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Efficient three-dimensional field documentation methods for labour cost studies: Case studies from archaeological and heritage contexts

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ABSTRACT

The aim of this paper is to present alternatives for three-dimensional field documentation methods which can be used to record architectural features for econometric labour cost studies. Combining reflectorless total station line-drawing with photogrammetry produces high-quality three-dimensional models of the targets which can subsequently be analysed to derive volumetric data of the employed building materials and the sizes of the individual elements. The case studies compare how different variations and combinations of three-dimensional architectural documentation can be used to create sufficiently accurate models for architectural energetics studies with varying degrees of time and expense in the field and in the post-processing phase of the research. The documentation method has been developed by the first author of this paper and disseminated through annual fieldschools conducted on archaeological sites. The standard documentation procedure is to establish ground control points and an alternative based on inbuilt instrument GPS systems is also discussed.

1. Introduction: architectural labour cost studies (A. Brysbaert – J. Pakkanen)

Labour cost studies, also frequently called architectural energetics and building econometrics, are based on quantification of employed materials, human and animal labour and transport. Construction is one of the key activities of all complex ancient societies and numerous studies have demonstrated the usefulness of the approach in a wide range of different regions and contexts (e.g. Stanier, 1953; Burford, 1969; Clark, 1993; Abrams, 1994; DeLaine, 1997; Bessac, 2007; de Haan, 2009; Pakkanen, 2013; Devolder, 2013; several contributions in Brysbaert et al., 2018; McCurdy and Abrams, 2019). Today, quantification of volumetric data of construction materials and the energetic/labour input (Abrams, 1994: 5) can be used to investigate socio-economic conditions and changes, and this does not stand in the way of more qualitative research of the monuments. In the latter approach the relatively objective data from the econometric calculations can be taken to the next, more interpretive level (e.g. DeLaine, 1997; Pakkanen, 2013; Brysbaert, 2018; Brysbaert and Pakkanen, in press). Quantitative research on ancient building has had its opponents (see e.g. the overview in Osborne, 2014; more recently, Voutsaki et al., 2018; for a reply, see Brysbaert and Pakkanen, in press). However, the authors of this paper regard refining the research methodology as a process. For example, studies on ancient Greek construction have exaggerated the cost of building stones largely due to referring to the exceptionally well-preserved building accounts from Epidauros (Pakkanen, 2013: 64–65). Also, there have been discrepancies in how architectural energetics data has been published and how, from time to time, such data was copied over uncritically in subsequent publications (as critiqued in Turner, 2012, 2018; Fotou, 2016).

Accurate quantification of different building materials, well-argued labour rates and material costs and transparent calculations are the key factors behind persuasive research in architectural energetics (Stanier, 1953, Abrams, 1994; DeLaine, 1997; Pakkanen, 2013; Brysbaert, 2013, 2015; McCurdy and Abrams, 2019). Thorough documentation and studies of the archaeological remains should form the basis of the volumetric data and reconstructions used in the econometric calculations (see e.g. DeLaine, 1997; Pakkanen, 2013; Lacquemont, 2019; several papers in Brysbaert et al., 2018; McCurdy and Abrams, 2019; Turner forthcoming; Boswinkel forthcoming). Current digital field documentation methods such as total station line-drawing and photogrammetry provide the means of accurate and cost-efficient data collection, reducing also the time needed for post-processing of the data. These techniques, and combining them (Pakkanen, 2018), are evaluated in this paper from the point of view of labour cost studies. The presented case studies are from

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the sphere of monumental Late Bronze Age architecture (14th–13th century BCE) and the domestic structure is considerably later, from the Hellenistic period (3rd century BCE).

2. Three-dimensional field documentation for building econometrics: methods and techniques (J. Pakkanen)

The case studies presented in this paper employ three-dimensional (3D) documentation of architecture to estimate the volumes of materials used in the labour cost calculations, and to provide a detailed recording of standing architectural remains for archaeological and heritage contexts. The recorded volumes include different materials from removing the soil and bedrock before the construction started to the size of blocks and total volume of materials used in the buildings. The tested field documentation methods include 3D line-drawing using reflectorless laser total stations, georeferenced photogrammetry, and combining these (Pakkanen, 2009, 2018; Pakkanen et al., 2019).

Photogrammetry is currently the most common choice of 3D digital architectural documentation for cultural heritage largely due to the low cost of hard- and software (for studies related to Greek contexts, see e.g. Sapirstein, 2014, 2016; Thomas, 2016; Murray et al., 2017; Pakkanen, 2018; Pakkanen et al., 2019; for a recent summary of 3D techniques for cultural heritage, see Siebke et al., 2018). Deriving accurate linear representations of the features from the models, though, is challenging (in relation to lithic artefacts, see Barone et al., 2018). In direct reflectorless total station drawing the choice of how to draw the features is made already in the field and not in the post-processing phase (Pakkanen, 2009: 3–6; 2018: 119–123). By using the laser option of the total station it is not necessary to have a second person holding the prism, so the size of the survey team is reduced to one. The instrument operator codes the start and end of each line and its attributes and stores these, and the coordinates of the points, into the total station memory (Fig. 1). These data can then be directly translated into a layered CAD drawing (on the computer program *ts2dxf.exe*, see Pakkanen, 2018: 119). The key considerations for fast and accurate drawing of the architectural features are a dense network of laser backsights (GCPs) allowing relocation of the total station to any position at the site, and keeping the instrument close to the documented targets so that oblique views of the documented targets can be avoided and the laser pointer is clearly visible (Pakkanen, 2009: 3–6).

In photogrammetry, or Structure-from-Motion (SfM) methods, 3D data is derived from two-dimensional images. The target surfaces have to be photographed from multiple viewpoints and there has to be significant overlap between the photographs. In these techniques, the geometry of the 3D objects is reconstructed on the basis of their projection onto the two-dimensional image plane of the digital camera's sensor (see e.g. Mosbrucker et al., 2017). Since 2014, the Finnish Institute at Athens (under the direction of the first author in 2013–2017) has integrated the use of 3D total station drawings with photogrammetry in its fieldwork projects and also arranged fieldschools to train colleagues and students in these methods (Pakkanen, 2018). Photogrammetry can be used to add textured surfaces to the 3D total station line-drawings. If the primary documentation method is photogrammetry, introducing 3D linear data to the models, orthomosaics and point clouds can make the subtle changes in the texture and surfaces easier to discern.

In all of the fieldwork case studies, a differential GPS (DGPS) was used to first establish a georeferenced site grid, and the location of each Ground Control Point (GCP) was subsequently resurveyed using a total station to minimise the local errors of the grid. The documentation of the first case study was employed to test the use of photogrammetry without GCPs. Relying on the inbuilt GPS receivers to model the building foundations, this strategy was used to assess if a highly cost-effective documentation method could still be sufficiently accurate for econometric calculations.

A range of reflectorless total stations were in use in the fieldschools to give the participants the possibility of becoming familiar with different generations of equipment: the oldest instrument in use was Leica TCRA1103+ and the latest Leica FlexLine TS06. The digital cameras used in photogrammetry were Canon EOS 6D with an inbuilt GPS receiver (with 20MP full frame sensor, used on Salamis) and Nikon D7200 (with 24MP sensor, at Tiryns, Menidi and Mycenae). The Unmanned Aerial Vehicle (UAV) employed on Salamis was DJI Phantom 4 (with 12MP sensor). The model of the DGPS used was Leica GS08plus. For photogrammetry, Agisoft PhotoScan was the software in use; for GIS, ArcMap,

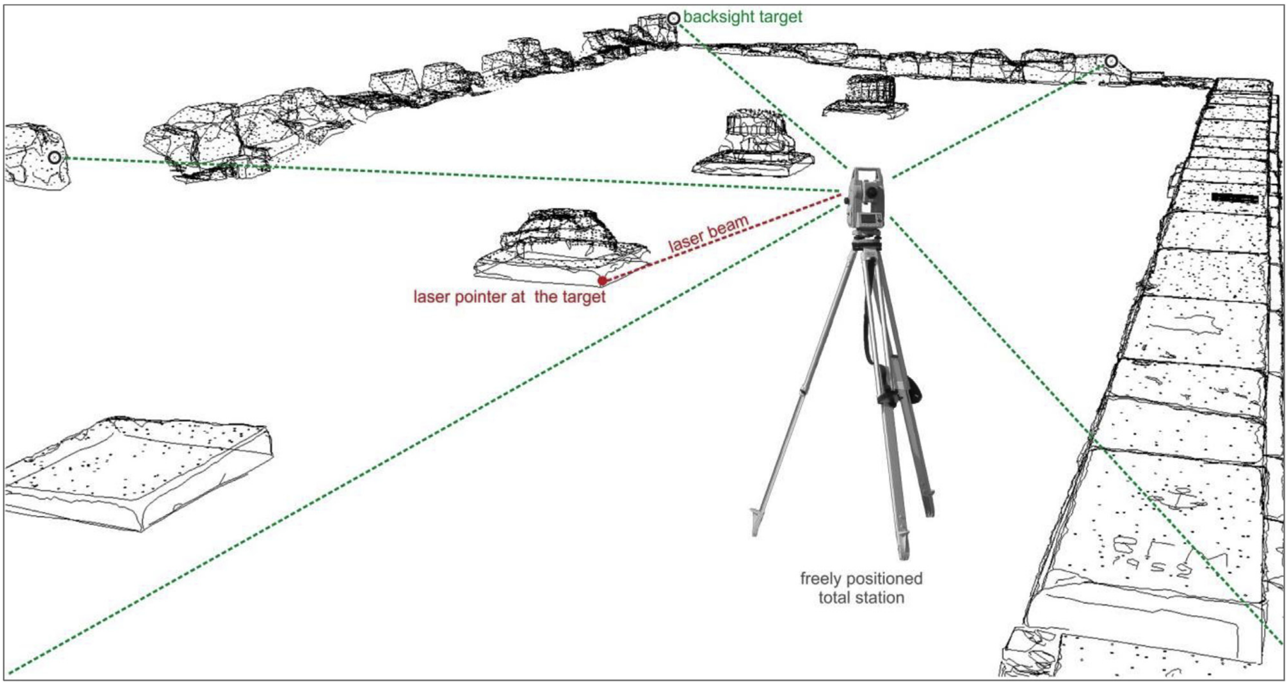


Fig. 1. The principle of total station line-drawing. The instrument is set inside the perspective projection of the surveyed wireframe model of Stoa A at Kalaureia, Poros. (J. Pakkanen).

and for CAD, AutoCAD. All post-processing has been carried out on a range of laptops.

3. Case studies on documentation

From the point of view of labour cost studies, the principal aims of documenting the architectural remains on the ground and approximating the cost of building are measuring the size of the structure and estimating the volumes of different building materials. The following case studies illustrate the range of methods used and different types of documented buildings and materials. A map of sites discussed in the paper is presented in Fig. 2.

3.1. Early Hellenistic private house on Salamis (J. Pakkanen)

Oikia Theta is the only fully uncovered house of the town centre of ancient Salamis near Athens. The private houses north of Odos Tefkrou and west of Odos Eurysakou were excavated by I. Dekoulakou in the 1990s (Dekoulakou, 2003, 2008). The finds and the architectural remains of the house have been recently published by I. Chairetakis who also had access to the excavation archives (Chairetakis, 2018: 14, 122–152). The earliest construction phase inside the boundary of the house plot can be dated to the Late Archaic period (Domi A, circa 550–500 BCE; Chairetakis, 2018: 123, figs. 140–147) and the currently visible architectural remains to the Early Hellenistic period (275–250 BCE; Chairetakis, 2018: 145–148, figs. 235–260). The stone foundations of the house are well-preserved but the mudbrick walls have entirely dissolved; a large number of curving Laconian-type roof-tile fragments was discovered in the excavations.

The ongoing *Urban Landscape of Salamis* project is a collaboration between the Finnish Institute at Athens and the Ephorate of West Attica, Piraeus and the Islands. As part of this project, the house and its surroundings were recorded in June 2016 using a UAV without carrying out extensive cleaning at the site to expose the wall foundations. In April 2018 the area was thoroughly cleared of vegetation and recorded using 3D total station drawing. In September 2019 further cleaning of the stone foundations of the house allowed additional documentation with total station and photogrammetry.

The fieldwork conducted in 2016–2019 can be used to evaluate the costs and level of expertise required to carry out the documentation work for architectural energetics. In the following, different approaches to produce the fieldwork data sets for econometric calculations are compared. Fig. 3 presents a summary of three alternatives based on GPS-referenced photographs and photogrammetry. Since not all archaeological projects have access to high-accuracy DGPS, no ground targets were used to scale and shift the resulting orthomosaics.

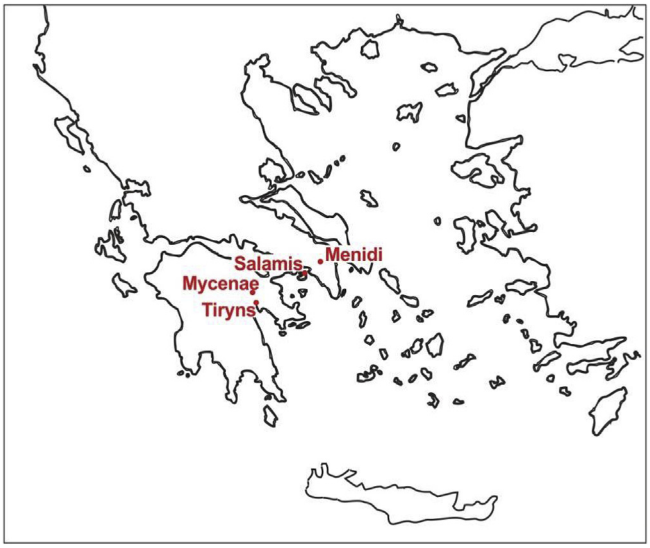


Fig. 2. Map of case studies. (J. Pakkanen).

Fig. 3a is based on 41 aerial photos taken by E. Tikkala in 2016 with a UAV and referenced using the on-board GPS. The black line drawn around Oikia Theta in the orthomosaic can be compared with the red line derived from documentation of the house georeferenced using a differential GPS and a total station. The orientation and dimensions of the house can be nearly correctly derived from the aerial documentation, though its location is shifted 1.6 m to south–southwest due to the accuracy of the UAV GPS. The size of the house plot based on the 2016 aerial documentation is only slightly smaller when compared to the DGPS-referenced data: the error is circa 1 per cent with the measured area of 280.0 square metres compared to the total station survey area of 283.2 square metres.

The orthomosaic of the 3D photogrammetry model in Fig. 3b is derived from 208 photos georeferenced using the inbuilt GPS of the handheld camera in use, Canon EOS 6D. The two-dimensional projection of the model outlined in black has substantially smaller dimensions than the house itself: the measured area is 227.8 square meters, circa 20 per cent smaller than the recorded house plot. The visible problems in the scale and orientation of the model are created by the inaccuracy of the GPS coordinates resulting in a tilted model. However, these inaccuracies are easy to correct by the introduction of a metal grid square and scales into the photographs. In Fig. 3c the location of the metal square is marked with a blue rectangle in the southeast corner of the house and the two 0.5-m scales with orange rectangles in the western and northern parts of the building. By positioning the square north to south and its shorter arm east to west it is possible to correct the tilt of the model, and the two additional 0.5-m scales ensure that the geometry of the model accurately reflects the archaeological remains throughout the area. There is hardly any discrepancy between the area of the house plot in the model and the total station measurements (283.4 vs. 283.2 square metres). The house foundations in Fig. 3c are shifted 2.8 m to the north–northeast of the DGPS-referenced location of the remains, but the difference is within the error margin of the camera's GPS.

Figs. 4 and 5 present the current situation of documentation after the 2019 campaign. The 3D line-drawing can be directly superimposed on the textured model in PhotoScan (Fig. 4 and Animation 1). The markers (GCPs) used in positioning the photogrammetry model are based on the site grid derived from a joint DGPS and total station survey. The total station was first positioned using five DGPS backsights which were subsequently resurveyed using a total station. This reduces the local grid discrepancies from centimetre-range errors using the DGPS to a maximum of a few millimetres. Using multiple backsights to position the total station ensures minimal positioning and directional errors and, equally importantly, allows free movement of the total station across the surveyed site. The reference markers (GCPs) for photogrammetry are evenly distributed around the house foundations (the blue flags in Fig. 4). The elements of the georeferenced model match with the line-drawing of the foundation stones with the accuracy of a few millimetres. Perhaps the greatest benefit of combining 3D line-drawing with photogrammetry is that the method can be used to produce highly accurate site plans (Fig. 5), sections and elevation drawings with minimal post-processing.

The econometric calculations of the construction of Oikia Theta stone foundations are based on a combination of 3D total station line-drawing and aerial photogrammetry carried out in 2016–2018 (for the cost calculation of the house, see Pakkanen, in press). However, if minimising the time spent in the field would have been the most important factor behind the decision which method to employ, we would have opted to carry out only photogrammetry. Line-drawing using multiple total stations is time-consuming, especially the recording of the foundations built largely of small to medium-size irregular stones. The purpose of the documentation fieldschools is also to train the participants to become confident in the use of the instruments and post-processing software which requires a significant number of repetitions.

a) UAV GPS; 41 aerial photos (2016)

b) Terrestrial camera with GPS; 208 photos (2019)

c) Terrestrial camera with GPS, grid square and two 0.5 m scales; 208 photos (2019)

Fig. 3. Salamis, Oikia Theta. Comparison of photogrammetry results georeferenced using inbuilt GPS receivers. Red: outline of the house remains georeferenced with a DGPS. Black: house outline based on the tested set of photographs. (J. Pakkanen). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

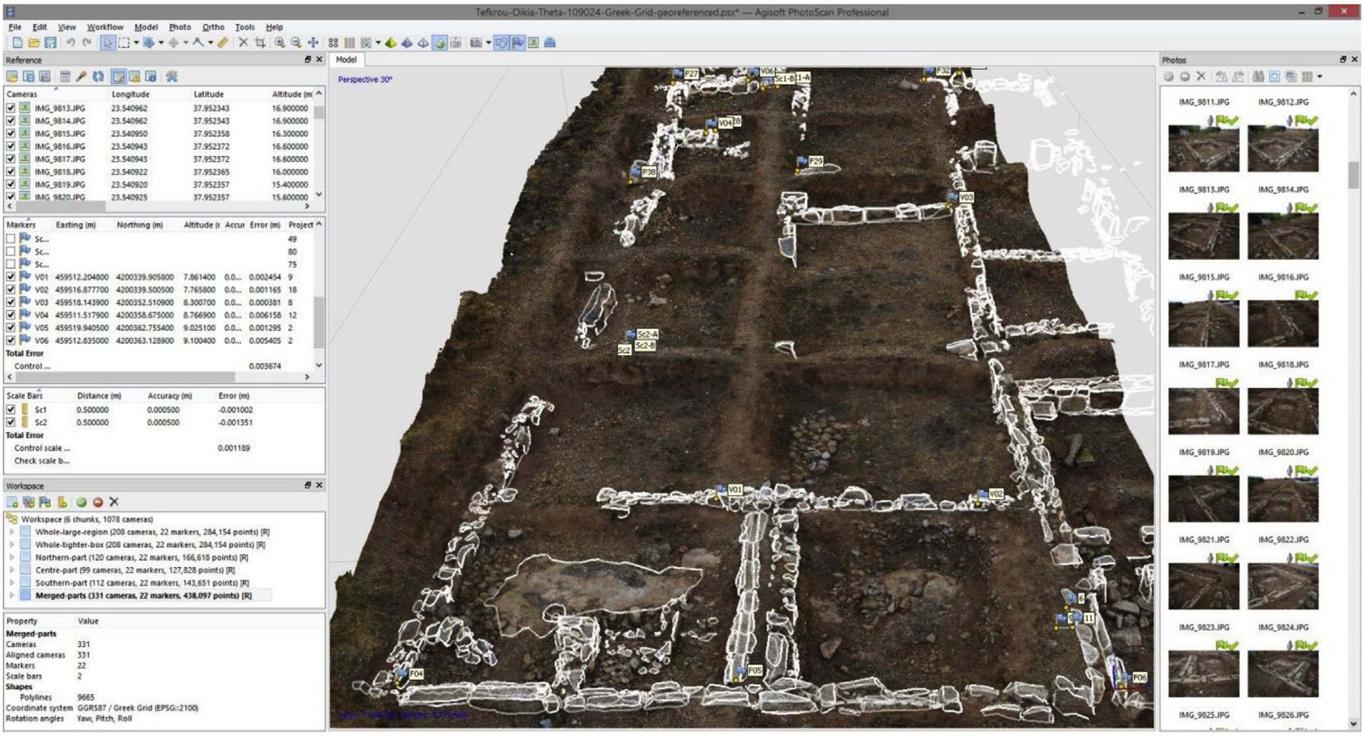
3.2. Late Bronze Age tholos tomb at Tiryns (A. Brysbaert)

The tholos tomb at Tiryns, with another unpublished one just adjacent to it, is located about 1 km east of the Tiryns citadel and is dug deep into the hill of Profitis Ilias. Its dromos is circa 13 m long, 2 m wide and runs west-east towards the entrance of the tomb chamber. The stomion measures 4.10 m in height and 4.7 m in depth and it is wider towards the bottom of the entrance (Fig. 6). The ceiling of this stomion leading into the chamber is built of three very large limestone lintel blocks, one of which is about 6.5 tonnes in weight. Apart from these and the upright large stomion jambs, the corbelled tholos is built of smaller and larger blocks placed almost in regular courses all the way to the capstone. On the outside façade of the stomion plaster remains can still be seen (Fig. 7); this was not an uncommon feature (Konstantinidi-Syvridi et al., 2015). Although this tomb was found completely empty of mortuary finds, it has been dated by Fitzsimons (2011, following Wace, 1921) to the 15th century BCE on the basis of stylistic criteria (this date is also followed in Brysbaert, 2018). However, Pelon (1976: 181) refers to Wace's suggestion (Wace, 1949: 17–18) that this tomb may be dated, instead, to the LH III period and would thus be a contemporary to the tholos found at the nearby Dendra cemetery and some of the later ones at Mycenae. Also Müller (1975) dates the tomb to LH III.

The tomb was documented in spring 2018 using georeferenced photogrammetry by A. Brysbaert with the help of I. Vikatou. The GCPs for the grid were established in June 2017 with a DGPS around the tomb entrance. A total station was used to measure 41 georeferenced markers along and above the dromos, the stomion, and the beehive chamber. The final point taken was at the capstone of the vault using the laser pointer of the total station. All 41 points were drawn on removable stones since no permission to draw these directly on the tholos stonework was given.

Before photography for photogrammetry could be carried out, vegetation growing between the stones was cleared. All green growth was clipped and removed while none of the roots themselves were taken away since these had grown into the actual structure and would destabilise the stonework if pulled out. For photogrammetry, the georeferenced photomarkers were recorded in their wider setting. The sets of photographs cover the dromos and a stretch of surface on both sides, the stomion, the entire inside of the tholos, and the earth cover on top outside. The photography outside was carried out at overcast moments to keep the lighting constant. The 3D model has been produced from 1311 photographs, and in PhotoScan the sets were divided into three chunks in order to speed up the post-processing. One chunk covers the beehive chamber and the stomion and the other two the dromos and the stomion to ensure enough overlap to join the two parts. Fig. 8 shows a 3D photogrammetry model of the tomb. The high number of photographs and reference points ensures that all necessary views of the tomb can be accurately produced in post-processing.

For the actual econometric calculations of the building of this tholos tomb, the data obtained by this 3D documentation will be compared in detail with the existing documentation data which can be extracted from Müller's line-drawings (Müller, 1975: Beilage 1–2). Part of the goal of this comparison is to assess the usefulness of the time spent on fieldwork rather than employing older published data already available. Based on a preliminary assessment of the 3D model, its plan and section (Fig. 9 and Animation 2), the height from the top to the bottom of the orthostate course and the diameter of the tholos are 7.25–7.26 m and 8.47–8.57 m. The discrepancies between these and Müller's dimensions (1975: 3–4: 7.50 m, 8.45–8.50 m) are not highly significant, but the new



Cameras	Longitude	Latitude	Altitude (m)
☑ IMG_9813.JPG	23.540962	37.952343	16.900000
☑ IMG_9814.JPG	23.540962	37.952343	16.900000
☑ IMG_9815.JPG	23.540950	37.952358	16.300000
☑ IMG_9816.JPG	23.540943	37.952372	16.600000
☑ IMG_9817.JPG	23.540943	37.952372	16.600000
☑ IMG_9818.JPG	23.540922	37.952365	16.000000
☑ IMG_9819.JPG	23.540920	37.952357	15.400000
☑ IMG_9820.JPG	23.540925	37.952357	15.600000

Markers	Easting (m)	Northing (m)	Altitude (r	Accur	Error (m)	Project
☐ Sc...						49
☐ Sc...						80
☐ Sc...						75
☑ V01	459512.204800	4200339.905800	7.861400	0.0...	0.002454	9
☑ V02	459516.877700	4200339.500500	7.765800	0.0...	0.001165	18
☑ V03	459518.143900	4200352.510900	8.300700	0.0...	0.000381	8
☑ V04	459511.517900	4200358.675000	8.766900	0.0...	0.006158	12
☑ V05	459519.940500	4200362.755400	9.025100	0.0...	0.001295	2
☑ V06	459512.835000	4200363.128900	9.100400	0.0...	0.005405	2
Total Error						
Control ...					0.003674	

Scale Bars	Distance (m)	Accuracy (m)	Error (m)
☑ Sc1	0.500000	0.000500	-0.001002
☑ Sc2	0.500000	0.000500	-0.001351
Total Error			
Control scale ...			0.001189
Check scale b...			

Workspace (6 chunks, 1078 cameras)
- Whole-large-region (208 cameras, 22 markers, 284,154 points) [R]
- Whole-tighter-box (208 cameras, 22 markers, 284,154 points) [R]
- Northern-part (120 cameras, 22 markers, 166,618 points) [R]
- Centre-part (99 cameras, 22 markers, 127,828 points) [R]
- Southern-part (112 cameras, 22 markers, 143,651 points) [R]
- **Merged-parts (331 cameras, 22 markers, 438,097 points) [R]**

Property	Value
Merged-parts	
Cameras	331
Aligned cameras	331
Markers	22
Scale bars	2
Shapes	
Polylines	9665
Coordinate system	GGRS87 / Greek Grid (EPSG::2100)
Rotation angles	Yaw, Pitch, Roll

Fig. 4. Salamis, Oikia Theta. Textured photogrammetry model with 3D total station line-drawing of the architectural remains. Georeference-markers highlighted with blue flags. (J. Pakkanen). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

documentation will make possible more accurate measurements of the sizes of the blocks and estimates of the total volume of building materials.

3.3. *Late Bronze Age tholos tomb at Menidi (D. Turner)*

The Menidi tholos in Acharnes 11 km north of Athens city centre was used primarily during the LH IIIA–B period (ca. 1400–1200 BCE), though finds in the entrance passage indicate a persistent tomb- cult centuries later (Alcock, 1991: 451; Antonaccio, 1994: 402; Whitley, 1988: 176). Excavations led by the German Institute in 1879 left detailed drawings and a notable haul of rare grave offerings (Lolling et al., 1880; Stubbings, 1947). Apart from its impressive contents Menidi, has received little attention on its own. Comparisons have been made in passing for its mortuary customs – notably a raised area or 'bench' (now gone) within the burial chamber (Kontorli-Papadopoulou, 1995: 118) – and its architectural form in terms of other, better known tholoi. The tomb falls into Pelon (1976: 338–339, 391) Type II Class C with masonry similar to Thorikos and Marathon and a size on par with Tiryns, Prosymna, and Vapheio (Fitzsimons, 2006: 153), having a dromos (entrance passage) 27 m long and burial chamber diameter just under 8.5 m.

The stonework at Menidi, however, is memorably terrible. Small, 'rough schist slabs' run in dizzying courses that are fractured and patched (Cavanagh and Laxton, 1981: 111). The dromos has a clear break in stonework showing collapse and hasty reconstruction of the upper walls with rubble and very different stone types intermixed. What appeared to be patches of poured concrete at a glance points to reconstruction for stability after excavation. The chamber's apex has shifted slightly, likely from millennia of seismic activity, and small stones shaking loose from the roof of the chamber prompted recent installation of a net. Balancing on fractured laminar stones stacked nearly 9 m high, it is remarkable that the hypotholion has not collapsed and taken much of the roof with it. In a similar engineering gamble, an experimental relieving system of large stacked slabs (Fig. 10) set with horizontal gaps above the stomion (threshold) offers no mechanical advantage beyond a simple trabeated style (Cotterell and Kamminga, 1990: 120–121; Fitchen, 1986: 208). Structurally questionable as it is, it is one of the few bold choices remaining from Menidi's builders. Architectural choices here, taken together with the tomb's contents and location, suggest socio-political distance from Athens (Mee and Cavanagh, 1990: 239–242), and the commissioners of the tomb, particularly their role in the wider network of Attica's LH III sites, would be worth further study.

For all its challenges, Menidi held much potential for digital modelling and architectural study. Fieldwork to that end was undertaken in late June and early July 2016. Drawing the stones with total stations proved too laborious to complete in the available time, although an earnest attempt drew nearly every stone below the safety net within the chamber and a few representative samples from the dromos, resulting in more than 21,000 total station measurements. Those several hundred drawn stone samples aligned well with the concurrent photogrammetric modelling, which captured what the stations and our eyes could not in the half light of the chamber. Being large and light enough for focusing cameras with little effort, the chamber performed better than expected in its photomodel. Stones camouflaged by shadows and staining, or fractured enough to frustrate us with forced arbitrary drawing choices, were captured accurately. The craggy stonework also provided as many ledges as one could reach for placing temporary photomarkers, in this case gravel pebbles painted with a target and carefully placed among the original stones at varying heights. Separate models captured the brightly lit dromos and dim burial chamber, requiring the two to be refitted into the model depicted in Fig. 11 and Animation 3. Since we found Agisoft PhotoScan to function better with a minimal number of photos with the processing power available, fewer than 160 photos and 10 photopoint markers for each model sufficed to capture the dromos and burial chamber. Volume and linear measurements derived from these models aided an ongoing tomb and labour comparative study (Turner forthcoming).

3.4. *Late Bronze Age fortification at Mycenae (Y. Boswinkel)*

The site of Mycenae needs little introduction. As the namesake of an entire epoch, Mycenae is well-known for its rich (mythological) past as

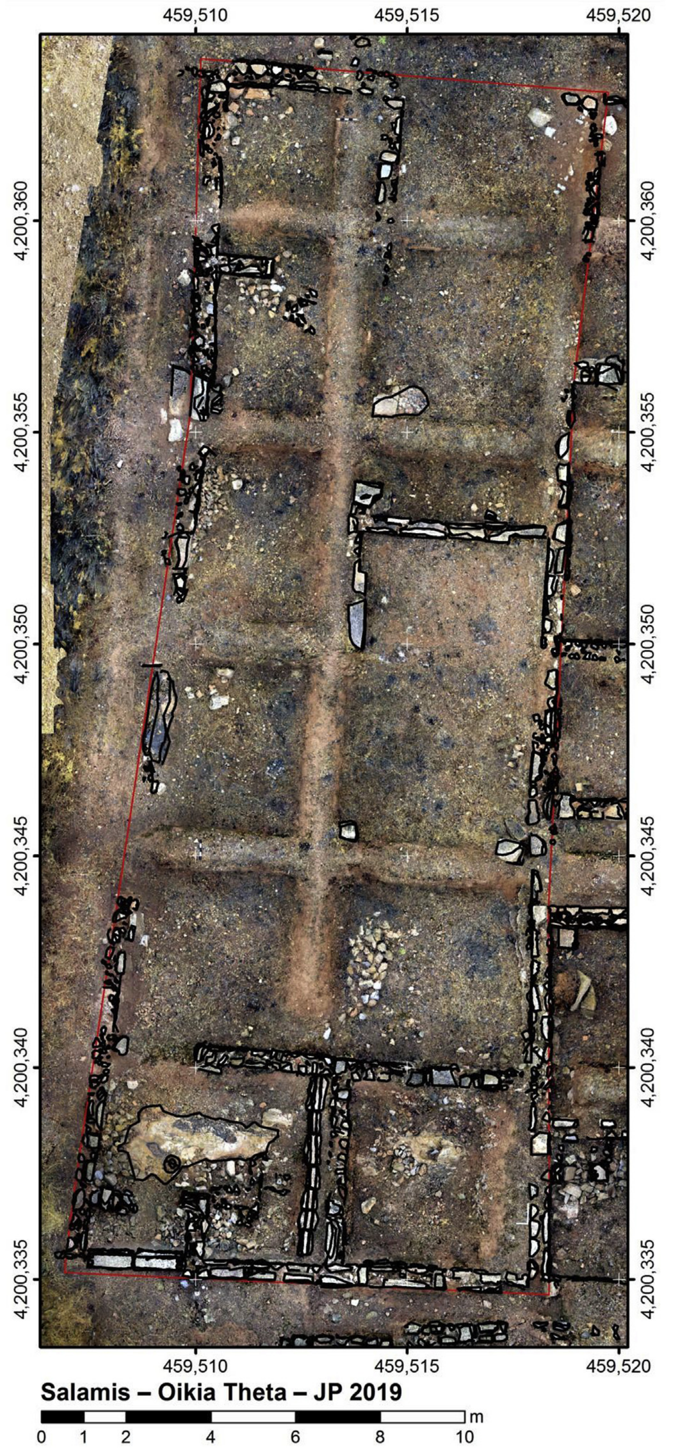


Fig. 5. Salamis, Oikia Theta. Orthomosaic with total station line-drawing. (J. Pakkanen).

Fig. 6. Tiryns, tholos tomb. View of the stomion narrowing towards the top. (A. Brysbaert).

well as the long excavation and research history (e.g. Schliemann, 1878; Wace, 1921; Mylonas, 1966; Iakovidis, 1983; Iakovidis et al., 2003). The site is located in the eastern Peloponnese and has numerous features that are potentially interesting for labour cost studies (see e.g. Cavanagh and Mee, 1999; Fitzsimmons, 2006; Harper, 2016; Boswinkel forthcoming). Within the context of the SETinSTONE research (see acknowledgements), our focus here lay on the impressive fortification walls which enclose an imposing 3 ha (Simpson and Hagel, 2006). Due to the size it would be impractical, if not impossible, to document the entire fortification with terrestrial photogrammetry and total station line-drawing. Rather, a selection was made to document a relevant sample (Fig. 12). This selection comprises sections on both the inner face as well as the outer face of the wall. Furthermore, it encompasses different stages of the two expansions of the fortifications at the site: the West Wall, both the Lion and North Gate and finally the North East Extension (cf. Iakovidis, 1983: 29–37). Furthermore, with the experience gained during fieldwork at Menidi, we limited total station documentation to parts of the selected sections of the wall while covering entire sections with photogrammetric modelling.

Similar to Tiryns and Menidi, no markings of any kind could be placed on the walls at Mycenae, so we also used small loose stones wedged between the stones here for reference points. Unlike the tombs at Tiryns and Menidi, the walls at Mycenae are built in cyclopean style. This technique is characterised simply by the presence of large boulders with smaller stones intermixed (e.g. Loader, 1998: 1), as seen in Fig. 13 and Animation 4. The rough shapes of the stones challenged decisions on what line to follow with the total station to accurately record the blocks. The obscure fracturing and shadowing at Menidi did not hinder work here. Two different issues arose at Mycenae. First, due to the height of some sections (up to 9 m) it was often difficult to properly document the upper courses with the total station. Ideally, the total station is moved so that it is always in the most opportune position for unobstructed sight-lines (Pakkanen, 2009: 4). Higher walls prevent views from above, unless a drone is available for photogrammetric modelling (Boswinkel forthcoming). Roughly shaped blocks compound the problem of obscured lines. These difficulties extended to photo documentation, since for most sections there were no opportunities to take photos from an elevated position. The spread of locations from which the photos are taken helps the modelling process. The limited range in height of the photos taken (between 0.3 and 2.4 m above ground level) restricted resolution of the upper courses.

Recording by total station and photos both have their merits, but in terms of the aims of this research, the latter was definitively more suited

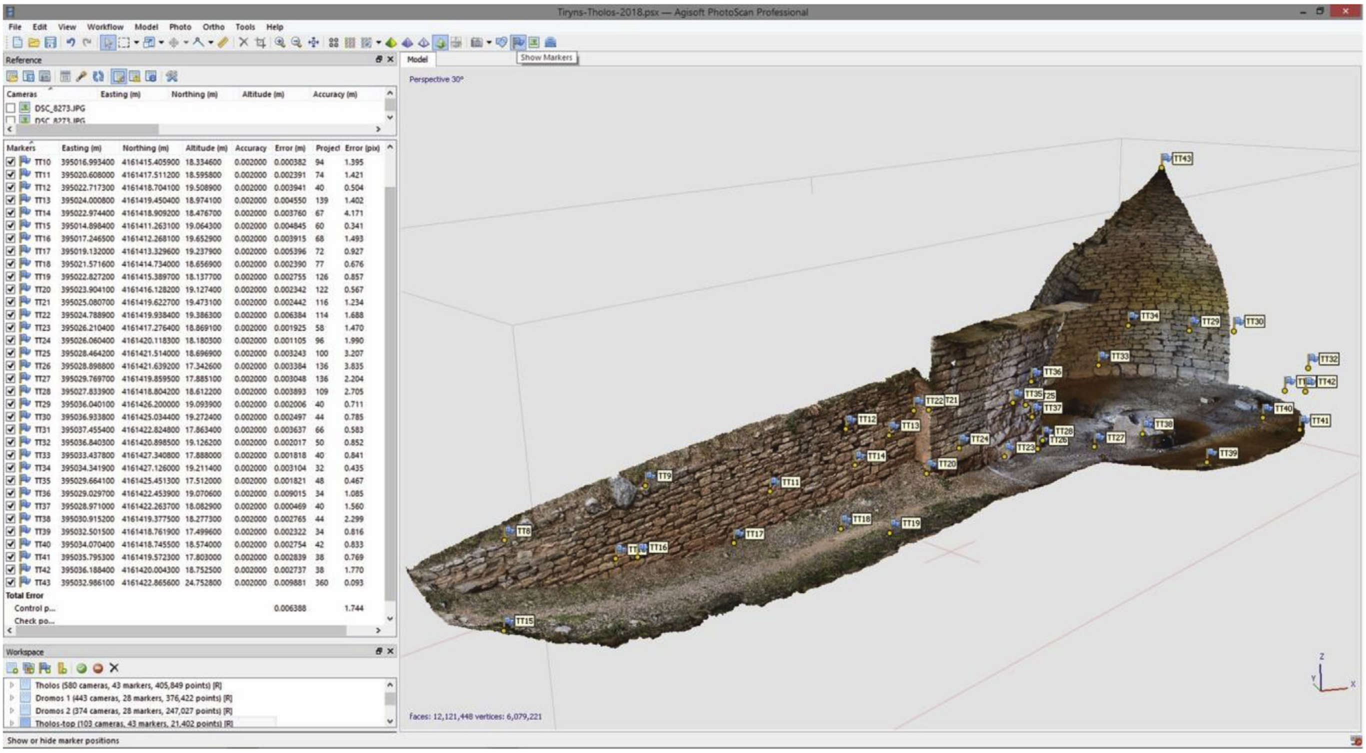
Fig. 7. Tiryns, tholos tomb. Remains of (painted?) plaster clearly visible on the façade-side of the stomion. (A. Brysbaert).

than the first. The volume of the walls and preferably even the blocks were required for the calculations of the labour investment required of these fortification walls (Boswinkel forthcoming). The high level of detail that can be documented with the total station, such as marks and cracks in the individual blocks, were not necessary from the point of view of building econometrics. The high speed and accuracy of photogrammetry supplies the required data for volume calculations.

4. Results and discussion

Based on the fieldwork on Salamis, using the UAV-based photogrammetry model (Fig. 3a) as the starting point of the econometric calculations would not introduce a significant additional error compared to using a DGPS and a total station to reference the documentation (Fig. 5). However, both of these alternatives introduce a substantial additional cost in hardware and expertise, and also the process of getting a permit to fly a UAV in an archaeological area in Greece can be rather complicated. Therefore, the option of using a terrestrial camera with an inbuilt GPS and reference scales (Fig. 3c) is the most cost-effective and precise alternative of the three GPS-based alternatives. If the digital camera in use does not have a GPS, it is also possible to record the locations where the photos are taken using a handheld device or a smartphone with a geologger, and to add the coordinate information in post-processing to the metadata of the images. Combining total station line-drawing with photogrammetry has been found highly useful both for the analysis of the building material volumes and subsequent architectural study of the house.

At Tiryns, the produced photogrammetric model is highly accurate in comparison with the older line-drawing. The average error of the 37 control points distributed around the tholos is 6 mm (Fig. 8). The new 3D model will be highly useful in the planning of any conservation measures of the monument in the future. Since the walls of the dromos are bulging and plant growth affects their stability, consolidation work will need to be carried out soon. Perhaps a full total station drawing of each individual stone would serve such purpose even better but, as indicated by D. Turner and Y. Boswinkel for Menidi and Mycenae (see below), the accuracy of photogrammetry is high enough to work with, even for such



Cameras	Easting (m)	Northing (m)	Altitude (m)	Accuracy (m)
☐ DSC_8273.JPG				
☐ DSC_8273.JPG				

Markers	Easting (m)	Northing (m)	Altitude (m)	Accuracy	Error (m)	Project	Error (pix)
☑ TT10	395016.993400	4161415.405900	18.334600	0.002000	0.000382	94	1.395
☑ TT11	395020.608000	4161417.511200	18.595800	0.002000	0.002391	74	1.421
☑ TT12	395022.717300	4161418.704100	19.508900	0.002000	0.003941	40	0.504
☑ TT13	395024.000800	4161419.450400	18.974100	0.002000	0.004550	139	1.402
☑ TT14	395022.974400	4161418.909200	18.476700	0.002000	0.003760	67	4.171
☑ TT15	395014.898400	4161411.263100	19.064300	0.002000	0.004845	60	0.341
☑ TT16	395017.246500	4161412.268100	19.652900	0.002000	0.003915	68	1.493
☑ TT17	395019.132000	4161413.329600	19.237900	0.002000	0.005396	72	0.927
☑ TT18	395021.571600	4161414.734000	18.656900	0.002000	0.002390	77	0.676
☑ TT19	395022.827200	4161415.389700	18.137700	0.002000	0.002755	126	0.857
☑ TT20	395023.904100	4161416.128200	19.127400	0.002000	0.002342	122	0.567
☑ TT21	395025.080700	4161419.622700	19.473100	0.002000	0.002442	116	1.234
☑ TT22	395024.788900	4161419.938400	19.386300	0.002000	0.006384	114	1.688
☑ TT23	395026.210400	4161417.276400	18.869100	0.002000	0.001925	58	1.470
☑ TT24	395026.060400	4161420.118300	18.180300	0.002000	0.001105	96	1.990
☑ TT25	395028.464200	4161421.514000	18.696900	0.002000	0.003243	100	3.207
☑ TT26	395028.898800	4161421.639200	17.342600	0.002000	0.003384	136	3.835
☑ TT27	395029.769700	4161419.859500	17.885100	0.002000	0.003048	136	2.204
☑ TT28	395027.833900	4161418.804200	18.612200	0.002000	0.003893	109	2.705
☑ TT29	395036.040100	4161426.200000	19.093900	0.002000	0.002006	40	0.711
☑ TT30	395036.933800	4161425.034400	19.272400	0.002000	0.002497	44	0.785
☑ TT31	395037.455400	4161422.824800	17.863400	0.002000	0.003637	66	0.583
☑ TT32	395036.840300	4161420.898500	19.126200	0.002000	0.002017	50	0.852
☑ TT33	395033.437800	4161427.340800	17.888000	0.002000	0.001818	40	0.841
☑ TT34	395034.341900	4161427.126000	19.211400	0.002000	0.003104	32	0.435
☑ TT35	395029.664100	4161425.451300	17.512000	0.002000	0.001821	48	0.467
☑ TT36	395029.029700	4161422.453900	19.070600	0.002000	0.009015	34	1.085
☑ TT37	395028.971000	4161422.263700	18.082900	0.002000	0.000469	40	1.560
☑ TT38	395030.915200	4161419.377500	18.277300	0.002000	0.002765	44	2.299
☑ TT39	395032.501500	4161418.761900	17.499600	0.002000	0.002322	34	0.816
☑ TT40	395034.070400	4161418.745500	18.574000	0.002000	0.002754	42	0.833
☑ TT41	395035.795300	4161419.572300	17.803000	0.002000	0.002839	38	0.769
☑ TT42	395036.188400	4161420.004300	18.752500	0.002000	0.002737	38	1.770
☑ TT43	395032.986100	4161422.865600	24.752800	0.002000	0.009881	360	0.093
Total Error							
Control p...					0.006388		1.744
Check po...							

Tholos (580 cameras, 43 markers, 405,849 points) [R]
Dromos 1 (443 cameras, 28 markers, 376,422 points) [R]
Dromos 2 (374 cameras, 28 markers, 247,027 points) [R]
Tholos-top (103 cameras, 43 markers, 21,402 points) [R]

faces: 12,121,448 vertices: 6,079,221

Show or hide marker positions

Fig. 8. Tiryns, tholos tomb. 3D photogrammetry model with combined plan and section views. (A. Brysbaert – J. Pakkanen).

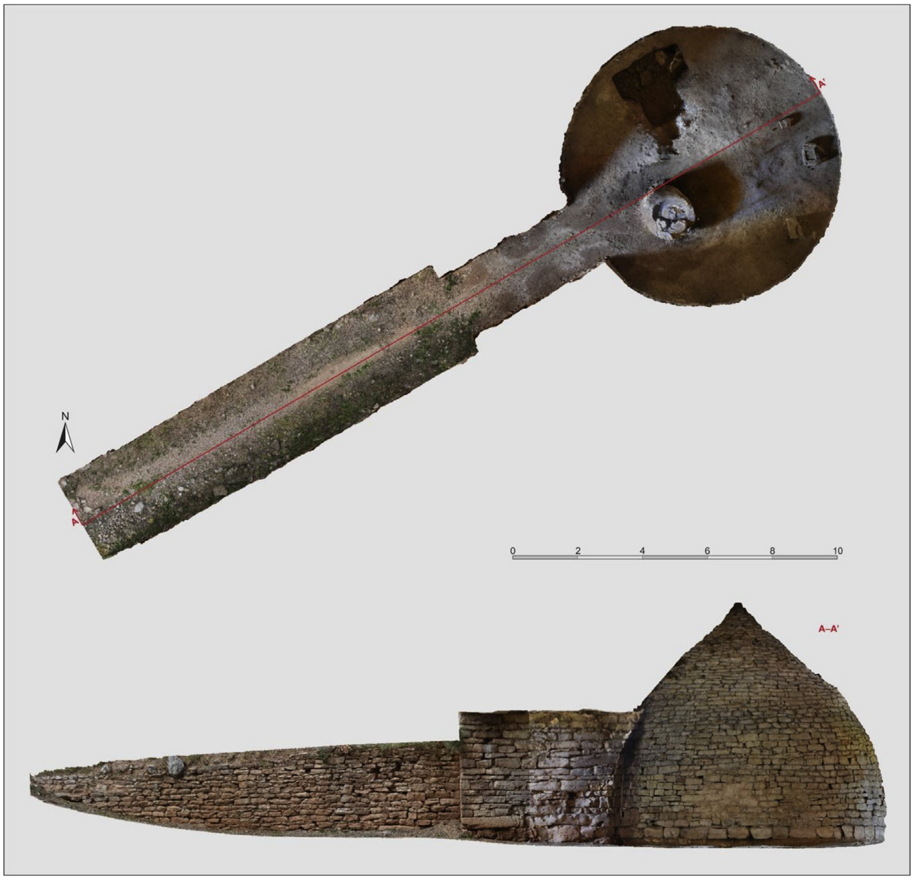


Fig. 9. Tiryns, tholos tomb. Plan and section derived from the 3D photogrammetry model. (J. Pakkanen – A. Brysbaert).

Fig. 10. Menidi, tholos tomb. Façade showing stacked slabs above the stomion. (D. Turner).

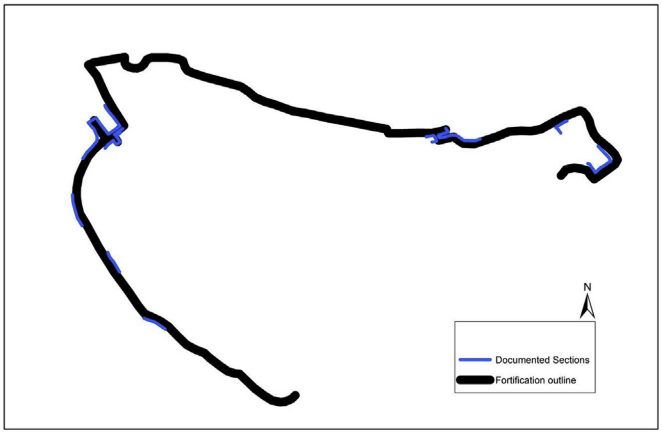


Fig. 12. Mycenae, citadel. Documented sections using total station line-drawing. (Y. Boswinkel).

Fig. 11. Menidi, tholos tomb. Cross-section of photogrammetric model for the tholos, facing southwest. (D. Turner).

Fig. 13. Mycenae, citadel. A section of cyclopean-style wall with the large boulders and smaller stones in between (left), showing contrast with the well-fitting stones of a later Hellenistic repaired section of the wall (right). (Y. Boswinkel).

purposes. Moreover, the photogrammetry model emphasises the three-dimensionality of the monument compared to two-dimensional images and aids the recognition of potential issues in stability of specific sections of the stone work.

Architectural documentation of the Menidi tholos benefited mostly from photogrammetry. Insufficient lighting, safety netting, and irregular slabs stacked more than 8 m high in the burial chamber limited use of total station drawing to representative sections. Visibility was the determining factor. While stonework near eye-level could be comfortably drawn, courses more than a metre above or below that mark were less reliable. Backsighting necessitated a walking corridor between the total stations and the walls, leaving a gap that proved troublesome to discerning the edges of dark stones in very low lighting. Irregular shapes seldom presented ‘faces’ to outline without arbitrary choices, and split beams were a frequently encountered error where edges veered out of view. Ideally, temporary scaffolding could improve visibility for recording upper courses within both the burial chamber and the dromos. More intensive documentation, including detailed three-dimensional drawings, may prove necessary in the short-term if the upper courses destabilise further.

At Mycenae, it is clear that photogrammetry is the preferred documentation method as the potential of total station recording of minor details is somewhat lost on the cyclopean walls. This is particularly the case in light of the need for building material volumes in the labour cost study. More detailed information can certainly aid in fine-tuning the calculations, yet bigger issues at play here, such as the difficulties of determining the volume of individual blocks, have a far larger influence on the calculations of the required investments. Nevertheless, the photogrammetry models allowed some nuances to be found that previous studies have overlooked. In light of such results, the used approach with an emphasis on photogrammetry, improved the understanding of the actual construction of the fortification walls at Mycenae.

Based on the four case studies employing photogrammetry, the varying sensor size and resolution of the different cameras did not have a significant effect on the usefulness of the 3D models in labour cost calculations (for a recent general evaluation of the use of consumer-grade digital cameras in photogrammetry, see Mosbrucker et al., 2017). Sub-centimetre accuracy of the models can be comfortably achieved with diligent use of georeferenced GCPs.

5. Conclusions

Photogrammetry is currently the most widely used method for 3D recording of architecture in archaeological contexts, largely due to the low cost of both soft- and hardware. As demonstrated by the case studies of this paper, the full procedure of establishing site grids with georeferenced GCPs, measuring the accurate locations of the photo-markers with a total station, taking several sets of photographs and producing the preliminary 3D models can be comfortably achieved even during short field campaigns. This makes it possible to return to the site during the same season and to take additional photographs or even full new sets. Cleaning the target area is in many cases the most labour-intensive part of the documentation projects.

In this paper we have explored the feasibility of combining photogrammetry with 3D line-drawing using reflectorless total stations. Both techniques can be used to produce the data sets needed for volumetric building material data for econometric modelling of architecture. Accurate textured models, the speed of recording even the large structures and resulting lower cost of fieldwork are perhaps the greatest advantages of photogrammetry. However, if it is also necessary to produce traditional architectural line-drawings for publication, these are quick to produce based on total station documentation (Pakkanen, 2009, 2018). The limitations of total station documentation discussed in relation to Menidi and Mycenae above are rather site-specific: better lighting and the possibility of moving the total stations more freely would compensate for the problems with the sightlines.

The importance of field-training in architectural and archaeological contexts cannot be excessively emphasised. The effects of varying conditions have to be learned in the field. Total station line-drawing is quick to learn and requires rather limited post-processing on the computer. Photogrammetry is more site-dependent and, in the beginning, requires testing out which sets of photographs work out the best to produce sufficient detail while facing the limited processing capacity available in the field. The first author of this paper has trained colleagues and students in 3D documentation in the field since 2008 and specific annual fieldschools at Tiryns and Salamis were organised in 2014–2017: all participants have learned the use of total stations and become productive members of the documentation teams, as has also been witnessed by all authors of this paper.

CRediT authorship contribution statement

Jari Pakkanen: Conceptualization, Data curation, Funding acquisition, Resources, Investigation, Methodology, Project administration, Visualization, Writing - original draft. **Ann Brysbaert:** Conceptualization, Data curation, Funding acquisition, Resources, Investigation, Project administration, Supervision, Visualization, Writing - original draft. **Daniel Turner:** Data curation, Investigation, Writing - original draft. **Yannick Boswinkel:** Data curation, Investigation, Writing - original draft.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.daach.2020.e00141.

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