Using Terrestrial Laser Scanning and Digital Images for 3D Modelling of the Erechtheion, Acropolis of Athens

Abstract
This work is part of the project “Development of Geographic Information Systems at the Acropolis of Athens”. Within this project one of the aims was the generation of a textured, high-resolution, accurate 3D model of the Erechtheion and a realistic computer animation. For most parts, we used a medium-range time-of-flight (TOF) phase-based laser scanner with minimum lateral data spacing of 1 mm and depth uncertainty of 0.2 mm. We also used high-resolution digital images for image-based reconstruction on some parts and for texture mapping. We present data capture, processing, and model generation techniques with emphasis on the encountered problems and solutions when dealing with a large complex structure, huge datasets, and field work under time constraints and challenging conditions. The experience gained, and the tools adapted for some tasks, will be valuable for other large-scale 3D modelling projects.

Keywords: Cultural Heritage, Acropolis, 3D Modelling, Registration, Image Matching, Data Integration, Texturing, Visualisation

1 Introduction
The Acropolis of Athens is a UNESCO World Heritage site, under pressure from millions of tourists and significant pollution in Athens. Of its monuments, the Erechtheion (figure 1), which was built between 421-406 B.C., is the only restored one (1979-1987). The monument remains impressive in spite of the fact that it is partly in ruins and missing most of its art and original decorations. For example, as shown in figure 2, the friezes (a) are missing their triglyphs (b) and metopes (c), and only very small parts of the pediments (d) remain. The porch of the Maidens, or Caryatids, has replicas of the original statues while some mouldings on the entablature and the podium remain and others replaced with new marble. The goal of the project is the development of GIS with associated databases for documentation, restoration management, and presentation of the monuments and surrounding walls and landscape, starting with the Erechtheion.
To achieve this, an accurate high-resolution 3D model including fine-detailed geometry and colour is one of the objectives to provide a precise baseline for future preservation. This paper deals with data acquisition, 3D construction, and visualisation issues associated with large complex monuments such as the Erechtheion. The initial results and some analysis are presented.

Figure 1: Two views of the Erechtheion in its current state

Figure 2: Missing architectural elements.

1.1 Previous Work

Models of some Acropolis structures have been created in the past few years. A computer animation, The Parthenon, virtually reunited this main Acropolis structure with its sculptures, which have been in various museums for over two centuries (Stumpfel et al., 2003, Debevec, 2005). The models were created using 3D laser scanning, structured light, Photogrammetry, and photometric stereo. Image-based rendering and inverse global illumination were also used in the movie. A project on digitising the Parthenon with a TOF laser scanner at 12mm spatial resolution (Lundgren, 2004) was reported. Managing the resulting huge datasets, starting with about 7 billion raw 3D points, was attempted by using a volumetric approach that divide the data into voxels of different sizes. The produced highest-resolution model contained 87 million polygons. Extensive study of changes to the Erechtheion from the 16th century to 2004, including an
AutoCAD-based 4D model was carried out (Blomerus & Lesk, 2007). The model was based on paintings, drawings, and photos from those periods. Also pertinent to our project, issues with detailed scanning of large marble statues were addressed (Levoy et al., 2000). Difficulties to digitally reconstruct large complex sites, particularly due to the considerable manual work, were identified (Beraldin et al., 2006). Thus, automating some steps such as registering multiple scans and texture mapping is highly desirable (Allen et al., 2005).

1.2 The main Requirements

To capture the details needed for documentation and restoration, the lateral data spacing (spatial resolution) of the 3D reconstruction in most parts should be about 5 mm and 1-2 mm on the highly detailed parts. The local depth uncertainty and overall accuracy must be 1 mm and 10 mm, respectively. For interactive visualisation the 3D model must be possible to view on a standard workstation. A movie with photo-realistic colour and lighting is also required. The procedure and techniques we adopted to fulfil these requirements will be discussed next.

1.3 The General Modelling Procedure

Range sensors, such as laser scanners, can provide highly detailed accurate representation of most shapes (Blais 2004). Combined with colour information, either from the sensor itself or from a digital camera, a realistic-looking model can be created. On the other hand most scanners can be bulky, which is a disadvantage on difficult terrain. The captured data is influenced by surface light scattering and absorption properties, thus marble surfaces are problematic (Godin et al., 2001). One must also be careful in selecting a range sensor for a given project as they are intended for a specific range and volume therefore, one designed for close range is not suitable for medium or long range. Image-based modelling (IBM) techniques can produce accurate and realistic-looking models using low cost portable devices: digital cameras. But they are highly interactive which limit the amount of details a model can have. Fully automated methods are still unproven in real applications and require large number of closely spaced images, which is impractical for large monuments. Occlusions and lack of textures are persistent problems for automatic IBM. Due to all of the above, we decided to use a combination of technologies in this project:

1. A high accuracy mid-range laser scanner for most of the monument.
2. A long-range laser scanner for high sections unreachable by first scanner.
3. IBM from ground-based images to fill gaps in areas difficult to access by either scanner.
4. IBM from images taken from a balloon to fill-in top surfaces invisible to the scanners and ground-level images, and to model the landscape.

Figure 3 outlines the data acquisition and 3D reconstruction steps designed for this project. The most time consuming operations for large complex site, are:

1. Deciding on the next best view
2. The registration of the multiple scans
3. The registration of the texture images with the geometric model
4. The editing and filling remaining holes to create a watertight model.
   Developing procedures to facilitate or fully automate these four operations is
   a necessity and remains an active research area.

In the remainder of the paper we describe the main problems (section 2),
some details on modelling from range sensors (section 3) and images (section 4),
data integration (section 5), and preliminary results and analysis (section 6).

2 Taxonomy of the Main Challenges

Modelling large and complex objects and sites has challenges in every phase,
from data acquisition to the visualisation. A summary of those issues follows.

Figure 3: Data capture and modelling pipeline for large sites.

Figure 4: Examples of difficult on-site scanner setting
2.1 Data Acquisition:

The size, setting, and surface of the monument created several problems. The monument height made coverage from ground level difficult on top parts. Some problems due to terrain and obstructions (figure 4) caused delays and resulted in missing few areas. Shape complexity of some parts caused self-occlusions, and impediments from plants/trees created holes in the coverage. Due to many restorations, the monument marbles varied in age and amount of dirt deposits on surface, which resulted in laser spot light scattering and penetration being variable from one part to another thus hard to correct systematically.

2.2 Data Processing:

The huge size of data makes it impossible to process at high resolution, yet processing at low resolution creates accuracy problems. Also the combination of data taken by different sensors at different resolution, accuracy, and viewpoints affect the overall accuracy of the full model if not properly considered.

Despite using several sensors, some gaps and holes lingered. This raises a key question: should we fill those with interpolated, but possibly inaccurate, surface patches or leave them out even though they may be visually unpleasant?

2.3 Realistic Appearance

Photo-realism, defined as having no difference between a view rendered from the model and a photograph taken from the same viewpoint, goes much further than simply draping static imagery over geometry. Due to variations in lighting, surface specularity and camera gain settings, sensed colour and intensity for a segment shown in images taken from separate positions will not match. This is particularly problematic on large open-air site like the Acropolis. Measurement of surface reflection properties must also be included for proper model lighting. Moreover, texture images contain whatever illumination existed at imaging time. This illumination should be removed and replaced by dynamic illumination consistent with the rendering point of view. Also the range of brightness in the scene cannot be captured in a single exposure by current digital cameras. This causes loss of details in the dark areas (shadows) and saturation in the bright areas (sun) if both coexist in a scene. Thus high dynamic range (HDR) images must be acquired to recover all scene shades of colours (Reinhard et al., 2005).

2.4 Interactive Visualisation

The ability to interact with 3D models is a continuing problem due to the fact that the demand for detailed model is growing at faster rate than computer hardware advances. The rendering algorithm should be capable of delivering images at real-time frame rates of at least 20 frames-per-second even at full resolution for both geometry and texture. Luebke et al., 2002 and Dietrich et al., 2007 cover many aspects of this subject. We use the Atelier 3D system, which is a view-dependent real-time technique for multi-resolution models (Borgeat et al.,
When at close up the full resolution is shown then it decreases when moving away. It uses geo-morphing to smoothly interpolate between both geometric and texture patches composing a hierarchical level of detail (LOD) structure to maintain seamless continuity between adjacent patches.

3 Range Sensors Data Capture and Modelling

Bernardini & Rushmeier, 2002, give a review on creating 3D models from range sensors. Here, we summarise the acquisition, processing, and texture mapping of data from such sensors as implemented for this project.

3.1 Data Acquisition and Field Work

As with this type of project, adequate planning before the actual fieldwork demands a systematic approach to identify problems, estimate time, and define parameters affecting data quality. The fieldwork must be completed within a specific time, one week, dictated by the availability of equipment and support personnel, allowed access to the site, and the project limited budget. Therefore, it is important to assemble an effective team on the site to handle all operations optimally. As a result, and based on experience from past projects, five days with three persons were spent as follow: one person for scanning; one person for initial scan alignment (see section 3.2), guidance for next best view, and data backups; and one person for digital imaging for texture mapping and IBM.

A 3D scanner that satisfies project requirements is Surphasergy® 25HSX, a TOF phase-shift based scanner allowing dense and accurate measurements (Figure 5). It can acquire data from about 5 m range with a noise level of 0.25 mm (verified with our own tests on and off site), and accuracy of less than 1 mm (maximum error). This accuracy can only be achieved after correcting for apparent marble penetration errors (about 5 mm). The number of captured points exceeded 3.2 billion. Data were acquired from a tripod at height not more than 2.5m due to the constant windy conditions. This results in missing few parts on the top of the structure, thus a long-range TOF pulsed scanner, Leica HDS3000®, was used to fill-in those gaps by setting up the scanner on raised grounds at 80-100 meters away. For example, figure 6 shows the top of the Maidens porch, which was not visible to the close-range Surphasergy scanner.

For texture mapping, HDR images were taken. This requires taking at least 4 images at different shutter speed and combining them to create one HDR image.

Figure 5: The Surphasergy® 25HSX laser scanner
3.2 Range Data Processing

The data processing was performed with commercial as well as our own in-house software tools, which were developed to achieve high geometric accuracy and visual quality while increasing automation. However, an amount of user interaction and editing is still unavoidable. The raw scans, which are collections of XYZ points in the scanner coordinate system, contain errors and noise that must be filtered out and holes that should be filled (Weyrich et al., 2004). Next step is the aligning or registration of all the scans in one coordinate system. Due to object size and shape and obstacles, it is necessary to use multiple scans from different locations and directions to cover every surface at the desired spatial resolution or level of detail. Aligning large number of scans requires significant effort and affects the final accuracy of the 3D model. It is performed in two steps: (1) initial alignment using positioning device, or the data itself by selecting common points between the scans; followed by (2) a more precise Iterative Closest Point (ICP) technique (Salvi et al., 2007). A global alignment is done at the end to minimize and distribute remaining errors equally. We perform the first step in the field on a 64-bit notebook PC with 4 Giga Bytes of RAM. As soon as a scan is completed, it is first simplified to 2% of its original size for faster processing then three common points are selected and used for initial alignment with the preceding scan. This is done while the scanner is acquiring a new scan, so it does not consume additional time. We also use this to ensure full coverage before moving the scanner to the next position. Once the scans are aligned, they need to be integrated to remove redundant points in the overlap region followed by the reconstruction of a triangular mesh that closely approximates the surface of the object (Varady et al., 1997).

After the mesh has been reconstructed, some repairing is often needed to fill cracks and holes and fix incorrect triangles and degenerate surface parts (Borodin et al., 2002, Liepa 2003). These errors result in visible faults, and cause lighting blemishes due to the incorrect surface normals. Another problem is due to the fact that the object is rarely sampled optimally. Some areas such as edges and high curvature surfaces are usually under-sampled and end up joined by a transitional surface rather than a sharp edge, while flat areas are often over-sampled. For accurate documentation and visual realism, edges and sharp corners must be accurately preserved in the model. Dey et al., 2001 proposed a technique for automatic detection and correction of such sampling problems while Luebke et al., 2002 survey simplification techniques needed to deal with over-sampling. Surface subdivision is another way to improve under-sampled
areas (Zorin et al., 1996). The triangles in these areas are subdivided into smaller triangles with points shifted according to pre-set rules. Several other methods to sharpen edges in meshes are available (e.g. Lai et al., 2007).

### 3.3 Texture Mapping

We used the Canon 5D digital camera, a 12M Pixels full-frame SLR camera, to acquire the colouring or texture. The images are registered with the geometric model using common points. In effect, this is finding the camera pose using the XYZ coordinates of model points as reference. This must be done for every image unless the camera is fixed to the scanner, in which case it is only done once. However, mounting and fixing the camera to the scanner means that the images are taken at the same time and location as scanning. This is not necessary the best for texture images since we need to select the time of day that provides the best lighting, take images in a short period of time to ensure small lighting changes, and select the best distance, viewing angle, and camera setting. Thus, we opted for taking the texture images independent of the scanner, which necessitated the development of an automated approach that registers and calibrates each image with the 3D geometry. One technique to facilitate this operation registers the texture images together first then use only one of the images to register with the geometry (El-Hakim et al., 2004, Stamos et al., 2008). For this approach to be accurate, it requires taking images with sufficient overlap and strong configuration, which imposes restrictions in the field. We use this approach only as an initial estimation for a more accurate registration based on matching of features in the texture image and the scanner intensity image.

### 4 Modelling from Images

Images from ground level for IBM were taken with the same Canon 5D camera used for texture mapping, and images from a balloon were taken with a 22Mpixel Mamiya ZD camera. Our IBM technique (reference omitted) requires only limited amount of human interactivity and is capable of capturing high-resolution fine geometric details with high accuracy. It can also cope with wide image-baseline compared to fully automated techniques. It relies on well-calibrated camera positioned to ensure strong geometric configuration between images to guarantee high geometric accuracy. Image position and orientation are determined by Photogrammetric bundle adjustment. The IBM approach is sequential starting with a basic sparse model created with a small number of interactively measured points. This model is segmented into surface patches and then acts as a guide for an automatic procedure to add the fine details. Two techniques are used, each where best suited: for areas with natural texturing suitable for stereo matching we use a multi-image matching technique (figure 7 shows image set and the resulting model); and for segments unsuited for stereo matching, such as those with smooth un-textured surface (figure 8), we employ depth from shading (DFS) method that computes the deviation from approximate shape, for example a plane, by a value function of the grey-scale.
5 Registration and Integration of Individual Models

Individual models created from range sensors (section 3) and IBM techniques (section 4) need to be combined into a single watertight model appropriate for documentation and visualization. They must have correct scale and orientation, and joint primitives such as surfaces, edges, and vertices from adjacent models must match perfectly. The final model must have no gaps, redundant surfaces, or intersecting edges. Some of these issues are not dealt with in commercial software, thus special techniques and software tools were developed.

The individual models were directly created in the same coordinate system using surveyed points. A number of reference targets were placed, where permitted, on some surfaces on and around the Erechtheion and measured with surveying equipments. These points were used to position and orient all data from all sensors in one geo-referenced coordinate system. The models are then more precisely registered in modelling software such as 3ds max® using common points, then further editing is performed with our in-house software to fill holes and remove redundant patches.
6 Results and Analysis

6.1 An Interactive Lower Resolution Model

The first phase of the project entails the creation of a lower resolution model (10 million polygons, 15mm resolution or lower on flat surfaces) that is complete and interactively viewable on a high-end PC. The objective is to make sure that all the monument has been covered and that the data can be processed and integrated successfully. The result of this phase is shown in figure 9. Work on the full resolution model is in progress since merging and repairing such huge data sets remains time consuming. Figure 10 shows the full resolution model of a completed part; a Maiden statue column.

At the time of writing this paper, data from the balloon has not yet been completed due to several delays caused mostly by the constant windy conditions.
Therefore, some top sections and the landscape and surrounding walls have not yet been modelled.

6.2 Testing and Comparison of Different Techniques

Test regions of the Erechtheion, with variable surface roughness and marble age, were selected for detailed comparison between laser scanning and IBM. The first test was to have an estimate of the amount of apparent laser penetration on this type of marble. A sheet of paper was placed flat on a region of one of the monument walls and it was scanned along with the surrounding region. As shown in figure 11 (left) the colour-coded depth indicates that the marble surface is about 5 mm lower than paper surface, which is not true since the paper was right on the marble surface (the thickness of the paper is about 0.1 mm). This may be attributed mostly to laser penetration. One also observes that adhesive lines between the stones look as if they were higher than the marble surface, while in reality they are lower.

Another test computes the 3D surface from multiple images with our IBM technique (section 4). The computed surface is registered with the same surface part computed from the laser scanner using common points selected from the marking/dirt on the surface. The colour-coded difference is plotted in figure 11 (right) and it shows that the surface computed from image matching is again about 5 mm higher than the surface from the scanner. This result agrees also with the first test using the paper sheet. Since the accuracy of both techniques is a fraction of one mm, this shift may be attributed to laser penetration into marble.

![Figure 11: Marble penetration: comparison with paper (left) and stereo (right).](image)

7 Conclusions

The data acquisition, processing, problems encountered, and some results and analysis of the digital reconstruction of the Erechtheion have been presented. Several sensors and techniques were employed and some tools had to be adapted for use with large complex monuments. Such tools, along with the gained experience and lessons learned will be valuable for future projects. A full model at compressed resolution (10 million polygons) has been completed, while work
on the full resolution model (several billions of polygons) is currently in progress. Future work includes the integration of landscape 3D data produced by the balloon-based aerial images and the final texturing and lighting of the full model under different times of the day and different seasons, then the creation of high quality computer animation. The incorporation of the 3D model in a GIS database with other information is also in progress.

References


