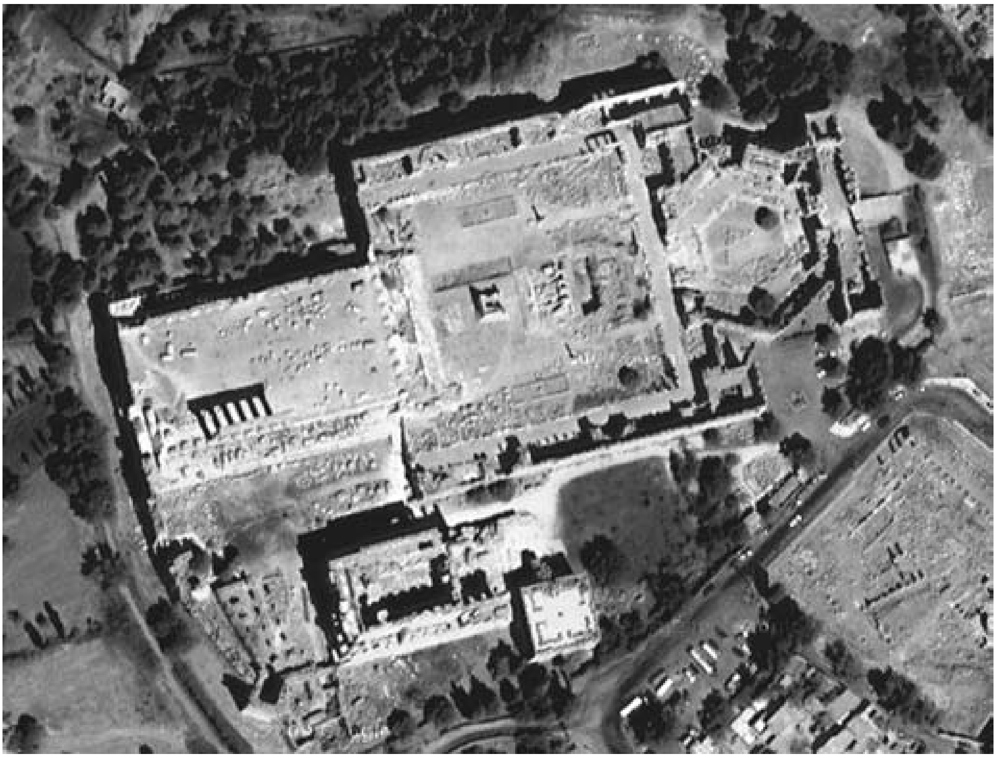

LASER SCANNING THE PAST FOR THE FUTURE

Baalbek Temple

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Figure 1. Aerial image of the Baalbek Sanctuary, Lebanon. (Google Earth)

This paper analyzes the use of 3D recording techniques as a basis for the generation of a risk preparedness strategy (RPS) for Baalbek (Lebanon) as a UNESCO World Heritage Property. Both laser scanning and photogrammetric techniques were adopted in a project that was financed by UNESCO's regional office in Lebanon under the framework of capacity building of human resources for digital documentation of world heritage sites affected by the 2006 war in Lebanon. The project was executed by a multidisciplinary group of experts from Lebanon, Taiwan, and Belgium and underlines the appropriate identification and understanding of hazards and threats affecting the significance and integrity of Baalbek's archaeological site by means of a three-dimensional survey of the site.

This paper describes activities carried out by consultants from the Raymond Lemaire International Centre for Conservation (RLICC) at the University of Leuven, University College St. Lieven, and Lebanon's Directorate General of Antiquities (DGA) for a project administered by UNESCO's regional office in Lebanon called "Capacity building of human resources for digital documentation of World Heritage Sites affected by the 2006 war in Lebanon." The project was a donation by the United Nations to Lebanon and aimed at building capacity of human resources in charge of, or potentially linked with, the conservation, development, and enhancement of tangible cultural heritage in Lebanon.

An initial analysis of the site provided an identification of five main threats for Baalbek: total disappearance (following, for instance, a natural catastrophe like an earthquake of large magnitude, war, or massive bomb explosions), complete or partial collapse (earthquake, storm, vibrations due to the local music festival), structural deformations, loss of components (robbery, biological attack, weather erosion, air pollution), and human safety (exposure to open excavation trenches, collapse).

The main beneficiaries of this project are the DGA staff and a team of local surveying experts. The main subject of the project was to prepare a risk preparedness strategy (RPS) for Baalbek's World Heritage Site, which is threatened by its environment through war, tourism, and seismic activity. Through an on-site pilot project, innovative 3D acquisition techniques were used and their effectiveness in providing the deliverables required to generate an RPS was analyzed.

In a time frame of 6 months spread over a 1.5-year period, the RLICC as international consulting institution was in charge of:

- Training local experts in archaeology and surveying on heritage documentation, and especially on laser scanning recording.

- Procuring and monitoring the laser scanning survey by providing training in the integrity and accuracy of the measurements obtained with a laser scanner.
- Creating guidelines and recommendations for preparation of 3D models and recording for future monitoring of the property.
- Providing guidance and training on condition mapping of archaeological sites.
- Creating a risk preparedness strategy for the site of Baalbek.

The RPS for Baalbek is meant to be a tool to help the site managers prevent or reduce the negative impacts of threats on the significance and integrity of the property and on human life.

The project was divided into two parts. The first part focused on the acquisition of a complete three-dimensional survey of the site's geometric configuration using laser scanning. Although previous measurements were made by different institutions, among them the German archaeological institute and ARS Progetti, their documentation consisted of hand-measurements, rapid-recording, and historical research of the site and as such did not provide sufficient information to conceive a risk assessment study.

Subsequently, the second phase aimed at analyzing the use of laser scanning data as an accurate 3D acquisition technique to provide optimum baseline information for a risk preparedness strategy. Because of the limited time frame, only a pilot area was analyzed. The proposed deliverables were true-color orthophotographs, which are in fact orthogonal projections of the 3D data resulting in elevations with additional color information that could then be used to map the surface conditions, and a complete three-dimensional model for structural analysis of conditions relating to both seismic and human threats (e.g., tourists, war). Future recording is proposed every three to four years to be able to monitor significant displacements of the structure. The required accuracy for these purposes was discussed among the experts and was set to a one-centimeter change detection in a one-square-meter area.

Description of the Archaeological Site

Baalbek, with its colossal structures, is one of the finest examples of Imperial Roman architecture at its apogee.[1] The site has a long history, which is well represented by the remains. Archaeological findings show evidence of human occupation as early as the Early Bronze Age (2900–2300 BCE).[2] The property was inscribed on the UNESCO World Heritage list under criteria I and V in 1984.[3] It is a masterpiece of Roman "baroque style" and comparable to the Temple of Artemis at Gerasa, Jordan; the Temple of Bel at Palmyra, Syria; and the like; however, its grandiosity and architectural elaboration differentiates Baalbek from these other sites.

The erection of the temple possibly began during the time of Augustus with an imperial initiative. Enlargement and improvement of the sanctuary continued until the third century CE. The uncovered site consists of the Jupiter Sacred Complex, composed of the propylaea, the hexagonal court, the grand court, and the Jupiter temple, of which only six columns remain standing. The complete sanctuary is approximately 120 m wide and 400 m long, progressively raised to create a dramatic effect for the approaching visitor. To the south of the Jupiter temple, the Bacchus temple was erected, which was transformed into a huge castle in Ayyubid times. Due to the restricted time frame and also because of previous analysis of the site including the Bacchus temple, the scope of this project was limited to the Jupiter Sacred Complex.

Data Acquisition: Capturing the Fabric's Geometric Configuration

Recent developments in digital visualization and sensor technology have led to an emerging awareness of their benefits and uses for the geometrical recording of objects in many disciplines. In general, all these techniques use some form of light source and can be divided into two categories: active (laser scanning) and passive (photogrammetry) techniques. A detailed comparative evaluation of active and passive recording techniques has been published by El-Hakim.[4]

Active scanners emit a form of controlled radiation and detect its reflection in order to probe an object or environment. Laser scanners are typical examples of active scanners. An overview of the principles of laser scanning, which largely affect the accuracy, can be found in Blais.[5] In spite of their high cost, their very simple and fast acquisition has led to their widespread use in the heritage community. Although laser scanning offers many possibilities, generating appropriate deliverables still requires an intensive manual processing phase. Therefore its use should be justified by the goals of the project. As we will conclude, the main discovery in this project was that the software available for processing the laser scanner data is not yet optimized for the delivery of conventional products expected for assessment by the heritage specialist.

On the other hand, passive scanners do not emit any kind of radiation themselves, but instead rely on detecting reflected ambient radiation such as visible light. Passive methods can be very inexpensive because they often do not need any particular hardware other than a digital camera. One major problem, however, is that they rely on finding spatial correspondences between 2D images, which is sometimes ambiguous. For example, repetitive patterns tend to "fool" the correspondence search, resulting in falsely reconstructed 3D points. The accuracy of these methods depends mostly on the lens characteristics, the resolution of the imaging system, and the density of identifiable features (texture) in the image.

A wide range of applications in cultural heritage documentation benefits from the three-dimensional recording and modeling of real-world objects and scenes. Generally, the application itself involves certain requirements such as the level of accuracy, the required detail, and the level of photorealism.[6] However, because of budget restrictions and lack of competence, additional specifications such as full automation, low cost, portability, flexibility, and efficiency are often desirable.

For the Baalbek project a combination of laser scanning and photogrammetry was chosen to address the restricted time frame (30 days) and the different object scales of the site. Laser scanning was used to acquire the major structures, while close-range photogrammetry was used to reconstruct some of the most important sculptures within the site. The combination of both techniques leads to an accurate recording with proper detail that can be used for archiving, structural analysis, condition mapping, or the generation of “as-is” plans of the site. The remainder of the paper addresses the subsequent phases of the project.

Phase 1: Reconnaissance

The first phase of the project was a reconnaissance phase. The recording project scope was analyzed by assessing the complexity of the physical configuration of the site. This involved making test scans in different areas using different recording resolution. In close collaboration with heritage specialists of the DGA, an appropriate level of detail (resolution) was agreed on, taking into consideration the project scope (risk assessment), time frame, and available funds. Based on the physical condition and importance of the surfaces, differentiation was made between the general physical configuration of standing structures, which were scanned at a resolution (point-to-point distance in a point cloud) of 2 cm, and structural surfaces that contain high ornamental detail and are in danger of degradation, which were scanned at a 5-mm resolution. When choosing the resolution it must be noted that most laser scanners work with an angular type resolution setting. This means the intermediate angle between scan points is fixed using the resolution at a certain distance, the probe distance. As such all points lying closer than the probe distance will be closer together (higher resolution), while all points beyond the probe distance will be further apart. Therefore chosen resolutions were always defined on the farthest probe point in the field of view of the scanner. This point is defined by probing several points in the scan area and choosing the furthest one.

Furthermore, scan stations were defined. As the DGA staff did not have any experience with laser scanning, all stations were planned beforehand. Each station was marked on a 2D map together with the field of view to be scanned. Taking into account the effects of heat and the lack of power sockets for the laptop and the scanner, it was decided to make approximately six scans a day. Some scans covered a field of view of 360 degrees, while others were focused scans on specific detailed areas. Since the scanner converts the resolution setting to an internal angular resolution, the resolution of points for example on a nearby wall will change drastically when comparing the points close by to those further from the scanner. In this case, in order to get a proper spread of points, which is better for the postprocessing of the data, the scanner’s field of view had to be split into multiple parts defining a new resolution for each subsection.

Phase 2: Control Network

The second phase was to set up a survey control network to connect, link, and merge the laser scanner data. This network ensures the integrity of the different sets of data, as well as the fact that the scan data from each day can be registered to a global coordinate system. The control network was divided into an inner network inside the temple and an outer network outside the temple. Both networks were interconnected at certain areas and a full network adjustment resulted in a strong, robust control network.

Additionally, the purpose of this control network was to provide a means of monitoring changes affecting the integrity of the property over the years. Since the Baalbek site is situated in a seismic area, it is important to monitor the movement of certain structures to ensure the safety of visitors but also to ensure structural stability in the event of a man-made or natural disaster. It is planned to carry out regular scanning of specific critical areas every five years in order to detect any movement before collapse.

Phase 3: Laser Scanning

The laser scanning was done using a Leica Scanstation 2 by the DGA team in cooperation with an external local surveying company.[7] This type of scanner is the latest generation of scanners able to scan from 200 to 300 m with a scan rate of 50,000 points per second. The planned six scans a day did not seem to be a problem; however, the heat severely affected the accuracy of the scans. In some scans it can clearly be seen that thermo columns of hot air refract the laser beam, resulting in excessive noise in the final point cloud. In order to overcome this problem, scanning was mostly performed early in the morning. Scans containing this type of problem were redone at another time.

At the start of the project it was identified that heat had an important impact on target precision. Several scan targets were placed strategically to be visible from all recording positions of that day in order to be able to register all scans tightly. These targets were surveyed from the control network so as to integrate each day of scanning into a complete data set of the site. However, since the temperature changed dramatically during the day, these targets moved slightly because they were exposed to direct sunlight. In order to partially solve this problem, targets were covered with pillow covers. All targets used for registering the scans were scanned both at the beginning as well as at the end of the scan. Using both measurements, any movement of a target could be detected. As a minimum of three target correspondences are required for a registration, at least six targets were set up for each scan position so that in case of movement the respective target could be removed from the set. The final registration of all scans of the whole project had an RMS (root-mean-square) error of 2 mm, and the maximum individual error for the constraint did not exceed 3 mm. As the scanner itself guarantees a per point accuracy of 4 to 5 mm, it can be concluded that the overall accuracy of the scans was 5 mm.

The Leica Scanstation 2 has a built in photographic 5 MP camera. However, the camera does not have automatic exposure settings and the quality of the final images does not satisfy the needs required. Therefore a high-resolution digital reflex camera equipped with a fisheye lens mounted in the same position as the scanner eye was used to capture spherical panoramic images. The colors of these high-resolution panoramas were later mapped onto the point cloud data from the laser scanner to provide more information and texture of the physical configuration of the fabric.

Phase 4: Photogrammetry

Using the science of photogrammetry, images can be used to extract accurate measurements. Image-based methods are low-cost techniques able to recreate lost objects and monuments, preferably with regular shapes.[8] As these techniques require user interaction, their use is often limited to experts. Recently, algorithms to fully automate or semiautomate this process have been developed.[9] A thorough analysis of the accuracy of these automatic techniques is given in Remondino.[10] The fact that photogrammetry is closely related to human vision leads to a better interpretability of its principle. Today digital consumer cameras are a part of our daily lives and the images are accepted as a normal way of storing visual data. They are lightweight and allow for a quick and easy way to capture a building's visual appearance. Although digital images are arrays of pixels, they contain more information than just the position of these pixels in the image. Differences in color and luminance allow us to identify and classify objects and detect high-contrast edges, which often indicate the location of surface discontinuities.[11] This ability differentiates between a photogrammetric measurement and a laser scanner survey. Laser scanners sample surfaces, as such they are not good at identifying fine edges or specific points. Nevertheless, state-of-the-art photogrammetric techniques tend to automate the photogrammetric process, especially in the selection of corresponding points, and deliver point clouds similar to those derived from a laser scanner. More intelligent systems try to incorporate edge information to refine the resulting point cloud.

In order to capture some of the sculptures on the stones that were scattered over the site, tests were performed using photogrammetric reconstruction. Several stereo shots were taken of detailed ornaments using a precalibrated camera. These stereo couples were then processed in a software called PhotoStruct, which is part of the Studio Clouds software from the AliceLabs[12] company. This system performs dense stereo matching and generates point clouds based on photographs similar to those of a laser scanner. The resulting point clouds are very detailed and provide a good documentation tool; however, for now the software is only able to work with stereo pairs. This implies that a full reconstruction can only be composed out of multiple stereo pairs from which a 3D model is reconstructed and that are registered using a cloud-to-cloud registration algorithm that can be found in the Studio Clouds software. As already mentioned, the processes used in this kind of software rely on sufficient texture in the scene and automatically try to find corresponding pixels in different images. This matching process can sometimes be fooled by lack of texture or repetitive structures resulting in noise in the final point cloud.

The result of this process needs some postprocessing (cleaning and meshing), but the final result is a point cloud similar to that of a laser scan. The accuracy of the photogrammetric survey is in the order of 2 to 3 cm (depending on the distance of the scene to the camera) and is as such lower than the accuracy of the laser scanner. Both data sets (the laser scanner data and the photogrammetry data) can be seamlessly combined, providing a better understading of the texture, color, and geometry of the fabric, which is a precondition to understanding the surface integrity.

Postprocessing

A lengthy postprocessing phase was necessary to generate useful data representations that could be used for risk assessment. The main deliverables of this phase were orthophoto-

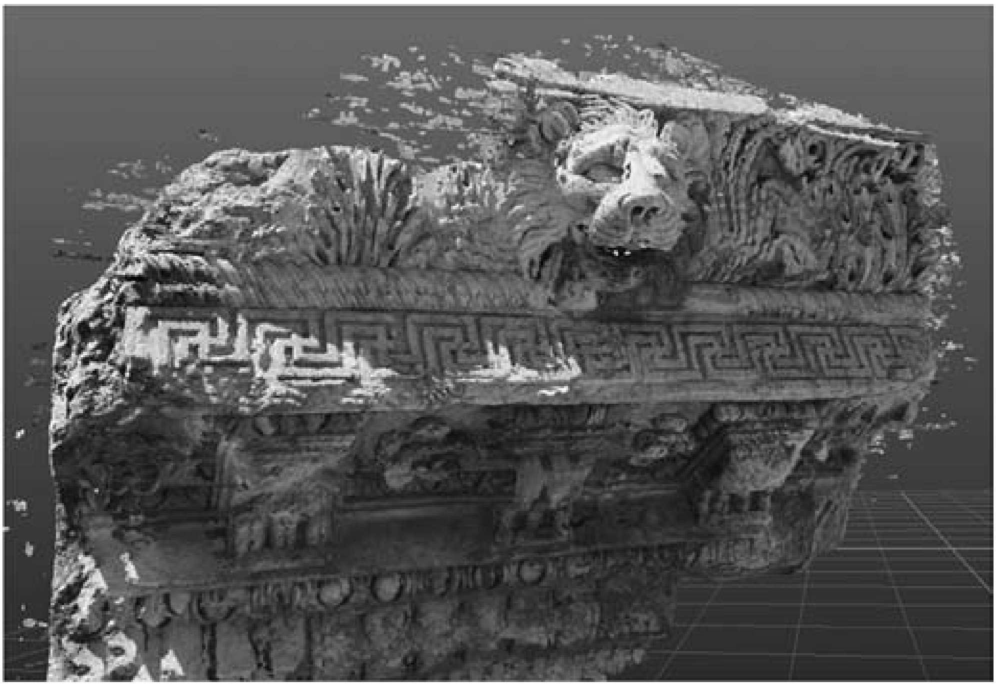

Figure 2. Photogrammetric reconstruction of a sculpture using PhotoStruct (Alice Labs). (Björn Van Genechten)

graphs for condition survey (construction material and weathering forms) and 3D meshed models for later structural analysis.

Generating Orthophotographs

Several methods for creating orthophotographs from laser scanning data exist. They all require the geometry of the object to be described in the form of a mesh. As the time frame was very limited, it was decided to generate the orthophotographs directly from the point clouds using the Leica Cyclone software. Alternatives to the lengthy mesh creation were suggested by Georgopoulos and Natsis[13] and Van Genechten,[14] however, these algorithms were not considered here.

The first problem to consider was the mapping of the high-resolution panoramas onto the laser data. For each of the scanner positions, the respective panorama was mapped to the point cloud using Leica Cyclone. Unfortunately Cyclone needs the user to manually pick at least three point correspondences between the cube map images (created from the panorama) and the point cloud. This process takes around 5 minutes per panorama. Bearing in mind that the whole data set contains over 150 scans, this mapping process alone is already time consuming. The slightest parallax is visible in the mapped cloud, as Cyclone does not perform any type of visibility analysis. Once all scanworlds are color mapped, they can be registered.

In order to create an orthophotograph based on the laser data, Cyclone provides an

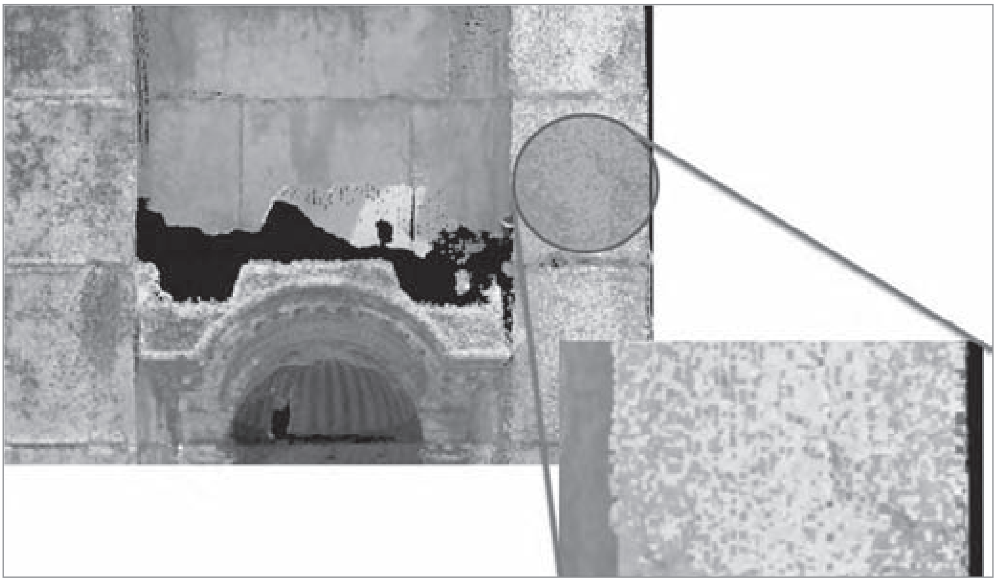

Figure 3. An orthophotograph created using Leica Cyclone; a problem with colors results in noise. (Björn Van Genechten)

orthographic camera tool. To ensure the proper view is created, we start by defining the plane for which we want to create the orthophotograph based on three points. Then we set up a new coordinate system using this plane and align the viewpoint of the orthographic camera with this coordinate system. To get the correct scale, we calculate the proper resolution of the orthophoto versus the size of the displayed image. Finally, the point thickness can be altered in order to close small gaps in the point cloud due to lack of point cloud resolution. However, special care needs to be taken when using this option as some blurring may occur in areas which actually do have sufficient resolution.

A major issue in the production of orthophotographs using this approach was that the final orthoimages were composed out of different scans. Each of these scans was taken at a different time of the day as were the high-resolution panoramic images. The large differences in color between different scanworlds were not relevant in the 3D point cloud; however, in the final orthophotographs this resulted in significant noise, as shown in Figure 3.

A suggestion from the Laser Scanning Forum[15] was to take HDR photographs and use tonal mapping to get better images. However, since the images were already taken, this was not an option. Therefore a procedure was developed to overcome this problem in spite of the loss of resolution. For each scanworld (colored by a different panorama) a set of layers was created. The scanworld containing the maximum visible area of the structure for that particular orthophoto was taken as a starting point. Then the missing parts of that scanworld were filled in using pieces coming from other scanworlds. This method makes sure that there is no mixing of colors originating from different scanworlds. However, there is a severe loss of resolution and the final orthophotographs may look like a

Figure 4. An orthophotograph created with Leica Cyclone using the layering principle. (Björn Van Genechten)

mosaicking of different exposed images. Therefore the final orthophoto was postprocessed using Photoshop in which colors were balanced. An example of a final orthophotograph is shown in Figure 4. Some areas in the orthoimage are empty as there was no scan data.

Meshed Model

An area of the temple was chosen as a pilot case to perform the full risk assessment procedure. This area consists of a semicircular room with niches containing many decorations still in relatively good condition. The laser scan data of this part was used to create a full surface representation using the software Geomagic.[16] As the total point cloud of the room consists of 30 million points and Geomagic can only create meshes of point clouds up to 5 to 10 million points depending on the hardware, the point cloud was first split into multiple sections containing approximately 15 million points. Then each section was

Figure 5. A mesh of the semicircular room created using Geomagic. (Björn Van Genechten)

intelligently resampled based on curvature information to a point cloud containing approximately 6 million points. Each section was then meshed, and finally all meshes were again registered together to get a complete surface representation as can be seen in Figure 5.

The meshed model was at its turn used to create two-dimensional sections, exaggerated depth maps, and normal maps, which could then be used for the structural analysis.

Risk Assessment

The risk preparedness strategy (RPS) focuses on a comprehensive understanding of the property's vulnerability and the identification of hazards and risks described during the condition and structural survey. Due to the constricted time frame, it was decided to limit the area of interest to the northwestern semicircular chamber of the Great Court.[17] This room was mainly chosen for its historical evolution (a part of the colonnade and the roof were restored) and the fact that the existing surface and structural pathologies of this room represent very much the characteristics of the whole site, as consequences of weathering conditions and earthquakes are visible. The information and approach developed in this specific area of the property will provide the DGA with a methodology used to study other areas systematically.

The RPS is based on the 3D digital laser scan data and is split in two parts: a structural analysis and a condition survey. As already mentioned, orthophotographs were created to be used as a mapping instrument for the condition survey.

All condition assessment surveys consist of the qualitative and quantitative recording that describes the type, location (macro or micro), status (active or inactive), extent, and degree of severity for each condition observed.[18] The condition survey can help with the understanding of the condition of the monument at a certain moment in time. The main

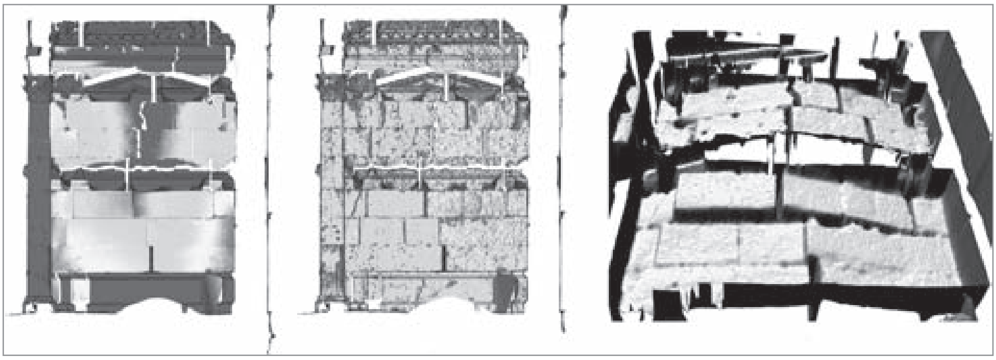

Figure 6. Derivatives from the mesh useful for structural analysis: color-coded depth map (left), normal map indicating the average direction of the stones (middle), and 3D view of an exaggerated depth map clearly showing the deformations in a wall (right). (Pierre Smars, National Yunlin University of Science and Technology, Taiwan)

benefit of using orthophotographs is that they provide both metric as well as nonmetric data. Together with an extensive condition survey, they can be used to compare the status of the structure at different times, for example, before and after a catastrophic event. For the site of Baalbek, the surface condition mapping was performed under the supervision of Dr. T. Patricio of the Raymond Lemaire International Centre for Conservation. In order to classify the pathology, the ICOMOS "Illustrated Glossary on Stone Deterioration"[19] and the Monument Damage Diagnostic System was used.[20] An example of an orthophoto including the pathological information from the condition mapping can be seen in Figure 7.

The pathological information was incorporated into a GIS database that allows more extensive analysis of the site and centralizes all the data. For now this database is only two dimensional; however, pilot tests were performed[21] to remap the pathology onto the 3D data, allowing an even better understanding of the structures' conditions based on the integration of pathology and geometry. Further investigation of the possibilities of this type of three dimensional GIS databases is necessary (see the paper "Terrestrial Laser Scanning" by Kottke, Hinchman, and Matero in this issue).

The structural analysis was performed by Dr. P. Smars of the National Yunlin University of Science and Technology in Taiwan. Using the laser scanner data, several "representations" are generated that provide an expressive description of the structural conditions of the room. Horizontal and vertical sections are made through the structure based on the mesh, which can be used to assess the stability of the walls (or parts of the walls) following transverse solicitations. The depth maps provide information about horizontal deformations and lack of verticality of the walls, and the normal maps give insight into the rotations of blocks. As the inside of the room is semicircular, the room was cylindrically unwrapped and isolines (lines of constant depth according to the cylinder center) were generated (see Fig. 8). All this information together with the results from the surface condition mapping, for example, the crack patterns and the surface degradations, provide

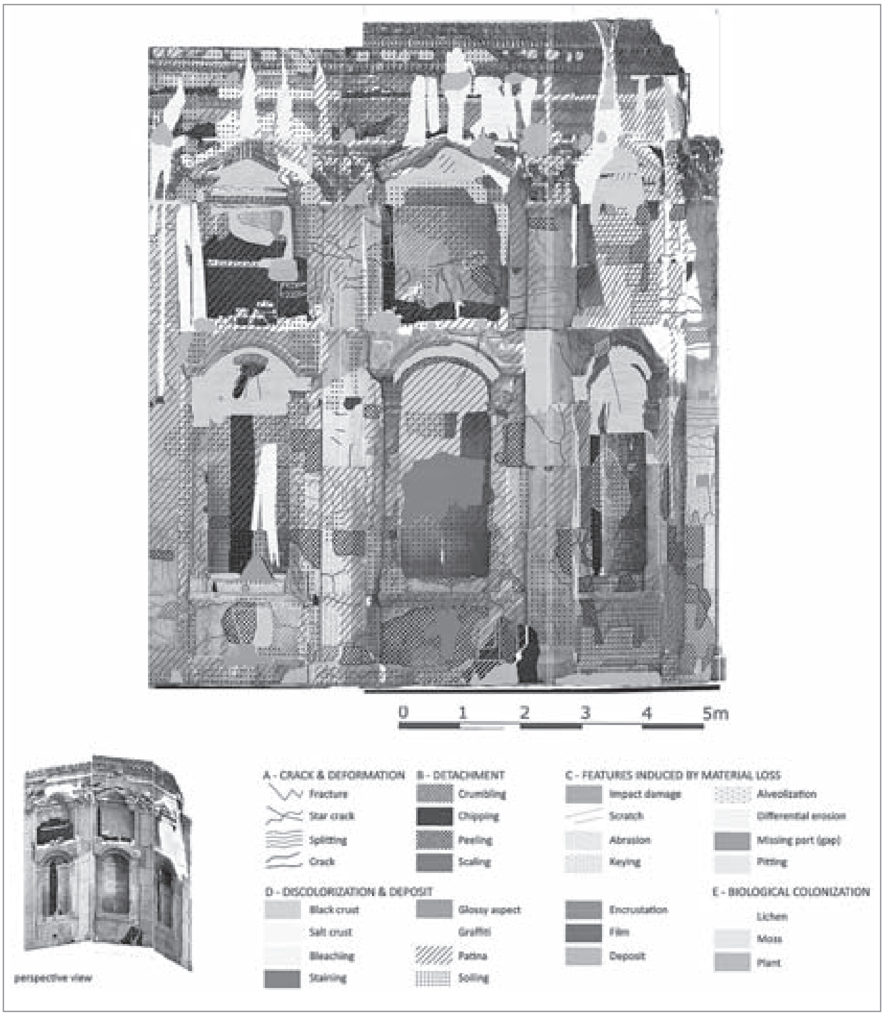

Figure 7. Example of surface condition mapping on an orthophotograph. (Teresa Patricio)

a better understanding of the structural behavior and allow an assessment of the structural safety of the room.

Conclusion

Recording of heritage places is an important phase during the whole process to protect, conserve, and preserve. Both surface condition mapping and a structural analysis provide insights and understanding of the structure, allowing the preparation of comprehensive risk preparedness strategies. Laser scanner data can provide a quick and reliable base to map the "physical configuration" of the property's fabric.

However, the project scope definition in the use of laser scanner data should ensure that it is useful to understand the surface condition and provide information to perform structural analyses. This is a lengthy and costly process, which is often disregarded but should be considered as an essential part of the heritage documentation process. A good

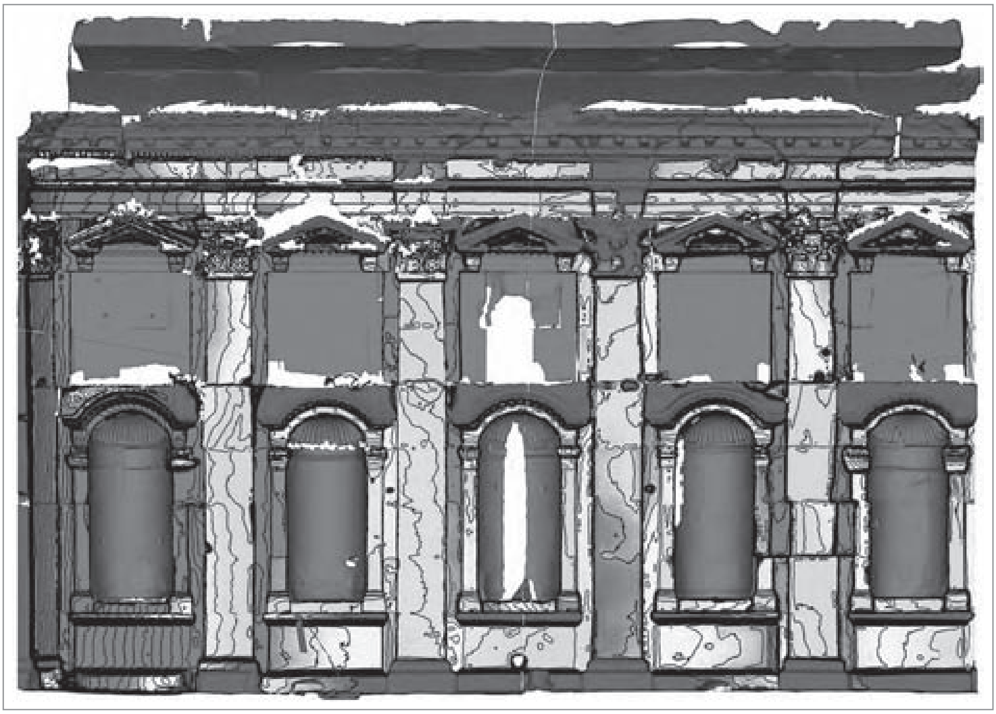

Figure 8. The cylindrical, unwrapped interior of the semicircular room; color codes and isolines based on distance to the cylinder center. (Pierre Smars, National Yunlin University of Science and Technology, Taiwan)

knowledge of the possibilities as well as the constraints of the laser scanner are needed, both hardware and software based. The evolution of the hardware forges ahead as scanners are becoming much faster, more compact, and nowadays integrate high-resolution cameras allowing the capture of even more data in a shorter amount of time. The resulting data sets offer an enormous amount of information. However, because of the limitations in the current processing software, the justification of the use of this kind of equipment can be questioned. During this project, many problems have arisen showing the lack of proper algorithms for the processing of the data stretching from improper color balancing for the generation of orthophotographs to the incapability to work with large point cloud sets. Specifically for Baalbek, because of the limited time frame, the orthophotographs were created based on the point clouds only. This implies that the resolution of the final orthophotographs is limited to the resolution of the scanner, which normally is not a problem because one surface area is scanned from multiple positions, increasing the local point cloud resolution. However, in this project the color differences between different scans forced the team to work with single scans only resulting in low-resolution orthophotographs, which were not always easy to use for the condition survey, as the cracks and surface deteriorations were not always clearly visible in the orthophotographs. The derivatives generated from the surface mesh did represent the structural integrity and were a valuable tool in making informed decisions concerning the risk preparedness strategy.

Although the third dimension is not always necessary and perhaps other surveying techniques such as simple photography will suffice for regular condition mapping, laser scanning allows for a better understanding of the structure and provides an incredibly detailed baseline survey that can be exploited further in the future.

The authors believe that this type of project is necessary to bring forward the requirements of the heritage community so that both hardware and software companies can elaborate on this and work on developing better, more efficient applications fulfilling the needs of the heritage sector.

References

1. "*Description of Baalbek,*" UNESCO World Heritage Centre (2010), http://whc.unesco.org/en/list/294/ (accessed 9/30/2009).
2. F. Ragette, *Baalbek* (Park Ridge, N.J.: Noyes Press, 1980).
3. *"Eight Ordinary Session-Reports,"* World Heritage Committee (WHC), 198, http:// whc.unesco.org/archive/repcom84.htm#294 (accessed 7/17/2010) and http://whc.unesco.org/en/list/294/ (accessed 7/17/2010).
4. S. F. El-Hakim, J.-A. Beraldin, and F. Blais, "A Comparative Evaluation of the Performance of Passive and Active 3-D Vision Systems," paper presented at the SPIE Conference on Digital Photogrammetry, St. Petersburg, Russia, 1995.
5. F. Blais, "Terrestrial Laser Scanning," paper presented at the International Summer School Digital Recording and 3D Modeling, 2006, http://www.photogrammetry.ethz.ch/summerschool/pdf/09_Blais_Terrestrial_Laser_Scanning.pdf (accessed 12/19/2007).
6. S. F. El-Hakim, "Semi-Automatic 3D Reconstruction of Occluded and Unmarked Surfaces from Widely Separated Views," *International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences* 34, no. 5 (2002): 143–48.
7. Leica Geosystems Website, Scanstation 2, http://hds.leica-geosystems.com/en/Leica-ScanStation-2_62189.htm (accessed 8/17/2010).
8. F. Remondino and S. El-Hakim, "Image-Based 3D Modeling: A Review," *The Photogrammetric Record* 21, no. 115 (2006): 269–91.
9. M. Vergauwen and Van Gool, "Web-Based 3D Reconstruction Service," *Machine Vision Applications (MVA)* 17 (2006): 411–26; S. F. El-Hakim, F. Remondino, L. Gonzo, and F. Voltolini, F. (2007). "Effective High Resolution 3D Geometric Reconstruction of Heritage and Archaeological Sites from Images," paper presented at the 35th Annual Conference on Computer Applications and Quantitative Methods in Archaeology (CAA Berlin, 2007); F. Remondino, "Detailed Image-Based 3D Geometric Reconstruction of Heritage Objects," paper presented at the Trinational Conference of SGPBF, DGPF, OVG (Muttenz, Switzerland, 2007).
10. F. Remondino and F. Menn, "Image-Based Surface Measurement for Close-Range Heritage Documentation," *International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences* XXXVII, part B5–1 (2008): 199–206.
11. E. Baltsavias, "A Comparison between Photogrammetry and Laser Scanning," *ISPRS Journal of Photogrammetry and Remote Sensing* 54, nos. 2–3 (1999): 83–94; M. Fradkin and U. Ethrog, "Feature Matching for Automatic Generation of Distortionless Digital Orthophoto," paper presented at the Integrating Photogrammetric Techniques with Scene Analysis and Machine Vision, 1997; N. Haala. and K.-H. Anders, "Acquisition of 3D Urban Models by Analysis of Aerial Images, Digital Surface Models and Existing 2D Building Information," paper presented at the SPIE Conference on Integrating Photogrammetric Techniques with Scene Analysis and Machine Vision III, 1997.
12. Alicelabs website, http://www.alicelabs.com/ (accessed 8/17/2010).
13. Andreas Georgopoulos and Natsis Stefanos, "A Simpler Method for Large Scale Digital Orthophoto Production," in *The International Archives of the Photogrammetry, Remote sensing and Spatial Information Sciences*, Vol. 37, Part B5, Commission V, WG V/2 (2008).

14. Björn Van Genechten, "Creating Built Heritage Orthophotographs from Laser Scan" (Ph.D. diss., Katholieke Universiteit Leuven, 2009).
15. Laser Scanning Forum, http://www.laserscanning.org.uk/ (accessed 8/17/2010).
16. Geomagic website, http://www.geomagic.com/en/ (accessed 8/17/2010).
17. Teresa Patricio, Report on Activity 3 & 4. Mission in Beirut and Baalbek. Under the scope of the "Capacity building of human resources for digital documentation of World Heritage Sites affected by 2006 war in Lebanon" project (2010).
18. Frank G. Matero, "Managing Change: The Role of Documentation and Condition Survey at Mesa Verde National Park," *Journal of the American Institute for Conservation (JAIC)* 42 (2003): 39–58.
19. ICOMOS-CSI, "Illustrated Glossary on Stone Deterioration Patterns" (Monuments and Sites XV) (ICOMOS International Scientific Committee for Stone [ISCS], 2008).
20. Teresa Patricio, "Surface Condition," Final Report. Baalbek, Lebanon-Great court North-Western semi-circular room. Under the scope of the 'Capacity building of human resources for digital documentation of World Heritage Sites affected by 2006 war in Lebanon' project (2010).
21. Liesbeth Lacroix, "The Use of Terrestrial Laser Scanning for Condition Mapping of Historical Sites, from Point Cloud to Orthoimage" (master's thesis, KULeuven, 2010).