

IMAGE-BASED 3D MODELING OF THE ERECHTEION, ACROPOLIS OF ATHENS

Fabio REMONDINO^{1,2,*}, Sabry EL-HAKIM³, Emmanuel BALTSAVIAS¹, Michel PICARD³, Lazaros GRAMMATIKOPOULOS⁴

¹ Institute of Geodesy and Photogrammetry, ETH Zurich, Switzerland- (fabio, manos)@geod.baug.ethz.ch

² 3D Optical Metrology Group - Centre for Scientific & Technological Research (IRST), Foundation B. Kessler, Trento, Italy

³ National Research Council Canada, Ottawa, Canada - (Sabry.El-Hakim, Michel.Picard)@nrc-cnrc.gc.ca

⁴ Elliniki Photogrammetriki Ltd. (Elpho), Athens, Greece - lazaros.pcvg@gmail.com

Commission V, Special Session SS-19: Recording and documenting the Acropolis of Athens

KEY WORDS: Image-based Modeling, Photogrammetry, Matching, Cultural Heritage, Erechtheion, Athens Acropolis

ABSTRACT:

In this contribution, we report on the image-based modeling (IBM) results of the Erechtheion monument, located inside the Acropolis of Athens, Greece. The work is part of the project “Development of Geographic Information Systems at the Acropolis of Athens“. An aim of the project is the 3D documentation of the whole Acropolis, one of the major archaeological sites world-wide included in the UNESCO World Heritage list. The largest part of the monument was digitised with laser scanning, while the main objective of IBM was to model difficult-to- access areas not covered by the scanner but also for comparison with laser scanning for scientific investigations. For the 3D modeling, as the Erechtheion contains some typical architectural elements (like columns, flat walls, etc), some manual measurements were necessary. On the other hand, for some detailed areas automated approaches for dense surface reconstructions are applied. For these parts we compared the image matching results with the surfaces coming from a laser scanner.

1. INTRODUCTION

The digital documentation of cultural heritage monuments and sites is receiving great attention in the last decade and 3D modeling of objects or sites is one of the main research topics in this field. The employment of computer technology to create digital archives of cultural heritage and artistic objects with different characteristics and dimensions (monuments, archaeological sites or finds, architectural features, etc.) is due on one hand to the availability of new technologies for digitalization and investigation purposes and, on the other, to the increased interest of archaeologists and restorers to find an advanced system able to provide innovative investigations and documentations.

Indeed, many improvements have been done in the generation of digital models of monuments and artifacts, using range sensors or IBM. But there are still a lot of open questions and problems in deciding which technique should be employed in which situation. While in the past years, when high level of detail was required, range sensors were usually preferred to image data, nowadays, due to the considerable algorithm improvements and increase of automation in the image-based modeling process, the digitization of cultural heritage based on close-range photogrammetry is a viable alternative.

This work is part of the project “Development of Geographic Information Systems at the Acropolis of Athens“ (Moullou and Mavromati, 2007). Within this project, one of the aims is the generation of a textured, high-resolution, accurate 3D model of Erechtheion and a respective movie. The work is done in parallel with image and range data (El-Hakim et al., 2008). The

two methodologies are also integrated within the project but in this contribution we only report about the image-based 3D modeling of the Erechtheion monument.

We present and discuss the problems and challenges of data capturing, processing and model generation when dealing with a large complex structure with data acquisition under time constraints and adverse conditions.

1.1 Brief historical background

The following description of the Erechtheion story is based on the WEB site of the Greek Ministry of Culture (http://odysseus.culture.gr/h/2/eh251.jsp?obj_id=973).

Erechtheion (Figure 1) was erected in 421-406 BC as a replacement of an earlier temple dedicated to Athena Polias, the so-called “Old temple“. Its name derives from Erechtheus, the mythical king of Athens, who was worshipped there. The building owes its unusual shape to the irregularity of the terrain - there is a 3m difference in height between the eastern and western parts - and the multiple cults it was designed to accommodate. The sanctuary also contained the grave of Kekrops and the traces of the dispute between Athena and Poseidon for the possession of the city of Athens. The temple was made of Pentelic marble, the frieze of Eleusian grey stone with white relief figures attached to it and the foundations of Piraeus stone. On its east side, an Ionic portico with six columns sheltered the entrance to the east part of the building. On the north side is the entrance to the west part of the building, sheltered by a pi-shaped propylon with four Ionic columns

* Corresponding author.

along the facade and one on either side. Four Ionic columns on a high stylobate, with metal railings between them, adorned the west facade. Finally, another door on the south facade of the western temple opened onto the porch of the Karyatides (Maidens porch), a pi-shaped structure with six female statues, each different, instead of columns to support the roof. Five of them are in the Acropolis Museum and another in the British Museum; those at the building are copies. The temple burned in the first century BC and was subsequently repaired with minor

alterations. In the Early Christian period, it was converted into a church. It became palace under Frankish rule and the residence of the Turkish commander's harem in the Ottoman period. In the early nineteenth century, Lord Elgin removed one of the Karyatides and a column and during the Greek War of Independence the building was bombed and severely damaged. Restoration was undertaken immediately after the end of the war and again in 1979-1987, when the Erechtheion became the first monument of the Acropolis to be restored.



Figure 1. Different views of the Erechtheion. (a) South side with the porch of the Karyatides seen from the top of the Parthenon. (b) East and (c) North sides with the ionic columns. (d) West side with its (natural and "unnatural") occlusions.

1.2 Previous work

Some of the Acropolis of Athens large monuments have been surveyed and modeled already in previous research work. The most impressive results were presented in the computer animation movie *The Parthenon*, where all the different parts of the monument, spread in various museums and countries for over two centuries, were virtually reunited (Stumpf et al., 2003; Debevec, 2005). The models were created using laser scanners, structured light systems, photogrammetry and photometric stereo and rendered with inverse global illuminations. Lundgren (2004) conducted a project on digitising the Parthenon with a laser scanner at 1.2 cm resolution. For the Erechtheion, different studies were carried out. Blomerus and Lesk (2007) presented an AutoCAD-based 4D model of the entire monument. The model was based on paintings, drawing and old photos.

2. PROCEDURES AND REQUIREMENTS IN 3D MODELING

Nowadays, 3D modeling of objects and sites is generally performed by means of images or active sensors (like laser scanner or structured light projectors), depending on the surface characteristics, required accuracy, object dimensions and location, etc. Active sensors (Blais, 2004) provide directly 3D data. Active sensors, combined with color information, either from the sensor itself or from a digital camera, can capture relatively accurate geometric details, but they remain costly, usually bulky, not easy to use, require stable platform and are influenced by surface properties. They have limited flexibility, since a range sensor is intended for a specific range and volume. They may acquire millions of points, even on perfectly flat surfaces, often resulting in over-sampling, but it is likely that corners and edged are not well captured.

On the other hand, image-based methods (Remondino and El-Hakim, 2006) require a mathematical formulation to transform two-dimensional image measurements into 3D coordinates. Images contain all the useful information to derive geometry and texture for a 3D modeling application. Nevertheless, recovering a complete, detailed, accurate and realistic 3D textured model from images is still a difficult task, in particular for large and complex sites and if uncalibrated or widely separated images are used. Indeed (1) the wrong recovery of the camera parameters could lead to inaccurate and deformed results, while (2) wide baselines cause a challenge to matching techniques since they reduce geometric and radiometric (especially for marble) similarities between the images and cause occlusions. For many years photogrammetry dealt with the precise 3D reconstruction of objects from images. Although precise calibration and orientation procedures are required, suitable commercial packages are now available, mainly based on manual or semi-automated measurements (ImageModeler, iWitness, PhotoGenesis, PhotoModeler, ShapeCapture). After the tie point measurement and bundle adjustment phases, they allow 3D object point coordinates determination, as well as wireframe or textured 3D models generation. Fully automated approaches (Vergauwen and Van Gool, 2006; Goesele et al., 2007) are getting quite common in the 3D modeling community. Nevertheless, they are not yet fully reliable for the daily and precise documentation of objects from any kind of image sequence and no commercial software is yet available. On the other hand, automated surface measurement and object reconstruction from calibrated and oriented images is making great progresses and the latest results are promising (Remondino et al., 2008).

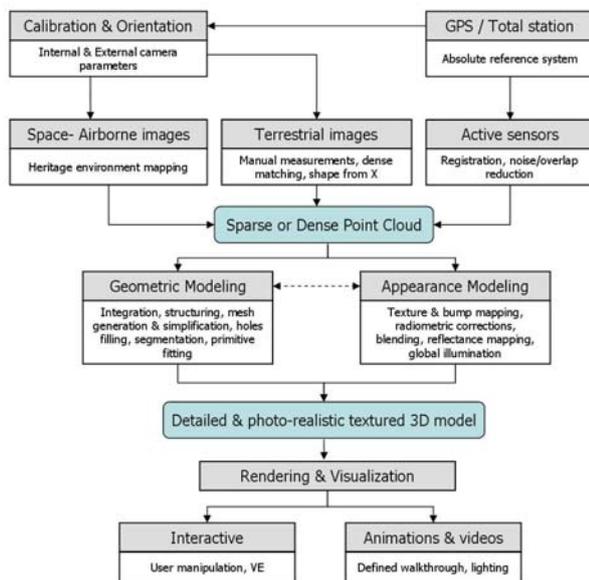


Figure 2. 3D modeling pipeline for Cultural Heritage objects and site.

Nowadays, to achieve a good and realistic 3D model, that captures the required level of detail, the better way is still the combination of the different modeling techniques. In fact, as a single technique is not yet able to give satisfactory results in all situations, concerning high geometric accuracy, portability, automation, photo-realism and low costs as well as flexibility and efficiency, image and range data are generally combined (El-Hakim et al., 2004; El-Hakim et al., 2007).

From our experience, and based on the current state of technology, in order to capture the information needed for the digital 3D documentation and conservation of large Cultural Heritage monuments, the resolution of the reconstruction in most parts must be about 5 mm with 1-2 mm on highly detailed parts, while for such details the accuracy should be about 1 mm.

For an interactive visualisation of the results, the 3D model must be viewable on a standard workstation with standard software, which limits the model resolution. A movie with photo-realistic colour and lighting is also required for dissemination and presentation of the detailed and full resolution models.

3. PROBLEMS AND CHALLENGES IN 3D MODELING

Modeling complex objects and heritage sites has challenges in every phase (Figure 3), from the data acquisition to the visualisation of the 3D results. In the following, we discuss the main challenges, in particular related to the image-based approach.

3.1 Data acquisition

The size, location and surface (geometry and material) of the object or site can create several problems. The dimensions and accessibility problems (due to location and obstructions) can cause delays, occlusions and can result in missing sections or enforce wide-baseline images and poor geometric configurations. The complexity of some parts creates self-occlusions or holes in the coverage, in addition to the occlusions from plants, trees, restoration scaffolds or tourists. The absence of high platforms for a higher location of the data acquisition might cause missing parts, in particular for the roof. Other limitations can include restrictions on using some platforms like UAVs, airplanes and helicopters, rough and/or sloped terrain also with stones, rocks and holes, unfavourable weather conditions etc., problems that have been encountered to one or the other extent in this Acropolis project. The object material, in this case marble, has an important influence on the results, both for image matching and laser scanning as it will be discussed below.

3.2 Data processing and point cloud generation

The cameras must be accurately calibrated, preferably in a controlled lab environment, with a 3D testfield and a bundle adjustment with additional parameters to fully compensate systematic errors (Remondino and Fraser, 2006).

As no commercial procedure is already available for automated markerless tie point extraction from terrestrial convergent images, the camera orientation phase is still highly interactive. For complex architectural objects, manual and semi-automated measurements are still much more reliable. For small areas or ornaments rich of details, dense matching or shape-from-X techniques can be instead selected to derive dense 3D point clouds.

3.3 3D modeling

Once a point cloud is available, a polygonal model (mesh) is usually generated to produce the best digital representation of the surveyed object or scene. This part is generally referred to as geometric modeling. Then photo-realism, defined as having

no difference between a view rendered from the model and a photograph taken from the same viewpoint, is generally required and obtained with the texture mapping phase. This is generally referred to as appearance modeling. Photo-realism goes much further than simply projecting a static image over the 3D geometry. Due to variations in lighting, surface specularly and camera settings, colour and intensity of an area shown in images taken from separate positions will not match. Measurement of surface reflection properties (BRDF) and illumination photometric measurements should also be included for better texture modeling. The images are exposed with whatever illumination existed at imaging time. This illumination may need to be replaced by illumination consistent with the rendering point of view and the reflectance properties (BRDF) of the object. Also the range of intensity, or dynamic range, in the scene can sometimes not be captured in a single exposure by current digital cameras. This causes loss of details in the dark areas and/or saturation in the bright areas, if both coexist in the scene. It is thus important to acquire high dynamic range (HDR) images to recover all scene details (Reinhard et al., 2005), e.g. by taking multiple images using different exposure times.

3.4 Visualisation of the 3D results

The ability to easily interact with a huge 3D model is a continuing and increasing problem. Indeed model sizes are increasing at faster rate than computer hardware advances and this limits the possibilities of interactive and real-time visualization of the 3D results. The rendering algorithm should be capable of delivering images at real-time frame rates, at least 20 frames-per-second, even at full resolution for both geometry and texture. For large models, a LOD approach should be used to maintain seamless continuity between adjacent frames. Luebke et al. (2002) and Dietrich et al. (2007) give a good overview of this problem.

4. IMAGE-BASED MODELING OF THE ERECHTHEION

4.1 Image acquisition and orientation

The image data were acquired with two SRL digital cameras: (i) a Canon 5D (12 MPixel) equipped with a 24 mm lens and 8.2 microns sensor pixel size; (ii) a Mamiya ZD Digital Back (22 MPixel) equipped with 45 mm lens and 9 microns sensor pixel size. Mamiya was used only for some test sites with a ground sampling distance (GSD) of 0.5 – 0.8 mm. The Canon was used for imaging and modeling the majority of the monument with a quite varying GSD. Both cameras were pre-calibrated in the lab, using the software iWitness (www.photometrix.com.au). The calibration of Mamiya was quite older than the time of image acquisition and thus not so accurate. The Mamiya images were employed mainly for modelling of the whole Acropolis from a balloon (will not be covered here) and in this work for research purposes, to test the potential of large format (48x36 mm) CCD cameras and to compare the image matching results from the two cameras and with the results from laser scanning. Thus, for Mamiya 6 test sites were selected and at each site, 5 images were taken, of which only the central 3 were used for matching (frontal and two convergent with an angle of about 22.5 deg). For the Canon images, only a few signalized and geodetically measured control points existed, due to limitations on targeting on a historic monument and difficulty to access the highest parts of the monument. These points were used to georeference

the final 3D model. For the Mamiya images, only a signalised scale existed (see Figure 8) and the surface models from these images were transformed to the model from laser scanning via the procedure described in Section 4.3. For practical reasons (mainly for manual modeling and use of few images), most of the images were acquired with wide baseline and relatively large convergent angles. This resulted in significant occlusions and light variations between the images.

4.2 Image quality and pre-processing

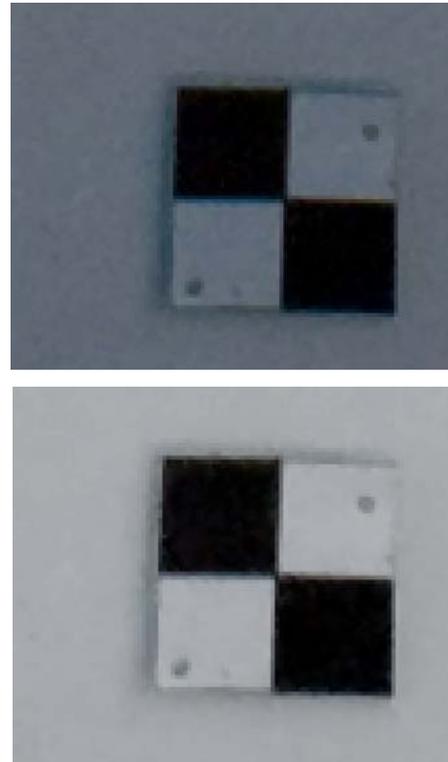


Figure 3. Top: original image with significant pattern noise visible in homogeneous areas and unnatural colour. Bottom: pre-processed image with noise reduction. Also the colour saturation was reduced and the brightness increased to generate more “natural” images (this however does not have an influence on matching). The images show a part of the used scale bar.

Typically, before applying the ETH matcher (Section 4.3) a Wallis filter (Wallis, 1976) is used to enhance the texture, brighten-up the shadow regions and radiometrically equalize the images, making matching easier. If the images are noisy, before Wallis, the noise is first reduced. While this was not necessary for Canon, Mamiya had significant pattern noise. In modern cameras, often sharpening functions are applied to make the image visually more appealing, this however increases the noise and introduces edge artefacts, both negative for automated image-based measurements. Thus, for Mamiya, first a strong noise smoothing was applied, but only to the lightness component not for the colour. Figure 3 shows a part of the original and pre-processed images. After this processing the R, G, B channels were inspected visually, and their histogram statistics examined. It came out that the blue channel had less noise, slightly better contrast and better definition of edges, with R being the worst channel. Thus, the B channel was selected for further pre-processing and matching.

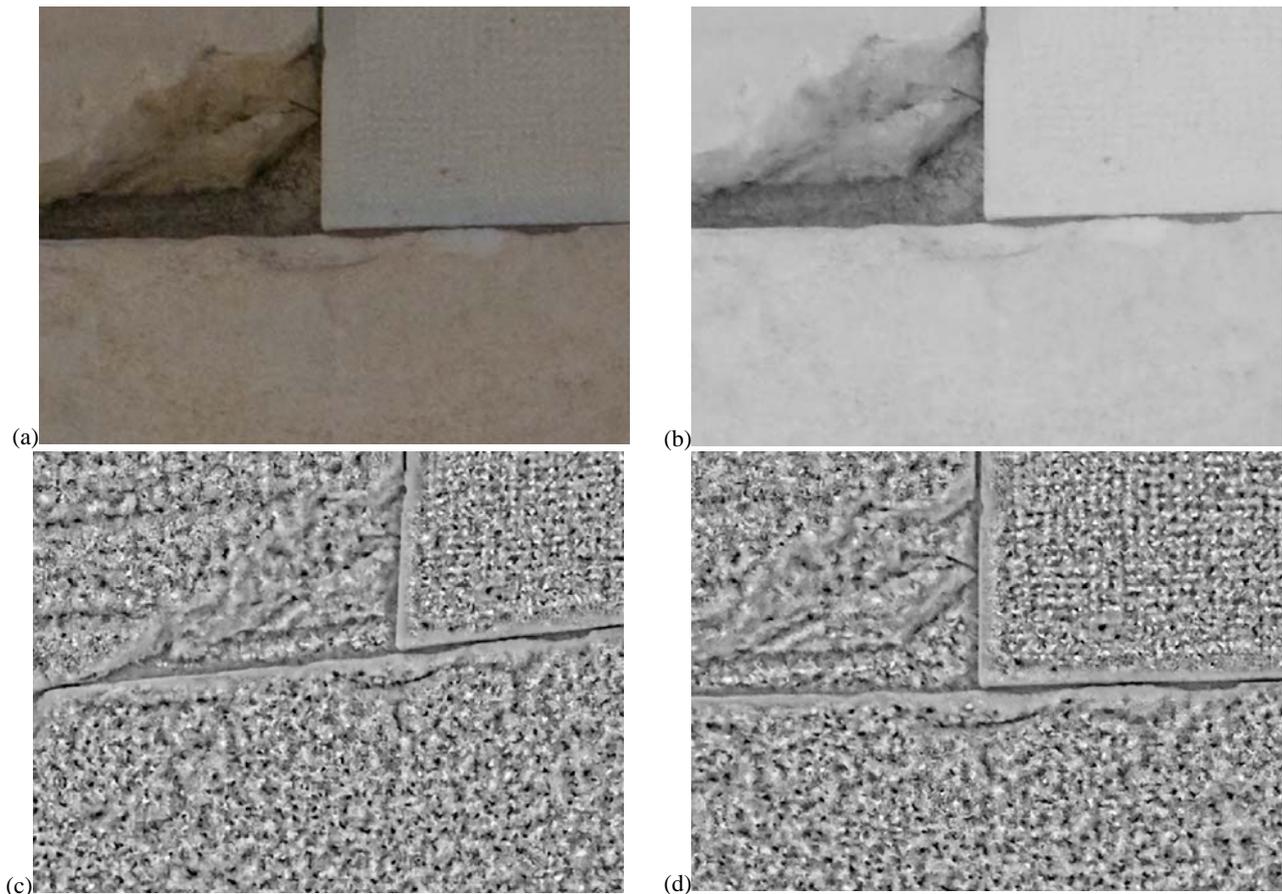


Figure 4. From top left clockwise. a) original image. The top right marble area is new with chiselled surface resulting in many repetitive bright dots. b) the blue channel of the noise-reduced image. Noise is reduced but also some signal is filtered out. The texture is very weak. c) Same as b) after Wallis filtering [Wallis, 1976]. d) same as c) with about 22.5 deg convergence angle. Note the good effects of Wallis mentioned in the text, and the small repetitive texture, which sometimes differ in c) and d) due to different viewing angle and marble properties.

For Mamiya, we tried three different parameter sets of the Wallis filter. Visual inspection of the matching results did not show any significant differences between the three versions. Figure 4 shows an example of Wallis filtering. The large texture improvement is apparent. But difficulties in matching such images might arise. Indeed, in homogeneous areas which often occur with marble surfaces, especially new marble, noise may have been enhanced and appear as texture. This underlines the importance of using cameras with good radiometric quality. The second problem is that when the camera view changes, different texture appears in the image due to the crystal structure of marble and the different reflectance and automated matching becomes impossible. This problem increases with larger convergence angle between the images and occurs in both sun-illuminated and shadow areas. The last problem is that the texture is often of small size and repetitive, leading to multiple solutions and wrong results in matching. Occlusions are an additional problem.

4.3 Results of 3D modeling and surface generation

For the image-based 3D modeling of the Erechtheion, as the monument contains different typical architectural elements (like columns, flat walls, etc.), manual measurements were applied (Figure 5). On the other hand, for some details (Karyatides, ornaments, etc.) and to investigate image matching problems on marble surfaces, automated approaches for dense surface reconstructions were used. For these parts we employed a (i)

Depth from Shading (DfS) method (Figure 6) (El-Hakim, 2006) and (ii) the ETH matcher able to recover dense and accurate results using simultaneously multiple images (Zhang, 2005; Remondino et al., 2008). The method combines multiple matching primitives and various area-based matching techniques to exploit all the content information of the images. It can also cope to a large extent with depth discontinuities, wide baselines, repeated patterns, occlusions and illumination changes by using several advancements over standard stereo matching techniques. Figures 7 and 8 show the 3D results from the Canon and Mamiya camera respectively.

To evaluate the accuracy of the image matching results and investigate possible penetration effects of laser light into the marble (Godin et al., 2001; Lichti and Harvey, 2002), we compared the photogrammetrically derived point clouds with the range data (Surphaser 25HSX, range accuracy specification: 1mm@15m, see www.md3d.uk.com/surphaser.html) acquired for the range-based modeling of the entire Erechtheion (El-Hakim et al., 2008). The average point density of Surphaser was 2 mm, and for the matching surface models 1mm and 2mm for the Canon and Mamiya respectively. The 3D comparison is performed within PolyWorks© IMAlign and IMInspect. Firstly, the two meshes have to be co-registered (rotation, translation and scale, the latter estimated manually) and then a best fit between them is computed, minimizing the distances between the mesh patches.

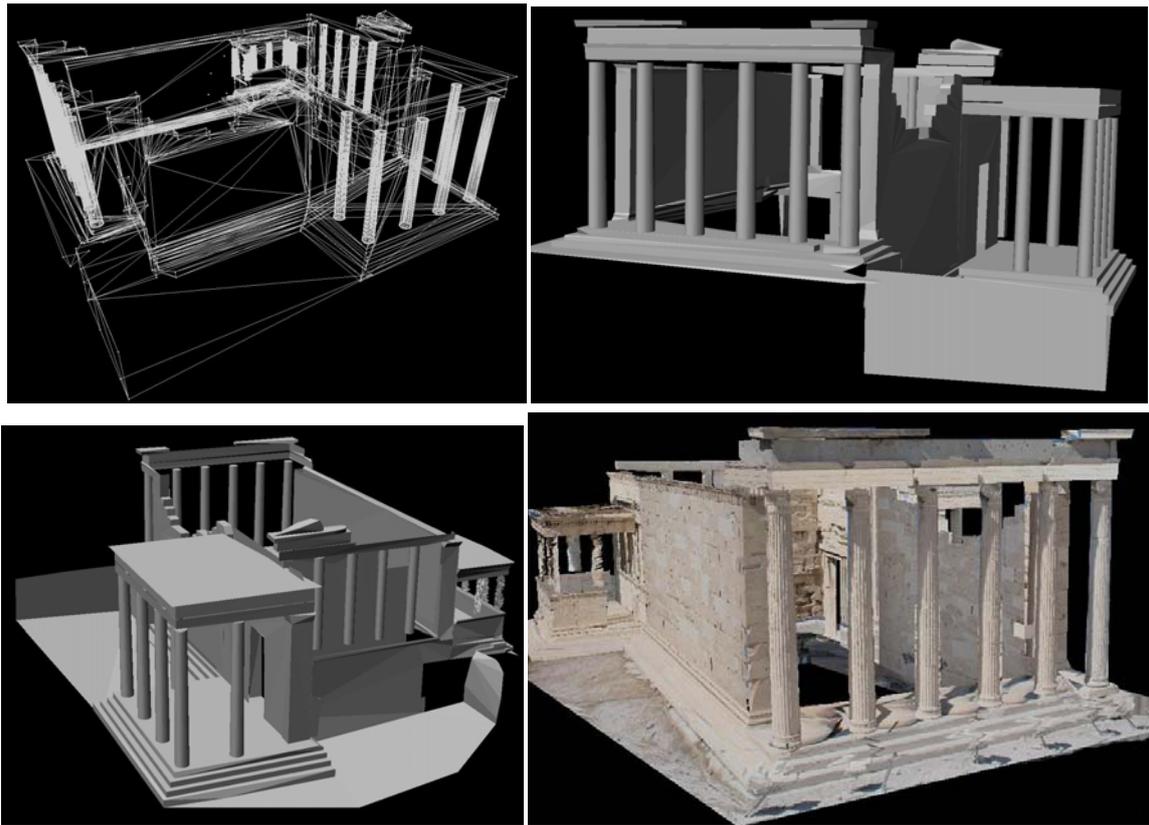


Figure 5. Results of the image-based 3D modeling of the Erechtheion in the Acropolis of Athens, shown in wireframe, shaded and textured mode.

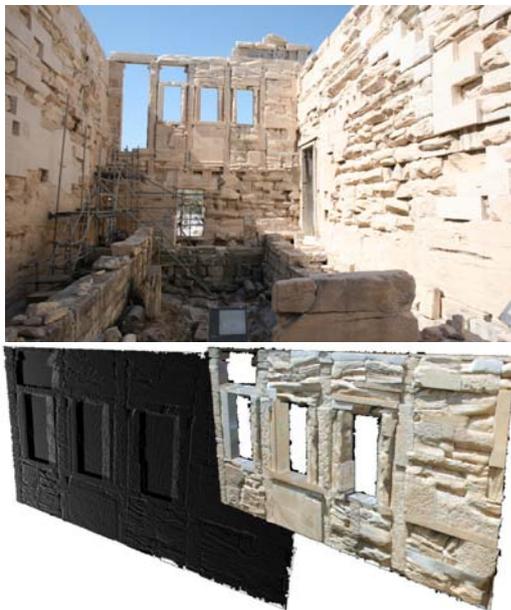


Figure 6. The interior room of the Erechtheion (above) and part of a wall modeled with Depth from Shading (below).

In the 3D comparison, if the minimization of the distances is done on the entire data, the laser's penetration error will be absorbed by the 3D transformation parameters. This is shown in Figure 9, with a colour-coded result of the comparison. Clearly, the error distribution shows that the largest errors are consistently near boundaries, at sharp surface gradients and, in

addition, at image areas with little texture or repetitive patterns (where matching often fails). All these are areas where the different modeling methodologies have problems.

The standard deviation of the differences between the scanned model and the image-based model is ca 1.4 mm. As expected, the apparent penetration's effect of the laser into the marble surface has been clearly absorbed by the ICP registration.

For this reason, the best way to register and compare the two sets of 3D data is (i) to apply a constraint in the depth direction (Z) and compute the shift parameters only in X and Y (Gruen and Akca, 2005) or (ii) to match fixed markers or small dark/dirt features. The latter method was used to compare image-based and range-based results of the area depicted in Figure 10. The matching results were compared to the range data, co-registering the two surfaces with common features (dirt and dark spots), assuming that there is no laser penetration on these features.

A better way would be to use for such test purposes flat, well-distributed targets, with good reflectance and no penetration for laser scanning and good texture for matching.

The graphical results of the comparison (Figures 10a and 10b) show an apparent penetration of the laser signal into the marble (red areas) with an average of ca 3 mm using both Canon and Mamiya. Regarding Figure 10, it is not possible to make any statement regarding whether image matching or laser scanning is more accurate, as better reference data are lacking and are difficult in general to get and compare.



Figure 7. Results of the multi-image dense matching reconstruction from the Canon data (0.3 mm GSD, 25-30 deg convergence angle) of a detailed area of new marble (ca. 560 x 220 mm) imaged in three images. 3D results presented in shaded, colour-coded and textured mode.

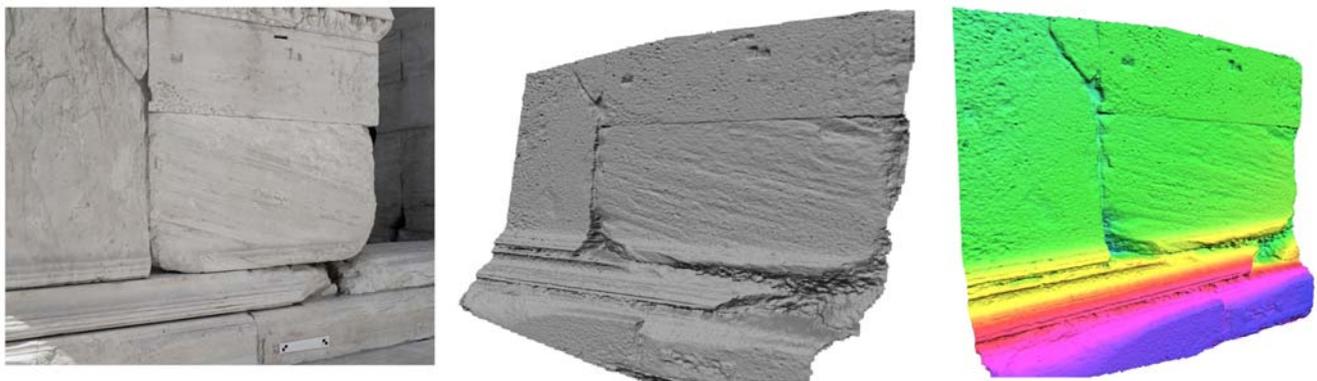


Figure 8. Matching results from the Mamiya camera (22 Mpixel, 0.6 mm GSD) on old marble (ca. 2 x 1.8 m), shown in shaded and colour-coded mode. The scale bar is visible at the lower part of the left image.

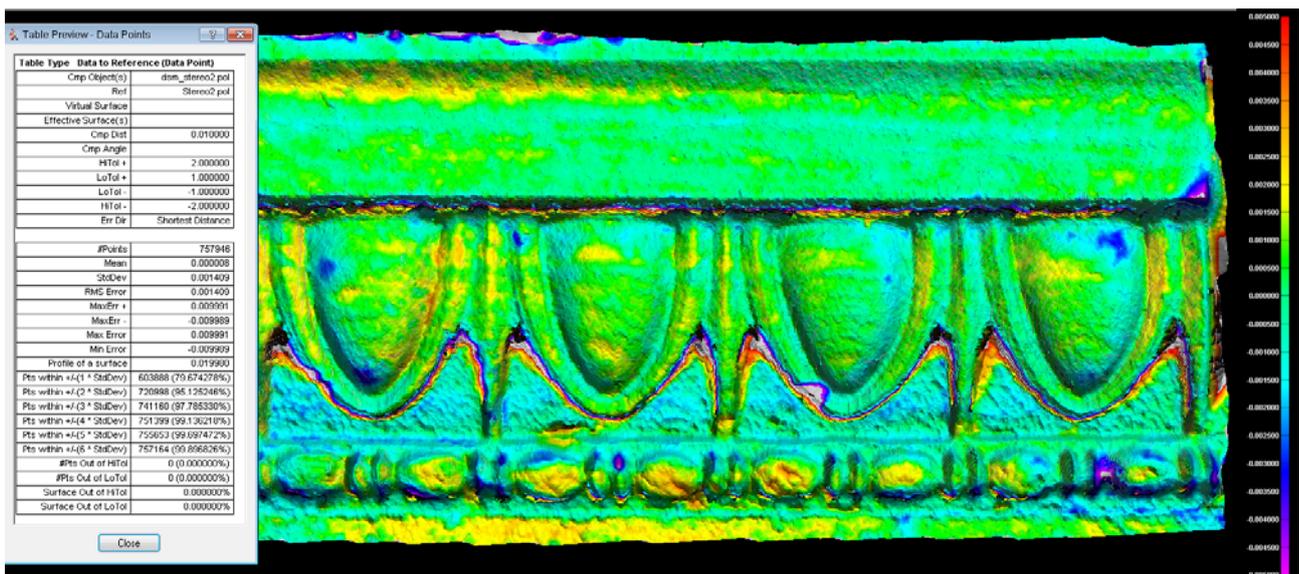


Figure 9. Result of the 3D comparison between image- and range-based surfaces on a piece of marble (standard deviation = 1.4 mm). The laser's apparent penetration effect is not clear in the graphical view as it was absorbed by the ICP registration of the two surfaces. The colour legend on the right shows differences between + 5mm and - 5mm.

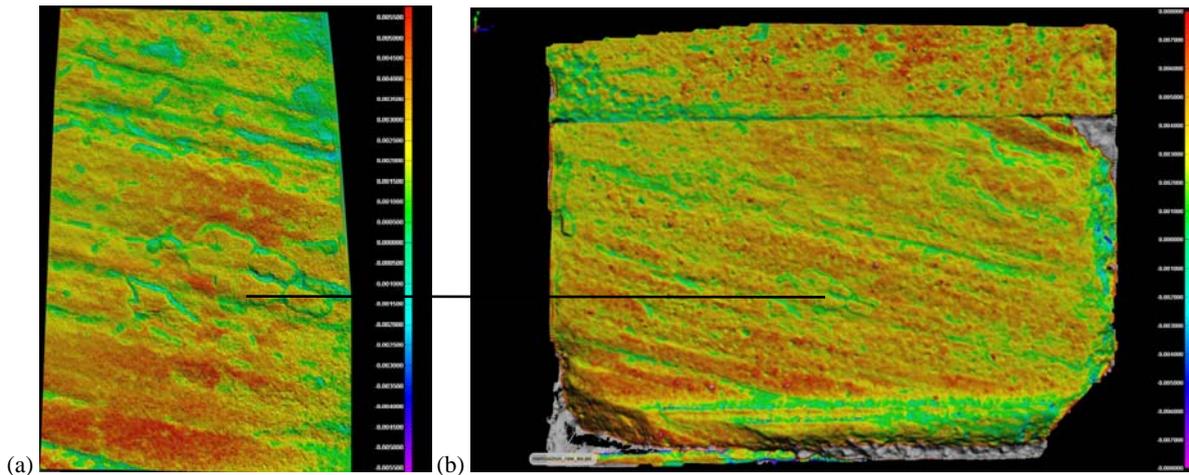


Figure 10. 3D comparison between laser scanner and image matching of the central area of the marble in Figure 8. The area has been modeled with the ETH matcher using three convergent images and then compared in IMInspect with the range data acquired with a Surphaser 25HSX laser scanner. The colour-coded differences of (a) Canon and (b) Mamiya show an apparent laser penetration of ca. 3 mm in both cases. The colour legend on the right shows differences between + 5.5mm and – 5.5mm for Canon and +8mm and - 8mm for the Mamiya. The Mamiya results are more noisy mainly due to the GSD of 0.6mm, while for Canon the GSD was 0.3mm. The black line shows identical regions.

5. CONCLUSIONS

In this contribution, we presented the image-based 3D modeling of the Erechtheion monument. Data acquisition, processing, problems encountered and the results of the digital reconstruction have been discussed. Due to the complexity of the monument, the relatively large baselines of the images and the significant occlusions, primary manual measurements were applied to reconstruct the 3D geometry. For some detailed areas, automated procedures able to recover dense point clouds were instead applied.

Advanced matching algorithms results have been reported, with an accuracy potential similar to that of laser scanning. Furthermore, we have shown that marble is a very challenging material due to either lack of texture and strongly anisotropic reflectance properties. For these reasons, the use of cameras with good radiometric quality and low noise, as well as good pre-processing are imperative.

Furthermore, comparison of IBM and laser scanning and the apparent penetration of laser pulses into the marble surface were investigated. The resulted effect of signal penetration seams quite strong (3 mm on the average). This effect needs deeper investigations and more tests with different laser ranging technologies and light/pattern projection ranging systems must be done in this context.

The lesson of the work reveals once more that a single technique is still not enough for the complete and detailed modeling of large heritage monuments and sites. The combination of different techniques is still the best choice for these kinds of projects, exploiting the inherent strength of each approach and each one where it is best suited.

Future work will include the detailed IBM of the Maidens porch and of top parts of Erechtheion using the balloon images.

ACKNOWLEDGMENTS

This work is part of the project “Development of Geographic Information Systems at the Acropolis of Athens“, financed by the European Union and the Government of Greece, and supervised by the Acropolis Restoration Service, Hellenic Ministry of Culture. The partners in this project are Elliniki Photogrammetriki Ltd (Elpho), Athens, Geotech O.E., Athens, ETH (Swiss Federal Institute of Technology), Zurich, National Research Council, Canada, Institute for Mediterranean Studies, Foundation for Research & Technology (FORTH), Rethymnon, Crete, with external cooperators, Leica Geosystems, Switzerland and Basis Software Inc., USA.

REFERENCES

- Allen, P., Troccoli, A., Blaer, P., 2005: Automating the 3D Modeling Pipeline, CREST 3D Modeling Symposium, Tokyo.
- Blais, F., 2004: A review of 20 years of Range Sensors Development. *Journal of Electronic Imaging*, 13(1), pp. 231-240.
- Blomerus, P., Lesk, A., 2007: Using AutoCAD to Construct a 4D Block-by-Block Model of the Erechtheion on the Akropolis at Athens, I: Modeling the Erechtheion in Four Dimensions. *CSA Newsletter*, Vol. XX(2).
- Debevec, P., 2005: Making "The Parthenon". 6th International Symposium on Virtual Reality, Archaeology, and Cultural Heritage, VAST 2005, Pisa, Italy.
- Dietrich, A., Gobbetti, E. and Yoon, S.-E., 2007: Massive-model rendering techniques: a tutorial. *IEEE Computer Graphics and Applications*, 27(6), pp. 20-34.
- El-Hakim, S.F., 2006: A sequential approach to capture fine geometric details from images. *International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences*, Vol. 36, Part5, pp. 97-102.

- El-Hakim, S.F., Beraldin, J.A., Picard, M., Godin, G., 2004: Detailed 3D reconstruction of large-scale heritage sites with integrated techniques. *IEEE Computer Graphics and Application*, 24(3), pp. 21-29.
- El-Hakim, S., Gonzo, L., Voltolini, F., Girardi, S., Rizzi, A., Remondino, F., Whiting, E., 2007: Detailed 3D modeling of castles. *Int. Journal of Architectural Computing*, 5(2), pp. 199-220.
- El-Hakim, S., Beraldin, J.-A., Picard, M., Cournoyer, L., 2008: Surface Reconstruction of Large Complex Structures from Mixed Range Data - The Erechtheion Experience. *International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences*, Vol. 37, Part B1 (in press).
- Godin, G., Rioux, M., Beraldin, J.-A., Levoy, M., Cournoyer, L., Blais, F., 2001: An assessment of laser range measurement on marble surfaces. *Proc. of 5th Optical 3D Measurement Techniques Conference*, Vienna, Austria.
- Goesele, M., Snavely, N., Curless, B., Hoppe, H., Seitz, S.M., 2007. Multi-view stereo for community photo collections. *ICCV 2007*, Rio de Janeiro, Brasil.
- Gruen, A., Akca, D., 2005: Least squares 3D surface and curve matching. *ISPRS Journal of Photogrammetry and Remote Sensing*, 59(3), pp. 151-174.
- Lichti, D., Harvey, B., 2002: The effects of reflecting surface material properties on time-of-flight laser scanner measurements. *International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences*, Vol 34(2).
- Luebke, D., Reddy, M., Cohne, J., Varshney, A., Watson, B., Huebner, R., 2002: Level of detail for 3D graphics. Morgan-Kaufmann Publishers, San Francisco, USA.
- Moullou, D., Mavromati, D., 2007: Topographic and photogrammetric recording of the acropolis of Athens. XXI International CIPA Symposium, 1-6 October, Athens, Greece.
- Remondino, F., El-Hakim, S., 2006: Image-based 3D modelling: a review. *Photogrammetric Record*, 21(115), pp. 269-291.
- Reinhard, E., Ward, G., Pattanaik, S., Debevec, P., 2005: High Dynamic Range Imaging: Acquisition, Display and Image-Based Lighting. Morgan Kaufmann Publishers, San Francisco, USA.
- Remondino, F., Fraser, C., 2006: Digital camera calibration methods: considerations and comparisons. *International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences*, Vol. 36, Part 5, pp. 266-272.
- Remondino, F., El-Hakim, S., Gruen, A., Zhang, L., 2008: Development and performance analysis of image matching for detailed surface reconstruction of heritage objects. *IEEE Signal Processing Magazine* (in press).
- Stumpfel, J., Tchou, C., Yun, N., Martinez, P., Hawkins, T., Jones, A., Emerson B, Debevec, P., 2003: Digital reunification of the Parthenon and its sculptures. In *Virtual Reality, Archaeology and Cultural Heritage, VAST 2003*, pp. 41-50.
- Vergauwen, M., Van Gool, L., 2006: Web-based 3D reconstruction service. *Machine vision and applications*, 17(6) pp. 411-426.
- Wallis, R., 1976: An approach to the space variant restoration and enhancement of images. *Symp. on Current Mathematical Problems in Image Science*, Naval Postgraduate School, Monterey CA, USA, November, pp.329-340.
- Zhang, L., 2005: Automatic Digital Surface Model (DSM) generation from linear array images. Ph.D. Thesis Nr. 90, Institute of Geodesy and Photogrammetry, ETH Zurich, Switzerland, 199 p

