PHOTOGRAMMETRY AS A TOOL FOR ARCHITECTURAL ANALYSIS: THE DIGITAL ARCHITECTURE PROJECT AT OLYMPIA

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Περίληψη/ Abstract

Το Digital Architecture Project (DAP) δημιουργεί μοντέλα τριών διαστάσεων και ψηφιακές αναπαραστάσεις Αρχαϊκών ελληνικών ναών. Πρόσφατη φωτογραμμετρική έρευνα του ναού της Ήρας στην Ολυμπία, του αρχαιότερου και καλύτερα διατηρημένου οικοδόμηματος Δωρικού ρυθμού στην Ελλάδα, οδήγησε στην κατασκευή ένος τριδιάστατου μοντέλου υψηλής ανάλυσης για το οικοδόμημα (διαστάσεων 20x50 μ περίπου). Η γραμμική ακρίβεια μέτρησης έχει καθοριστεί στο ± 1 χλστ. σε τοπικό επίπεδο, και στα ± 10 χλστ. σε παγκόσμιο επίπεδο (95% CI). Η ανάλυση των οπτικοποιήσεων έχει ήδη δώσει σημαντικά στοιχεία για την αρχιτεκτονική ιστορία του ναού. Για τη διαχείριση του μεγάλου όγκου των δεδομένων, τα μοντέλα έχουν αποδοθεί σε επίπεδα δύο διαστάσεων σε αντιστοιχία με τις συμβατικές κατόψεις και τομές. Το DAP προτείνει ένα ψηφιακό μουσείο για τη διάδοση αυτών των δεδομένων.

The *Digital Architecture Project* (DAP) produces 3D models and reconstructed visualizations of archaic Greek temples. Its recent photogrammetric survey of the temple of Hera at Olympia, the earliest well-preserved Doric structure in Greece, resulted in a high-resolution 3D model for the ca. 20x50 m structure. The linear measurement accuracy has been determined to be as high as ± 1 mm locally, and ± 10 mm globally (95% CI). The analysis of the visualizations has already provided valuable insight into the temple's architectural history. In order to manage the large amount of data, the models have been rendered in 2D layers corresponding to conventional state plans and elevations. The DAP proposes a virtual museum for disseminating this resource.

Keywords: Olympia, architecture, photogrammetry, accuracy, 3D recording, virtual museum

Introduction

Photogrammetry (PG), the process by which 3D coordinates are measured from a camera, has the potential to revolutionize how we study and document antiquity. While the principles have long been applied for aerial survey, only in the 1980s was 'close-range' PG successfully adapted for precise measurement of objects from the ground (Fraser & Brown 1986). With the development of inexpensive digital cameras in the 1990s and software for their calibration, PG has become widespread in many other applications (Luhmann 2010). Although not as reliable as metric cameras, a consumer SLR can still be calibrated for measurement accurate to 0.1 mm over a 2 m object (Fraser & Al-Ajlouni 2006, Rieke-Zapp *et al.* 2009, Zhenzhong *et al.* 2010).

Over the past 15 years, researchers engaged with cultural heritage (CH) have explored the potential applications of close-range PG (Cignoni & Scopigno 2008, Doneus *et al.* 2011, Kersten & Lindstaedt 2012, Pavlidis *et al.* 2007). Many CH projects have used PG to extract coordinates for CAD modelling, typically at the scale of a building or a larger complex, such as a castle. With commercial software like PhotoModeler (© EOS Systems), cameras were calibrated by alignment to control points so that new features could be measured by manually marking them on several images. Because this process is time-consuming, the network of extracted points was typically limited to diagnostic features, which can then be imported into a CAD interface for building an idealized 3D surface model (e.g. Arias *et al.* 2007, Styliadis 2007, Yilmaz *et al.* 2008). At first, close-range PG found a niche as a proxy or supplement for time-of-flight laser systems, especially a Total Station (TS) (e.g. Sahin *et al.* 2012, Yastikli 2007). Unlike the high accuracies attained in controlled tests of PG, many of these CAD-oriented CH projects have reported significant levels of error, with 2-10 cm inaccuracies common in field reports. The focus on measuring coordinates for idealized CAD modelling has meant that the preponderance of CH projects used PG for publicity and education, its implementation being too unreliable and time-consuming for finer analysis.

The situation has changed radically over the past five years. Modern PG software has been enhanced by the incorporation of computer-vision algorithms that automatically match features – a process variously termed Multi-Image PG, Image-Based Modelling, or Structure from Motion (Cignoni & Scopigno 2008, Luhmann 2010, Vergauwen & Van Gool 2006), and which I will refer to as ‘automated PG’ in this paper. Software automation has been applied throughout the procedure, from the initial stage of camera alignment to the subsequent extraction of a point-cloud interpolated from automatically matched points. With automation, PG really begins to shine: rather than requiring a full day for an operator to measure a few hundred points manually, automated software can reconstruct millions of features within hours or even minutes. With the increases of processor power and RAM capacity in modern computers, detailed 3D reconstruction can be obtained even with a laptop. The software can rapidly produce clean 3D surface meshes with high-resolution photographic textures, making PG an increasingly appealing alternative to laser-scanning (e.g. Koutsoudis *et al.* 2013, McCarthy 2014).

Still, the potential for automated PG demonstrated in the laboratory has yet to be fully realized in practice. While errors below 1 mm have been established in controlled conditions (Jennings and Black 2012, Koutsoudis *et al.* 2013, Remondino *et al.* 2009), measurement mistakes on the order of 5-10 cm are typical in automated PG projects at buildings and sites (Bhatla *et al.* 2012, Dai and Lu 2010, Doneus *et al.* 2011, Klein *el al.* 2012, Remondino *et al.* 2012, Sahin *et al.* 2012). A standard error of about 1 cm has been reported in a few applications at the trench- and building-scale, implying mistakes in the 1-5 cm range would occur in these datasets (De Reu *et al.* 2013, De Reu *et al.* 2014, Dellepiane *et al.* 2013, Kertsen & Lindstaedt 2012, Koutsoudis *et al.* 2014, Olson *et al.* 2013, Riveiro *et al.* 2011).

As the software becomes increasingly powerful, automated PG promises to surpass illustration by hand and laser-scanning as the standard recording technique in the field and museum. However, the quality and accuracy of PG under the demanding conditions of the field, the potential research value of the resulting 3D meshes, and how digital 3D data are best published have yet to be established. I consider each of these questions in light of my recent implementation of PG at Olympia. This paper focuses on mesh quality, but it also considers PG as an analytical tool and describes plans for publishing these 3D data in a virtual museum.

1. The Digital Architecture Project

The *Digital Architecture Project* (DAP) exploits the power of automated PG for field recording and publication of ancient architecture. In service of its broader investigation into the emergence of the Doric style in the Archaic Period, the DAP is creating 3D models of the current state and reconstruction of temples from Mainland Greece and Italy. The high-resolution ‘state model’ for each ancient building is intended to support architectural analysis, by superseding the kinds of 2D plans and elevations used in traditional architectural illustration.

The first subject of the DAP is the Temple of Hera at Olympia, chosen for its excellent preservation, early date (*c.* 590 B.C.), and importance to the development of early Doric architecture (e.g. Dörpfeld & Schleif 1935). Initial fieldwork was completed in July 2013, resulting in the 3D models presented here. Although fieldwork will continue, the recording of the building is already largely complete.

Objectives: The recording system developed for Olympia was designed to test the effectiveness of PG under difficult field conditions. A major question is whether PG can supersede manual illustration, which continues to be the standard approach to recording ancient architecture. There are five aspects to consider (compare to Pavlidis *et al.* 2007):

(1) Scale: The field methods must be efficient enough to be applied to buildings and large complexes. In addition to the *in situ* remains, the DAP plans eventually to digitize displaced architectural fragments in the museum, but for now the process is only evaluated for a whole building.

(2) Quality: The precision for architectural study and analysis must be as high as for manual recording. Dimensions are published to the nearest mm or cm in most architectural studies, and features down to individual tool marks or joint surfaces are recorded. Thus, PG models need a resolution of 1–2 mm or less, or else fine details will be lost and mm-level measurement will be impossible. The error for manual recording is relatively high, however; at the building scale, manual or TS linear measurement error is at least ± 5–10 mm, and often greater.

(3) Practicality: for widespread adoption, the PG method should be simple enough to be implemented by CH researchers with some technical skills. The equipment must be portable and be able to function even at an active site like Olympia with thousands of visitors every day.

(4) Budget: While 3D modelling for CH has in some cases attracted tens or even hundreds of thousands of dollars in funding – e.g. for laser-scanning significant monuments – minimizing cost is essential for most field projects. Processing time after the fieldwork concludes must also be considered.

(5) End-product: The 3D data should be presented in formats usable by researchers without demanding special technical skills or costly software.

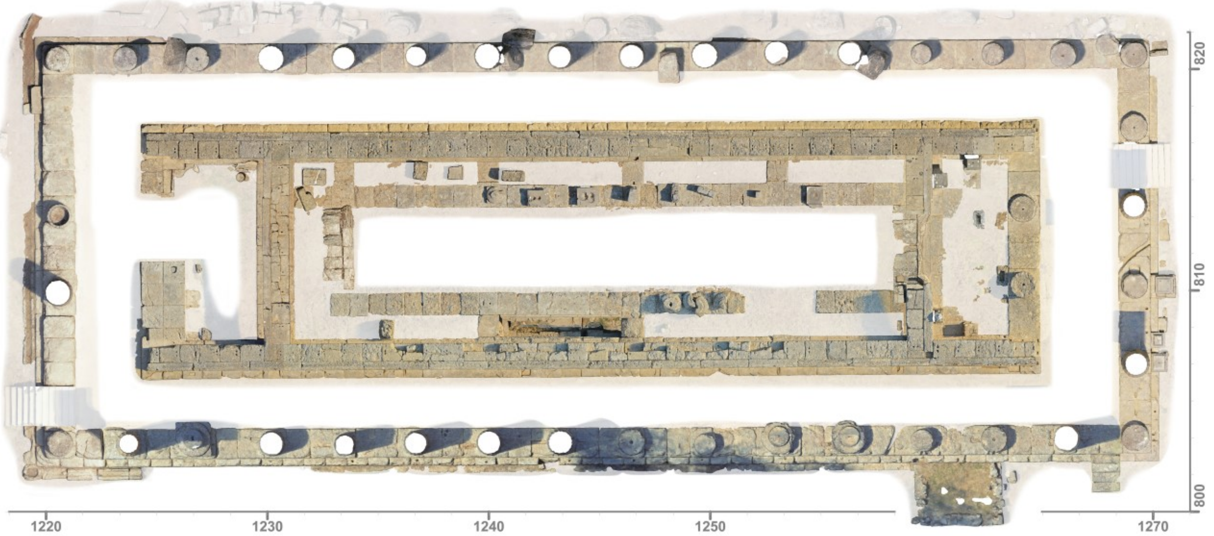

Figure 1 Digital top plan of the Heraion at Olympia (DAP, © 2013 Sapirstein)

2. Photogrammetry at Olympia

Implementation on site: The DAP used a TS for measurement on site, establishing a network of 190 control points in the excavation's grid coordinates. At least 100 points would be necessary for a building as large as the Heraion. A Nikon D800e, a 36.3 Mpx digital camera, equipped with a zoom lens set to 28 mm was used for photography. The 36x24 mm sensor is sharper than other digital SLRs currently available, more than doubling the linear pixel resolution compared to a 12.3Mpx Nikon D5000 also tested on site. The D800e can capture the full dynamic range of light under direct midday sunlight. In comparison, if the D5000 is metered to capture detail in direct sunlight, it loses definition in the shadows, and vice-versa. The D800e sensor reduces the number of photographs required to capture the stone surfaces at a given level of detail, which improves accuracy, increases how much area can be recorded on site, and reduces processing times.

The Heraion is a large structure, but detailed imagery of its stone surfaces is required for architectural study. The temple occupies a roughly 55x25x7 m volume, and the exposed surfaces exceed 1,100 m^2 in area. While it might be possible to photograph the entire structure at once from the air, the resolution would be limited to about 1 cm per pixel—falling short of the desired 1–2 mm resolution (Objective #2). Instead, I took photographs at a distance of 2.0–2.5 m, on the ground or a ladder, for an initial photographic resolution below 0.5 mm per pixel.

Due to the rapidly changing light as the sun moved through the sky, I was limited to no more than a half hour of photography at one time: otherwise the shadows changed too much in orientation and character for the software to locate matching points accurately. Because it was physically impossible to photograph the entire structure this quickly, the job had to be divided into segments. One might document the entire building under the same lighting conditions by shooting only at the same period each day — which would take about two weeks for the Heraion. However, as an architectural historian, I wanted to have raking light cast on the surfaces, which emphasizes tooling and other subtle inflections in the stone texture that are difficult to see in full shadow or direct illumination. For example, I elected to photograph the south and north faces of the cella walls at different times of day so as to record both sides under raking light, even though this required separate batches of photographs. This also allowed me to finish the job more rapidly by photographing segments of the building when optimal lighting was available at various times of day. The whole temple was captured in 17 different groups of photos. Although the software cannot align these groups to one another directly, they are oriented to the same control points. The final imagery blends segments with different lighting conditions, as can be seen in Figure 1.

Processing in the office: Automated PG requires intensive computation to extract dense 3D meshes. The DAP used two laptops with 8GB of RAM and dedicated graphics cards. The commercial software used for PG, Agisoft PhotoScan Pro, is the least expensive of the commercial options with survey capabilities (De Reu *et al.* 2013, Koutsoudis *et al.* 2014, Olson *et al.* 2013, Remondino *et al.* 2012). The program has four primary phases requiring user input. First, one must load a group of photographs into a new project file and calculate the alignment. Although fully automated, the calculation of the camera orientations and calibration took up to three hours for the largest groups of photos (up to 300). Second, one must identify the control points measured with the TS, which at Olympia were nails driven into the ground and marked with a 1 mm dot. While sturdy and easy to measure with the TS, the

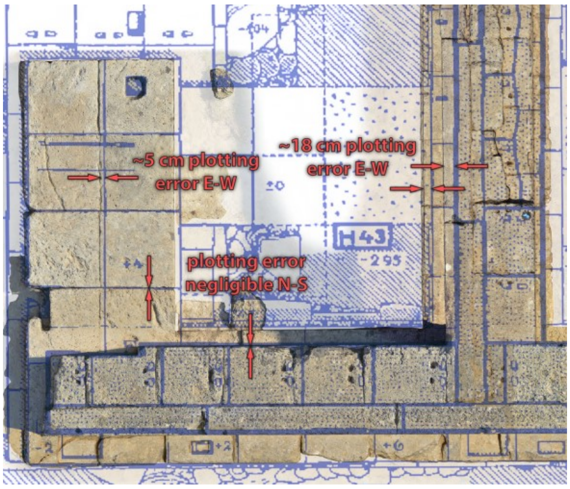

Figure 2 Comparison of the DAP and manual plans at the opisthodomos (Dörpfeld & Schleif 1935, pl. 9)

nails had to be marked manually in the software. The software then calculates a Procrustean fit of the marked PG points to site grid coordinates recorded with the TS. Manually marking points was the most time consuming of the processing stages. While I could finish smaller sets in as little as 30’, the largest groups took 2–3 hours. I also made mistakes, necessitating a time-consuming search to discover which incorrectly marked point had thrown off the PG measurement. The third phase is dense surface reconstruction. This requires almost no user input but is the most computationally intensive step. The processing times vary depending on the parameters and RAM capacity, but I limited calculations to about five hours. Fourth, the photographic texture is projected on the resulting 3D mesh. This requires little user input and computes quickly.

The 17 groups of photographs had to be aligned and rendered separately. Although there were 2000 photographs in total, no group had more than 300 images. To save computing time, I used the program’s ‘Medium’ quality settings, which down-samples to 1/4 of the pixels in the original images. The largest sets still had to be subdivided into smaller segments for processing because of RAM limits. In the end, the Heraion was divided into 50 processing segments, each decimated to 4Ma vertices and draped with an 8192x8192 pixel texture. Although the resolution of the 3D geometry is high for sharp features, like corners, small perturbations below about 2 mm, like chisel marks, are blurred in the 3D mesh — whose vertices are spaced 3 mm apart on average. However, the textures have a 1.0 mm pixel resolution and capture finer details even if their 3D geometry has been blurred.

Accuracy: While the precision of this data is high, it is critical to examine its accuracy. Although the error in manual illustrations of ancient architecture is seldom discussed explicitly, a standard error greater than 1 cm can be assumed for drawings plotted by hand at this scale (1:50 or smaller), due to the 5% error in human perception (Eerkens 2000). As can be seen in a comparison of the DAP plan to that published in 1935 (Fig. 2), there are in fact manual plotting errors up to 15–20 cm in some parts of the cella, although in most places these earlier drawings agree within a few cm of the DAP photogrammetric plan. This example demonstrates how the scale of human error can increase massively in areas where the illustrator is less concerned about accuracy. While the photogrammetric process can also make blunders, these are immediately apparent to the human operator and corrected. Nonetheless, the standard error in PG varies greatly depending on the job and must be determined empirically by testing the results against known points. The publications to date of field applications using automated PG have yet to consider the problem of error methodically.

There are several potential sources of error. First, the internal orientation of the 16–35 mm zoom lens used at Olympia is less stable than that of a fixed focal-length lens (Fraser & Al-Ajlouni 2006, Rieke-Zapp *et al.* 2009). Tests suggest measurement accuracy would be improved with a fixed lens, although the effect is minor at the scale of the Heraion. Second, the stone surfaces of the temple are rough, pitted, and covered with lichens, creating high-contrast random textures ideal for automated PG. However, I found that camera misalignments are common at sharp external corners, where it is difficult for the software to identify comparison points across the adjacent perpendicular faces. This was problematic during testing. For the final images, I took extra photographs at corners, which fixes these alignment problems though slows processing. Third, the DAP relies on a TS to survey the network of control points, which has a standard measurement error. With the survey prism, the Leica TCR 407 Power has specifies a σ of 3 mm for distance error, to which must be added at least 1–2 mm error from setup over the base point, and another 2–3 mm from the prism not being exactly over the point being measured. In practice, the TS readings will differ by ca. ± 10 mm from the true point at a 95% confidence interval (CI).

For quantifying error in the DAP models, I distinguish *global* from *local* error. Global error represents the divergence of PG-derived points from true site coordinates, whereas local error represents the internal consistency over shorter segments of the model. Local error was examined by comparing models at the intersection of the north and west cella walls, where there are five separate groups of photographs. A total of 10 meshes with a 0.5 mm texture resolution were generated at different qualities (‘Low/Medium’ or ‘High/Ultra’) to test the error contribution of the program settings (Fig. 3). Nine test points on high-contrast features were marked in 2D, and each scan shifted to minimize the

	$\bar{x}$	*n*	σ	RMS
All scans (10)	0.9	78	0.76	1.19
High quality (6)	0.7	43	0.55	0.89
Low quality (4)	1.2	32	0.97	–

Table 1: Local coordinate error (x) in mm, by 2D distance from points 1–9 (Fig. 3)

	n	σ	95% CI	RMS
PG internal error	162	4.2	± 8	4.2
PG vs. TS	162	6.1	± 12	6.1

Table 2: Global measurement error in length (mm)

(Differences)	< 5	5–15	15–25	> 25
Clear features	12	6	–	–
Indistinct	7	4	6	–

Table 3: PG vs. legacy length measurements (mm)

distance from these points, thereby eliminating global error. The errors are summarized in Table 1. Higher quality settings (using 50–100% of the original image pixels) reduced error by 50% relative to lower settings (down-sampling to 12.5–25%); overall the 3D data from Olympia is repeatable within a 95% CI of ± 1 mm. Thus the internal PG alignments appear to be more accurate than the TS measurements. However, error in the control points has introduced minor distortions into the PG camera alignments, so one might attain an even higher local accuracy from more reliable control points.

As for global error, the 10 overlapping scans were shifted by an average of 5 mm (σ = 4.6) for local comparison. A more meaningful approximation of global error, however, is obtained by comparison of the coordinates measured in the TS to those estimated in the PG models. A subset of the 19 control points visible in at least three different PG groups was selected, and the lengths calculated between these points. Altogether 162 lengths could be derived from the PG control points for comparison to the original TS survey. The PG lengths are not entirely independent from those of the TS, but they are from a subset of the 129 points used to position and scale the PG models and thus are the best available test for the error in measuring length — which is key for architectural analysis. Table 2 presents an internal comparison of lengths (relative to control point coordinates averaged from all 17 PG sets), and the PG lengths against those from the TS survey. The former is an underestimate of the standard PG length error, whereas the latter is an overestimate because it disregards the internal accuracy of the PG network relative to the TS survey. The errors are normally distributed, indicating a 95% CI of ca. ± 10 mm for lengths.

These results for global error are corroborated by the comparison of PG lengths of features to measurements from the early 20th century (Dörpfeld & Schleif 1935). These legacy measurements (taken

Figure 3 Comparison points, north cella wall

manually with a tape) are published to the nearest cm and so only provide an approximate indication of the PG accuracy in mm. Some features are clear and consistent in width, whereas others are obscured by slight changes in dimension in the feature, either from damage to the stones, or from inconsistencies in the ancient workmanship. As recorded in Table 3, of the 18 clearer features, the PG measurement is indistinguishable from Dörpfeld's in 12 cases, and about 1 cm off in the other 6 cases. As might be predicted, the PG measurements of the 17 less distinct features differ more from the legacy data, but the two sets of measurements are all within 2 cm of one another, with a median discrepancy of 1 cm. Of note is the close correspondence in the stylobate width (18.75 legacy vs. 18.746 m PG) and length (50.01 vs. 50.012 m) and the column height (5.22 vs. 5.216 m), because these measurements are of particular concern for architectural analysis and would have been taken carefully by Dörpfeld.

These are approximations of the standard error, but we can be reasonably confident that linear measurements from the PG models are unlikely to differ by much more than 20 mm from the reality. The 3-σ linear measurement error (LME) is a useful standard for architectural analysis (Luhmann 2010; Rieke-Zapp *et al.* 2009). The global LME can be estimated at 18–26 mm, whereas measurements over smaller regions — such as individual orthostate blocks that were captured within a single photograph — are more accurate, with an LME below 5 mm. Although further improvements in the PG accuracy are possible, the existing models are already well within the accuracies required for most architectural analysis (Objective #2).

Cost is perhaps the most important consideration if PG is to be widely used for the study of architecture (Objective #4). First is the hardware kit: a TS (ca. \$6,000), the camera (ca. \$4,000), a computer with adequate RAM (ca. \$3,000), and the software (*c.* \$500). The DAP will acquire a boom for raising the camera above the level of the Heraion columns (*c.* \$1,500). This kit can be reused for many jobs, and both the TS and a laptop computer are commonplace

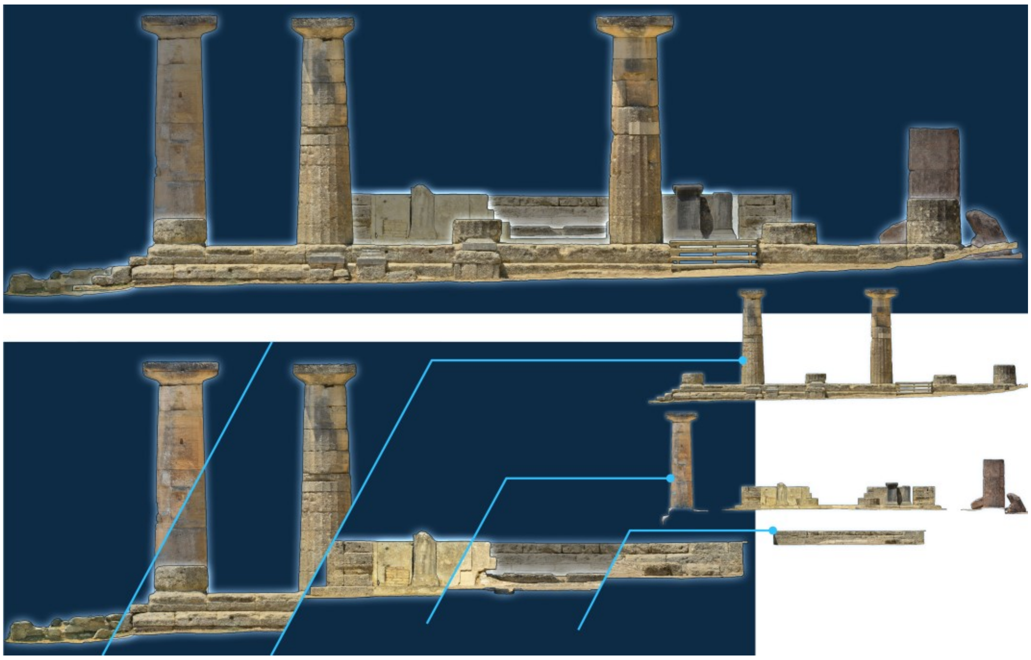

Figure 4 East elevation from the Heraion as 2.5D slices (DAP, © 2013 Sapirstein)

in fieldwork and can be borrowed or rented at minimal cost. If this hardware kit is used repeatedly, a budget of ca. $1,000 per project is conceivable.

Labor costs depend on the setting of the projet and are better reported by the hour. The TS survey lasted two days with a two-person crew (30 crew-hours). Two workers took four days to clean the site before photography (60 hours). Excluding practice sessions, photography was completed in three days (20 hours). Preparing the data in the software took 40 hours, spread out over two weeks between calculations. Cleaning, exporting, and rendering the tiles into combined 2D projections—described below—required ten days, due to some mistakes and experiments with the procedure, though could be streamlined to five days (40–80 hours). Altogether the Olympia project required about 130–170 hours for technicians and 60 hours of manual labour. The project was completed in five weeks: two on site, and three for rendering and exporting models.

Evaluation: The DAP was largely successful in meeting the five objectives laid out above. For (1) scale, the majority of the Heraion has been recorded, although the DAP is returning with a boom for aerial photographs of the taller columns. The (2) quality meets the desired resolution of 1 mm or less per texture sample. Accuracy is superior to manual illustration, although it could be refined with the addition of aerial photographs, a fixed-focal-length lens, and coded targets. The (3) practicality is well within the standards for fieldwork in Greece, with portable, commonly available equipment and inexpensive, highly automated software that can be learned within a few weeks of instruction and practice. The (4) budget is considerably less than that of 3D recording via terrestrial laser scanning, and post-processing is fast due to the clean mesh reconstruction produced by the PG software. It also is much cheaper than manual illustration, which for the Heraion would require more TS measurements and several months of drawing. I now turn to consider the final objective (5): a viable end-product.

3. Data Management and analysis

The technical limitations of current computer software and hardware have been a major obstacle to the publication of large 3D data sets (e.g. Cignoni & Scopigno 2008; Koller *et al*. 2009). The Olympia models together contain more than 200 million vertices, two gigapixels of surface textures, and 10 gigabytes of files — far too complex for simultaneous interactive display on a desktop computer, and too bulky for efficient Internet distribution. Currently the model exists as 50 separate segments. After a final season of survey and rendering, the DAP will decimate and combine the segments into a unified model for simultaneous display. However, current GPU limitations will require the elimination of about 95% of the 3D points and 80–95% of the texture detail for rapid visualization. Being no more than a small sample of the data, such a model is useful more for publicity than analysis. Even so, the file at this resolution will contain several hundred megabytes of compressed data, and an even coarser version would be needed for embedded display on a website.

The solution adopted by the DAP is to present the temple through a series of pre-rendered high-

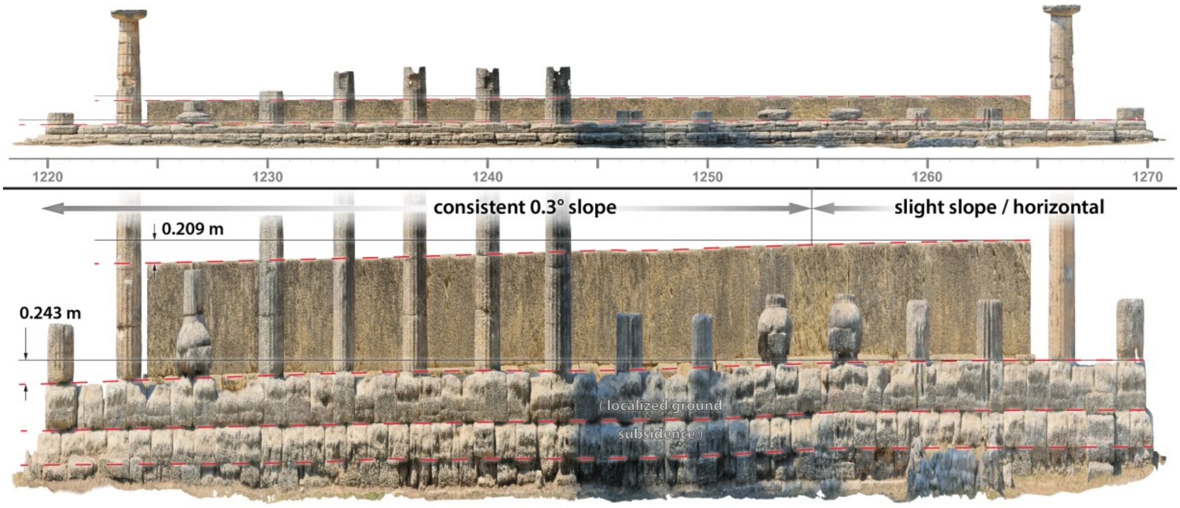

Figure 5 Horizontal inclination, viewed from the south (Below: vertical scale increased 500%; DAP, © 2013 Sapirstein)

resolution 2D views, which can be rapidly exported from the models (also see Dellepiane *et al.* 2013, De Reu *et al.* 2014). Separated into layers showing different depths of the structure, the 2D planes are orthogonal—taking advantage of the rectilinear design of the Heraion (Fig. 4). The third dimension can be retained in the flattened layers by depth-mapping, as in a DEM. This 2D/2.5D conversion has many advantages: it greatly reduces file sizes, improves interactivity, and visualizes the 3D information in a manner consistent with traditional architectural illustration, all while retaining the most critical spatial data for architectural study.

PG and architectural analysis: These 2D representations at Olympia have already led to the discovery of new features, with the potential to alter radically our understanding of the Hera temple. First, the DAP has documented clear constructional evidence to overturn the widely accepted theory that the external peristyle was initially constructed with wooden columns. Instead, these columns must have been initially executed in stone and are the same as those now *in situ*. Second, it is clear from the 3D models that the building is inclined, such that the long walls and east-west stylobates slope down substantially toward the west (Fig. 5). The consistency of these slopes throughout the building demonstrates that they were deliberately designed, although a variety of explanations can be imagined. The results will be published with my collaborator on site, David Scahill, so I will limit my discussion here to general remarks on the use of PG for analysis.

First, the PG models are as close to an objective recording as can be obtained with current methods (De Reu *et al.* 2013, 2014, Olson *et al.* 2013). Laser-scanning provides a costlier alternative to PG, and must integrate a separate camera to acquire textures at resolutions as high as those in the DAP models. This reduces the utility of laser-scans for examining the finer elements of Greek masonry such as tooling and joints. Hand-drawing is a more relevant comparison to PG, because it has been the prevailing standard for architectural recording for centuries. Drawing remains a valuable skill, but each line set to the paper reflects a choice by the illustrator. A drawing emphasizes certain elements—usually the perimeters of blocks and chiselled features—at the expense of the remainder of the building. Depending on her or his objectives and state of mind, an illustrator will often omit features during a session that may be important to another researcher. As can be seen in Figure 3 (above), the PG renderings obtained during raking light make these diagnostic features clear to an observer without eliminating other spatial and chromatic information.

The DAP recording of a subtle but consistent inclination in the Heraion platform emphasizes the importance of objectivity in recording. The slopes were briefly noted but dismissed as the result of later ground settling (Dörpfeld 1892), and all the manual renderings of the Heraion straightened out the building as if it were perfectly horizontal. Furthermore, these inclinations are difficult to record and visualize even with TS measurements due to the extensive damage of the blocks, which obscures the nature of the slope. An illustrator working on site would have difficulty understanding the nature of the slope, and like Dörpfeld would tend to turn his attention to other features of the building that are more easily intelligible to a human observer. In contrast, by collecting tens of millions of spatial measurements, the elevations from the PG model make the slopes and their consistent orientations immediately obvious. Another advantage of working with 2D imagery is that it can be compressed along one axis, like in the lower part of Figure 5, which emphasizes the slope by expanding the vertical scale by 5:1. Thus the PG analysis has revealed a critical design feature of the Heraion that has been

Figure 6 Draft design for linking remains and texts at Olympia (DAP, © 2013 Sapirstein)

overlooked for more than a century since its excavation, and is difficult to record or analyse by any other means.

Generally, the 3D data from PG allows researchers to pose questions and answer them immediately, instead of requiring a time-consuming return to the site and TS resurvey (Domingo *et al.* 2013, De Reu *et al.* 2014). One can go back repeatedly in this virtual environment to check features which were missed at first — like the sloping courses. Of course, working on the building in the field, and taking measurements by hand, still offers indispensable information. However, now that the DAP models have been created and rendered, every future visit to Olympia can be devoted to thinking through higher-level analytical problems about the temple.

4. Digital publication and the virtual museum

The 2D layers for analysis will also promote the digital publication of the Heraion. I have drafted specifications for a novel system for disseminating its models not only for publicity, but in a format amenable for detailed analysis and annotation by scholars and students alike. Currently in development, the DAP project website will allow the interactive exploration of the Heraion imagery at full resolution through the 2D layers (Fig. 6). The 3D models will be available for display at low quality embedded in the web browser, and as downloadable files for higher-quality offline display, but the core navigation will be panning and zooming through this flat, pre-rendered imagery.

The layered approach will enable the linking of the 3D models to texts and other imagery. Standard 3D data formats do not support linking with other sources of information. Methods to store annotations in 3D space are an active area of investigation, although implementations to date are experimental and have limited functionality (Aliaga *et al*. 2011, Koutsoudis *et al*. 2012, Soler *et al*. 2013, von Schwerin *et al*. 2013, Yu & Hunter 2013). There is a wide variety of information to include in a virtual museum of the Heraion in addition to its physical remains. The 3D models can be supplemented by texts, including metadata, higher-level explanatory and synthetic commentaries, and archival texts like excavation records or publications. The interface should incorporate 2D imagery, such as historical photographs or reconstruction drawings from past studies. By uniting all of the relevant knowledge about the Heraion under a single interface, the DAP website will be a 'virtual museum', replicating the types of information recorded in a print publication, even while enhancing their accessibility and clarifying their spatial relationships.

By means of web-based mapping and GIS technologies, specific coordinates or areas of the 2.5D layers from the 3D model can be linked using hypertext. This would enable a user, for example, to focus on a column setting to display further information (Fig. 6), search for all excavation notebook records referring to a particular part of the Heraion, or navigate the 3D model by clicking on features in an archival photograph. Besides providing a rich, comprehensive digital resource for the temple, this digital approach has the potential to streamline the publication process significantly. Whereas traditional architectural studies typically take a decade or more to appear in a print monograph, through this interface the DAP will be able to release high-quality imagery of the building and associated annotations as they are created. Finally, while the full 3D data set, such as the raw photographs and working models used to produce the project files, can be archived on an archaeological digital preservation service, the dissemination system described here will provide users convenient access to the polished 3D models for exploration and analysis of the Heraion.

Conclusions

In general, 3D reconstruction via PG is one of the most significant advances for the documentation and study of ancient architecture since the advent of the TS for field survey. While the TS enabled researchers to measure many 3D coordinates of points on a site, photogrammetric reconstruction offers a much greater potential. In just five weeks, the DAP successfully completed a working model of more than 95% of the Heraion, captured at 1-mm precision and rendered as a series of 3D models and layered 2D views of the building plan and elevations. Projection accuracy is good, such that linear dimensions measured from the models and images are reliable within 5 mm of reality for smaller features like individual blocks, and within 20 mm throughout the building. In addition to the high quality of the PG models, project costs and processing times are well below those of alternatives like laser-scanning or manual illustration. The data have already led to new observations about the Olympia temple and challenge the prevailing understanding of its design and phasing, which are central to hotly debated topics in architectural history such as the origins of the Doric style. The DAP plans to complete the field recording during a final season at Olympia, and then will implement the project website. This virtual museum will link the 3D models via 2D renderings to the relevant texts and images, creating a comprehensive resource for research and teaching about the Heraion.

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