolian wind. Attempts to correlate damage with this parameter failed to yield any consistent results. In Djin Block No. 9, insulation was proved to be a less relevant factor on the actual weathering, whereas water and wind were found to be more important (Akasheh et al., 2005; Heinrichs, 2008). A more promising approach has been recently reported in Lerma et al (2010a) using visual, and repetitive thermal measurements with statistics. However, the results regarding the eastern façade were not definitive because of a lack of data early in the morning (before sunrise) for that particular façade. Furthermore, there might be a correlation between the temperature values on the stone spots and the salt infestations.
4. Discussion

The common way to carry out documentation in cultural heritage is with either visible image-based solutions or with terrestrial laser scanning; the latter since 2000. There is little literature in which authors compile all the surveying and multispectral imagery together especially in 3D. In the research presented herein, the integration of all sources of imagery available (visible, NIR and TIR) has been registered and warped to deliver different photorealistic products coming from just one 3D model.

As regards thermography, the data acquisition from different times permits not only the analysis of thermal contrast but the visualization of different features or alterations coming from the same object (Lerma et al., 2011b). In this study, the thermal images were useful to measure temperatures as well as temperature differences, but not to create false colour compositions as reported previously by the authors (Lerma et al., 2011a). The reason of the latter statement was not only the low resolution of the thermal camera compared to the visible and NIR ones but the image scale due to the contextual factors: a riverbed crossing the Obelisk Tomb and the Bab As-Siq Triclinium.

Considering NIR false colour images, the results are promising as far as vegetation information is expected to be retrieved. NIR information complements colour visible imagery, and should be considered more in cultural heritage documentation as reported in Akasheh (2000). Probably better results would have obtained with a truly NIR digital camera. Due to economic restrictions, the NIR images acquired herein were acquired with a high-resolution but visible digital camera and a low-cost gelatine filter instead of a high-resolution NIR digital camera with NIR filter. Better results are even expected either with a dedicated NIR camera and multiple narrow-band filters for NIR photography or with a hyperspectral imaging sensor.

Another important point worth discussing is the power of the 3D dynamic visualization compared to the static 2D images. But a right dynamic interaction requires perfect fitting between images, i.e. an appropriate co-registration. More and more, images are coming from different sensors, with different spatial orientations, taken probably at different weather conditions, and last but not least, at different periods of the year. The best co-registration results will be obtained from truly multispectral or hyperspectral sensors, acquiring all sorts of information from the same viewpoint, in a way that all the multiples bands are perfectly co-registered together. However, the disadvantage of this latter high-end equipment is two-fold: the spatial resolution and the cost of the equipment. Regarding the former, the resolution of these systems is still low for the documentation of large and complex
monuments and sites as the one presented herein. Regarding the latter, the equipment is still too expensive.

The potential of terrestrial laser scanners is enormous to deliver quickly accurate 3D point clouds from which 3D models can be delivered. More and more, the equipment is becoming lighter, smaller, faster and even more accurate. Alternatively, image-based 3D modelling is also a true alternative nowadays (Remondino and El-Hakim, 2006; Barazzetti, 2010). Independently of the range-based and/or image-based approach followed to deliver an accurate 3D model, or better, a photorealistic 3D model, 3D models allow users to monitor over time complex monuments with high accuracy, difficult to reach by other means, despite other cheaper solutions are also possible based either on stereo-photographs or on image-based assisted total station.

5. Conclusions

Documentation of cultural heritage requires the synergy of experts and technologies to study large complex areas such as the Petra Archaeological Park. The research presented herein allowed us to enhance the 3D documentation and 3D monitoring of the Obelisk Tomb owing to the integration of multispectral content and laser scanning data. The effective integration of multi-source data can play a major role in the documentation and the interpretation of our cultural heritage. In this particular research, the multispectral content included visible, near infrared and thermal infrared imagery. The series of thermal images were also used to analyse the thermal contrast and the behaviour of materials and alterations on the Obelisk Tomb.

This kind of analysis is extremely useful to achieve a true representation of the existing condition of a complex object at a particular time. In case of series of data, accurate metric and thermal reports can be used to monitor the state of conservation and preservation of the monument. A combination and effective integration of state-of-the-art techniques can lead to accurate and quick results. Nevertheless, expertise is important to deliver highly realistic and accurate 3D models.

Among the several techniques used to document the stone monuments, the integration of multispectral image content and terrestrial laser scanning shows that there is potential to be a major tool to improve cultural heritage recording among professionals. It is worth mentioning the enhance capability to analyse complex carved architecture in 3D from normal and stretch false colour images. The recording of highly weathered monuments due to alveolar wind, flaking, cracks, efflorescence, vegetation and moisture, among others,
is enhanced by the combination of multispectral imagery and 3D models.

Further research is still necessary to improve the presented documentation approach: on the one hand, automating repetitive tasks such as warping and co-registration; on the other, analysing more spectral bands. Thus, the deliverables might be quickly delivered to information users such as cultural heritage managers, conservators, archaeologists and architects to extract useful information for identification, conservation and restoration.

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REFERENCES


