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New technology and archaeological practice. Improving the primary archaeological recording process in excavation by means of UAS photogrammetry

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ABSTRACT

In the last decade, archaeological fieldwork has seen the increasing use of Unmanned Aerial Systems (UASs, also: drones) and photogrammetrical techniques as tools for mapping archaeological traces in two and three dimensions. Drones allow for great control over the collection of imagery and in combination with photogrammetry put airborne 3D data capture at the disposal of archaeologists, whether they are dealing with excavations, monuments, or complete landscapes. The success of applying any new tool must however be judged in the end by a careful assessment of its tangible improvements of the primary data collection process considering expended project resources. In this context, it is important to point out that the added value of producing, often still laborious, 3D models for the primary process of data collection in field archaeology is not yet completely self-evident. Although 3D recording may be a useful additional layer of documentation for those who can afford it, the question remains to what degree the time, equipment and personnel investment actually improves our capabilities of doing archaeology. In this paper, I propose a new, well-defined, transparent and standardized mapping approach based on the combination of a budget UAS and straightforward photogrammetrical techniques, fully embedded in the workflow of knowledge production in archaeological excavation. I will reflect on the future potential of this approach, as well as engage with the ongoing discussion about developments in the processes of documentation and interpretation.

1. Introduction

In the last decade, archaeological fieldwork has seen the increasing use of Unmanned Aerial Systems (UASs) and photogrammetrical techniques as tools for mapping archaeological traces in two and three dimensions. This is perhaps no surprise. On the one hand, the use of data from remote sensing techniques such as aerial photography and satellite imagery, as well as Digital Elevation Models, are already firmly established as techniques for studying archaeological landscapes. And on the other hand, technical scale drawing of archaeological features and objects has been part of archaeological documentation since the dawn of the discipline. Given these traditions, it is evident that many archaeologists have been quick to explore the possibilities of these new tools and have been keen to engage in site-based experimentation. The reduced costs of UAS, in particular, has encouraged their deployment for aerial photography in studying a wide range of archaeological sites and landscapes (e.g. Brenningmeyer et al., 2015; Campana, 2017; Fernández-Hernandez et al., 2015; Lambers et al., 2007; Lang et al., 2015; Ostrowski and Hanus, 2016; Remondino et al., 2011; Rinaudo

et al., 2012; Sauerbier and Eisenbeiss, 2010; Stek, 2016; Verhoeven, 2009; Wernke et al., 2016). The optimization of Image Based Modeling techniques with Structure from Motion (SfM, see for explanation James and Robson, 2012) approaches for which the algorithms have seen rapid improvement, paved the way for comprehensive photogrammetry software, and made recording of 3D data with budget cameras possible, in the lab as well as in the field (for excavation e.g. Caro et al., 2016; Dellepiane et al., 2012; Dell'Unto et al., 2017; Doneus et al., 2011; De Reu et al., 2014; Forte, 2014; Olson et al., 2013; Roosevelt et al., 2015; Willemsen and Seubers, 2015; for architecture e.g. Lambers et al., 2007; Sapirstein, 2016; Wernke et al., 2016). A combination of the two techniques allows for precise orthomapping, and the concept of using an 'airborne camera' in combination with photogrammetry techniques for documenting landscapes in three dimensions has also been the subject of many studies (e.g. Barsanti et al., 2012; Brenningmeyer et al., 2015; Campana, 2017; Howland et al., 2014; Lang et al., 2015; Fernández-Hernandez et al., 2015; Ostrowski and Hanus, 2016; Prins et al., 2014; Remondino et al., 2011; Rinaudo et al., 2012; Sauerbier and Eisenbeiss, 2010; Sordini et al., 2016; Verhoeven, 2009; Verhoeven

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et al., 2012; Wernke et al., 2016). Drones allow for great control over the collection of imagery and in combination with photogrammetry put airborne 3D data capture at the disposal of archaeologists, whether they are dealing with excavations, monuments, or complete landscapes.

The success of applying any new tool must however be judged in the end by a careful analysis which weighs up investments against the yields. Of course there must be room for experimentation, and 3D models are clearly valuable for the purposes of public outreach, digital conservation and teaching. But for scientific data collection which, at least in archaeology, is very much under pressure these days, a reflexive stance is in order (also advocated in general for the application of digital tools by e.g. Gordon et al., 2016: 10; Kersel, 2016: 489). For the primary archaeological process, employing digital tools needs to bring clear improvements, demonstrable by well-defined, transparent and standardized procedures, which are usually lacking (Campana, 2017; Dell'Unto 2014: 151; Sapirstein and Murray, 2017: 337). In this context, although in general one could rightfully contend that archaeologists have a moral obligation to capture information as accurately as possible (Campana, 2014; Sapirstein and Murray, 2017), it remains important to point out that the added value of 3D models for the primary archaeological process in field archaeology is not completely self-evident. Archaeologists obviously routinely study materials in three dimensions, however, the translation of those subjects to a two dimensional documentation is not just a technical necessity, but part and parcel of the process of archaeological fieldwork practices (Campana, 2014, 2017). Field drawing is an ability that requires an understanding of the object of study and thus should not be undervalued, the interpretation that is essential to that procedure is a fundamental part of the archaeological process (Campana, 2014, 2017; Morgan and Wright, 2018). I would suggest that this is true within the context of a lot of archaeological excavations, and is well demonstrated in the field of Mediterranean excavation archaeology.

The main reason for this is that the documentation of archaeological features is typically quite difficult in many regions of the Mediterranean due to the soil conditions, i.e. hard and dry clays, as well as complex stratigraphy. It must be recognized that photographs cannot simply be used to replace handmade drawings in the field as photographs are unable to capture all of the often subtle changes in the properties of soils such as textures, minutely small inclusions, minor colour fluctuations, and combinations of all of these things (Campana, 2017; Powlesland, 2016; Willemsen and Seubers, 2015). The interpretation of these characteristics is one that typically takes place during drawing since that procedure calls for determining the spatial arrangement of features and strata. Making 3D models instead of drawing, as suggested or even adopted in some projects (e.g. De Reu et al., 2013; Prins et al., 2014; Roosevelt et al., 2015) would in this case be a very poor substitute. It would certainly seem to remove or at best defer close interpretation of layers and features in the field. Indeed some scholars have stated firmly that photographs could never be used as a substitute for onsite drawing (Dell'Unto, 2014: 152), and that such substitution might lead to actual “de-skilling” i.e. the loss of the archaeological ability that goes hand in hand with the interpretative process (Caraher, 2016: 435). The notion that creating a 3D model of an excavation compensates for the destructive character of archaeological excavation is therefore equally confounded. In cases where a setup is proposed in which identifying features, interpretation, describing/annotating and recording are embedded into a single 3D workflow, a clear description of how that would play out in practice is dearly lacking, appears rather convoluted and/or lacks a quantitative assessment of improvement over current documentation techniques (cf. Dell'Unto et al., 2017; De Reu et al., 2013: 1118; Roosevelt et al., 2015: 334–335). In cases where 3D recording is an *additional* layer of documentation next to handmade drawing, one should really assess in detail whether the effort of bringing in a new technology is actually worthwhile. After all, expenditure on drones and cameras can be considerable and not all projects have the financial resources or trained staff to deploy a

photogrammetrical workflow. At least one substantial workstation (or an equivalent in a couple of smaller workstations) is needed, and many projects mention a cost of deploying one skilled drone/camera operator for a full day (e.g. Willemsen and Seubers, 2015; Olson et al., 2013, even more when taking the photographs). Therefore, it is all the more pressing to think about the objectives, investments and workflows for photogrammetry that can actually contribute to the primary fieldwork processes.

2. Improving the primary archaeological process for excavations

Some authors claim that archaeologists engage better with the volumetric aspects of excavated stratigraphy through 3D recording (e.g. Roosevelt et al., 2015; Dell'Unto et al., 2017), but remain somewhat elusive in explaining concrete improvements over the ‘traditional’ processes and techniques (cf. Gordon et al., 2016; Morgan and Wright, 2018). If we look for more specific arguments about the production of knowledge in fieldwork, the following advantages for incorporating a 3D recording workflow in an excavation context have been mentioned in literature: easy comparison of excavated features and stratigraphy with remote sensed data such as geophysical prospection (De Reu et al., 2014: 261); building a 3D model of the excavation as documentation for excavated or reburied areas enabling reassessment of observations such as measurements and/or stratigraphic sequences (Campana, 2017; Dell'Unto et al., 2017: 642; Forte, 2014: 14; Powlesland, 2016: 28; Sordini et al., 2016: 389; Willemsen and Seubers, 2015: 43); recording difficult to draw geometrical properties such as varying thickness and inclination of layers (Roosevelt et al., 2015: 335; Sordini et al., 2016: 389), increasing its value with growing variation on the z-axis; using extracted orthorectified images as a base and enhancement for manual drawing (Forte, 2014: 15; Olson et al., 2013: 254; Powlesland, 2016: 28; Willemsen and Seubers, 2015: 42); creating orthorectified images of otherwise extremely difficult to capture surfaces such as underground tombs (Willemsen and Seubers, 2015: 42) and the aforementioned substitution of manual drawing, making it the primary recording process (De Reu et al., 2013: 1118; Prins et al., 2014: 193; Roosevelt et al., 2015: 334–335).

What unites these applications, and what could make a 3D recording workflow useful, is that most of them, if they are to be embedded into the primary excavation process systematically and on a large scale, require a good quality model in a short time after capturing the imagery. The application of the models to extract base plans on which to draw manually is, in case they are geometrically accurate and of high enough resolution, a big step forward in the primary process. With a model that would be equally or even more accurate than traditional electronic measurement equipment, one would have a model of the excavation with most of the features already in place, and need very limited use of taking additional measurements on site, which is something that takes up a lot of time. That requires however the production of a good quality model overnight or even faster, preferably of the complete excavation area so all visible features are wholly captured, otherwise the progress of the fieldwork would be stalled. Another possibly very useful application would indeed be to create a model of the complete excavation at the end of every day, to create an archive that maps the process on a daily basis and equip trench leaders every morning with a photorealistic overview of the state of the excavation the day before (e.g. on a tablet, possibly georeferenced in a GIS) so they can indeed reassess the ongoing excavation up to that point. Appropriately, it is argued that the arrival of these techniques could place an additional documentation phase early in the analytical sequence of fieldwork (Campana, 2017; Limp, 2016), which is very much in line with the view expressed in this paper. The challenge then appears to be to set up a photogrammetrical recording and data processing workflow in such a way that a standardized daily model of the complete excavation trench of good quality is achieved, against a minimal investment in person hours and with as little interruption as

possible to fieldwork.

In terms of quality, clearly the resulting model must have a high enough resolution to discern the smallest archaeological features and optimal lighting conditions, under the circumstances of common restraints in fieldwork. Additionally, the model must be accurate to the degree that it is at least as good as achieved with other means of measuring and recording. Although good results on achieving a high level of accuracy have been demonstrated (e.g. De Reu et al., 2014), quality issues have by no means become trivial problems; there are many sources of error and they depend very much on the setup of recording of the material and subsequent choices in modeling (e.g. Sapirstein, 2016). The sensible case has been made that for every unique photogrammetrical workflow, error estimations are required (Green et al., 2014: 181). Therefore, certainly in this stage of early adoption, explicitly dealing with geometrical accuracy is an essential part of employing a photogrammetrical approach to archaeological fieldwork.

In this paper, I propose a new, well-defined, transparent and standardized mapping approach based on the combination of a budget UAS (hereafter: drone) and photogrammetrical techniques for excavation, which exactly provides this quality respecting a reasonable investment in resources. This will be demonstrated in the context of a case study from excavations of Satricum, Lazio, Italy, where in two subsequent seasons a workflow has been developed, tested and implemented. Finally, I will reflect on the on future potential of this approach, as well as engage with the ongoing discussion about developments in processes of documentation and interpretation.

3. Satricum and the excavation trench of 2017

Satricum is a Latin settlement located some 60 km south of Rome near the modern-day village of Borgo Le Ferriere (Fig. 1). The site is known for its long history of settlement and burial starting in the 9th c. BC. and continuing up to the 3rd c. BC. The most conspicuous archaeological remains are those related to the sanctuary dedicated to the goddess of dawn, Mater Matuta, of which the first of several successive

phases was erected in the mid-7th c. BC. The excavations at Satricum, which by now run well over 40 years, have since 1977 been organized by the Koninklijk Nederlands Instituut Rome and the Rijksuniversiteit Groningen in the early phase; and from 1991 onwards by the Universiteit van Amsterdam under the direction of Prof. dr. M. Gnade (see e.g. Gnade, 2002, 2013, 2014).

The excavations take place in the typical hard, dry and clayey soils which contain a rich and varied archaeological record, consisting of architectonic remains, pavements, floors, burials, trenches and pits. The excavation trench of 2017 and 2018 measuring 450 sq.m. is located in the so-called PDC II area and is aimed at documenting and understanding the complex sequence of architectonic remains in the lower city area amongst which are the main road of the town running in an east-west direction, several side roads and large buildings alongside that have been found during the last couple of seasons, in order to be able to embed it in the stratigraphic sequence of the settlement's history.

4. Objectives and design of the experiments

As specified above, the objectives for the deployment of the drone and photogrammetrical processing were to minimize the investments in time and effort on one side, and to maximize eventual quality and accuracy of the models; defined as 'fit for their purpose'. The developed workflow is assessed using the following criteria:

1. Is there an improvement in the primary fieldwork processes respecting the same standards for accuracy?
2. Is there interruption or delay of the fieldwork?
3. Is the process automated to a degree where it doesn't take a full day of person hours to produce the final models?
4. Are the models available on time to be effectively used?
5. Is the process repeatable respecting the same parameters of precision and accuracy?

The deployment of the drone allows for automation of capturing

Fig. 1. Location of the site, historical map of Satricum (Mengarelli, ca. 1910), projected on a DTM of the LiDAR data of the region, *bw*, single column.

photos and facilitates repeatability due to its capacity to store a fixed route. The automated adjustment of shutter speed and ISO values ensure a consistent exposure (values were kept between 100 and 200 ISO and between 1/50–1/100 shutter speed, at a constant aperture of F/2.8). Since the fairly low resolution of the integrated camera, 12MP, necessitates a relatively large number of photos to arrive at a good resolution, the drone was set at a speed of 0.3 m per second, and one photo every 5 s. This setup resulted in one photo every 1.5 m of flight, which, together with a set of complementary low oblique photos shot manually, resulted in a total dataset of ca. 160 photos. Altitude of the drone was set at 6 m, and with an image resolution of 4000×3000 pixels, focal length of 3.61 mm and sensor width of 6.17 mm, resulted in a ground sample distance (GSD) of 1.6 mm for each individual photo, resulting in a 2.8 mm GSD for the resulting model, i.e. every pixel covering 2.8 mm of real space (for technical explanation see [Sapirstein and Murray, 2017](#)).

After some experimentation, it was clear that in August this procedure worked best in the early evening; 19.55 a.m. to be precise, just before sunset, creating a pocket of time in which there is still sufficient but no more direct light, avoiding the problem of cast shadows due to the low position of the sun. This recording moment is very convenient because fieldwork by then was already finished and the imagery captured was exactly the state of the excavation at the end of the fieldwork that day ([Fig. 2](#)).

A vital element of the applied setup used was the deployment of coded targets generated by the photogrammetrical software itself. These targets were positioned using a Total Station, and used for the initial alignment of the photos, enhancing the speed of that procedure and eventual precision ([Powlesland, 2016: 24](#); [Sapirstein, 2016](#); [Sapirstein and Murray, 2017](#)), as well as georeference the models for effortless integration within a Geographic Information System. The

Fig. 2. Capturing just before sunset, the drone hovering at 6 m above the excavation trench, colour, single column. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

targets were fixed only at the borders of the trench, so their considerable size, center point radius 30mm, did not cover any archaeology ([Fig. 3](#)).

After collecting the imagery, which takes about 20 min during a single flight, manual data processing cost ca. 20–30 min, after which the production of a high quality model, orthophoto and DEM could be run as a batch process.

5. Results

As outlined above, notwithstanding the various useful purposes a 3D model of your excavation may serve, for real integration within the documentation process, the quality of the model and the speed of production are essential. The criteria used for evaluating the method outlined here have been mentioned earlier.

5.1. Process

As for the speed and uninterrupted flow of the fieldwork, this setup proved efficient. The recording takes place outside of excavation hours and requires a short time. The capturing of information is standardized using automated settings and a fixed flight plan that should practically result in comparable series of photos, although extreme atmospheric conditions can of course always hinder the flight. Due to the increased stability of the DJI Phantom 3 as well as the independent moveable gimbal, the usual problem of wind (e.g. [Remondino et al., 2011](#); [Rinaudo et al., 2012](#); [Sauerbier and Eisenbeiss, 2010](#)) is much less prominent. Given that the markers are well-fixed, the TS mapping of the points has to be done only once and thus is a single investment of another 30 min at the beginning of the project. The processing work in Agisoft PhotoScan is one that takes about 20–30 min of manual work and then a full night of processing, depending on the hardware platform of course. The complete batched procedure in this case took about 10 h on a standard laptop (see below for hardware specifications), which, admittedly, means it is finished about 3–4 h after fieldwork has started. This is not ideal, though it must be stressed that this is principally a matter of upgrading the working system; in 2018 a gaming laptop was used that finished the complete procedure in 3 h (about twice the cost of the standard laptop).

With regard to quality, the GSD of 2.8 mm is sufficient to easily identify shapes and distinguish between pieces of pottery, tile and stones ([Figs. 4 and 5](#)). The colours and contrast of the model approach the quality of the photos most archaeologists are used to work with in the context of an excavation in the Mediterranean.

5.2. Geometry

As for the geometrical accuracy, it has already been found in several projects that photogrammetry, in combination with using targets, is able to produce very accurate results ([De Reu et al., 2014](#); [Sapirstein, 2016](#); [Sapirstein and Murray, 2017](#)). Photogrammetry is even likely to provide more accurate geometrical data than attainable with at least some TS ([Sapirstein, 2016: 138](#)). PhotoScan itself provides error estimations ([Agisoft LLC, 2017: 32–33](#)) which we can use to assess our model, the GCP Error and the Reprojection Error. The GCP Error is the root mean square error (RMSE) for the difference between the initial placement of the GCPs (the coded targets) based on the coordinates and the eventual placement of those points based on the calculation of their position ([Table 1](#)). The Reprojection error is the RMSE averaged distance between all tie points originally recognized on the photos and their calculated position in the 3D model. The average GCP RMSE of our model in cm. rounded to two decimals is 0.98 and the average Reprojection error of our model is 1.28 pix.

The GCP error with a RMSE of less than 1 cm is reasonable for our purposes, with average deviations from the true position of archaeology in the model is 0.98 cm in three dimensions. It should be remembered

Fig. 3. Screenshot of Agisoft PhotoScan with the coded targets recognized as markers, *colour, double column*. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

that the source of this error is at least as likely to be inaccuracies in the TS measurements used to position the GCPs as inaccuracies in the model. At any rate, the objective was not to achieve extremely high levels of accuracy (which surpass accuracy levels required for archaeological excavation, also noted by [De Reu et al., 2014](#): 260; [Doneus et al., 2011](#): 87), but to find a balance between acceptable quality and an efficient workflow. In order to be able to validate accuracy external of the software, it is necessary to check what these error estimations mean in the field. Therefore, a series of points have been compared with

their respective TS positions, which are shown here in this graph. Although, indeed it has recently been argued that TS systems do not offer enough precision to demonstrate the accuracy in comparison with SfM methods ([Sapirstein, 2016](#); 138–139), this already is a heartening thought; if we are having smaller errors than those with using a TS we would already have improved on the current standards. However, since there are in any SfM setup so many possible sources for error this must be checked.

With a horizontal error $\bar{x} = 16$ mm, $s = 11,4$ mm and a vertical

Fig. 4. Orthomosaic of the excavation, recorded at 19.35, *colour, double column*. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Fig. 5. Orthomosaic detail, slightly post-processed colour, double column. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Table 1

GCP error calculated by Agisoft PhotoScan, averaged over several models.

Count	X error (cm)	Y error (cm)	Z error (cm)	XY error (cm)	Total (cm)
32	0.47	0.51	0.68	0.69	0.98

error $\bar{x} = 17,1$ mm and $s = 6,2$ mm, for $n = 12$, it is clear that the procedure does indeed attain a considerable level of accuracy based on field measurements (Fig. 6). The mean error for the vertical checks is a little bit higher, but the two distributions of error are not statistically dissimilar, a T-test on sample means shows that the 1,08 mm difference is not significant ($t = 0.288$, $p = 0.78$). The low standard deviation of the vertical accuracy should be approached with some caution though, the deepest points of the trench have not been checked, where deviations may be greater (Fig. 7).

Admittedly, this validation could be stronger using more points but this has not been possible due to practical constraints. Nevertheless, applying a Student's T to check for significance, we find that the mean error of the model lies between 4,4 and 22,6 mm for the horizontal accuracy, and between 13,5 and 20,7 mm for the vertical accuracy, against a confidence level of 95%. For the purpose outlined above, this

is acceptable given the general accuracy of TS measurement that easily surpasses 2 cm errors in archaeological excavations.

Another approach to error assessment common for photogrammetrical techniques is performing repeatability tests (Dellepiane et al., 2012: 206 Sapirstein, 2016: 139). By comparing several models of a single subject created by separate batches of photos acquired using the same workflow, it is possible to estimate accuracy by assessing point discrepancies between models. Although it is a fairly crude indicator, it is a very useful one to get a sense of the level of reproducibility of the photogrammetrical workflow. For the current workflow, two subsequent models were compared to minimize error due to soil removal or displacement by wind or the ongoing traversing of people, in an area of $7 \times 7 \times 4$ mts where no excavation took place in those two days. Using CloudCompare, the sparse point cloud of one model was compared to the mesh of another; with a $\bar{x} = 2,7$ mm and $s = 25$ mm. Based on this repeatability assessment, we can safely conclude that the two recordings resulted in two geometrically similar models, which is a good result.

With a mean error in relation to the measurement grid of less than 2 cm average, and thus already at least as accurate as the usual TS measurements, low RSMEs in the photogrammetrical procedure, and an adequate reproducibility of the result, the geometrical quality of the

Fig. 6. Histograms of the 12 control measurements for horizontal and vertical accuracy, bw, single column.

Fig. 7. DEM (upper) and sky view factor model (lower) of the excavation trench, black crosses are control points, red triangles grid points and black circles coded targets, *colour, double columns*. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

model is in its current form readily sufficient for most common uses in the archaeological fieldwork practice.

6. Discussion

The presented case demonstrates the feasibility of a standardized workflow for photogrammetrical recording with a minimal investment in resources. The primary goal for its actual implementation has been to support the process of manual drawing at the excavation. Given the resolution, the accuracy and the overall clarity of the resulting orthophotos and 3D models, this is a very solid basis. A straightforward method was implemented, where the orthophotos most obvious features were digitized, used as background on mm sheets in the field, and then easily completed with missing data and the interpretations of the

trench leaders.

The potential of producing an accurate photogrammetric model on a daily basis has broader uses and implications, as mentioned earlier. Probably the most obvious practical advantage for the primary archaeological process is the potential for re-observing archaeological features and layers and their properties. Whereas I argued that the possibility for a full reinterpretation of archaeological stratigraphy is limited, there is a range of information that can indeed be reassessed, which is difficult, if impossible, from manual drawings and/or single photographs. Indeed, where the 2 dimensional abstraction is an act of interpretation that needs physical interaction with the soils, it is also a reduction of data, i.e. only that is captured that is deemed of interest to the interpreter (Limp, 2016: 353–357). Equally, the decision of the scenes that must be captured by the excavation's photographer is an act

of interpretation. Thus, producing a full detail photorealistic model of the excavation on a daily basis is likely to capture a lot of information that may potentially be of use, and in that sense provides a more neutral layer of documentation in the primary archaeological process. The objectification may not only provide useful insights on a single site, where it offers the possibility to reassess information that may have been missed earlier, but maybe even more so in between sites where documentation systems such as drawing standards, but also expertise related to specific periods or soils, may vary considerably between institutions and archaeologists.

On a more abstract level, having a daily produced complete 3D model of the excavation is likely to have an impact on the interpretative process, as argued in various places (e.g. Campana, 2017; Limp, 2016). As an additional layer of very detailed and strongly visual information of the larger whole, the 3D model allows evaluation of hypotheses, and/or provoke new ones, in a phase of fieldwork way before handmade drawings, digitization and aggregation in a GIS would have made them possible. For example, studying the layout of various wall remains may provoke the question whether they were all planned and constructed as a single operation, which might be assessed by checking the exact levels and orientation of the foundations. Digitally, this will now only require a single action from behind your desk at the moment of studying the plans, which could otherwise only be done by taking a series of new measurements the next morning or even waiting until after a final drawing phase. Due to the virtues of 3D models, such advantages become more significant in case of more complex geometries. In this sense, it does indeed have the potential to break the interpretative cycle at an excavation, or at least makes for smaller cycles and more recursive processes of understanding in the primary archaeological process (Limp, 2016: 350). The intrinsic quality of the 3D data collected through a daily standardized workflow with little investment in resources such as the one here described, surely creates a versatile and valuable addition to the primary archaeological process.

7. Final considerations

As for the quantification of efficiency, the eventual cost benefit cannot be gauged from the results of these two seasons. Evidently, for comparing to hand drawing without the use of the models generated by this procedure, one would need to actually calculate the true profit in person hours of the proposed workflow over mapping the area at 1:20 by hand. A ‘guesstimate’ from an experienced drawing specialists would be an increase in efficiency between 50% and 95%, evidently depending on the detail and geometrical complexity of the subject (Oggenhaffen, personal communication; Kriek, personal communication).

In addition to the limitations and possible issues mentioned in the text, a few more need to be addressed here.

The most evident one is that the case study worked with an excavation trench of moderate size, as compared to the often large trenches of the open area excavation approach common in Italy (Carandini, 1981). An increase in area will respectively amplify flying times, the number of photos and thus processing time. All results presented in this case study must be seen in the light of a maximum of ca. 450 sqm., and all workflow parameters thus need careful consideration in circumstances where trenches are substantially larger.

The designed workflow is based on a single image capturing moment each day. This might be insufficient with faster cycles of excavation and recording, and additional recording of photos may be required for smaller areas (cf. Olson et al., 2013; Roosevelt et al., 2015). Furthermore, in order to reach an optimal increase in efficiency, the 2D manual drawing on top of the 3D and 2D products from the model would also be done digitally (for 2D drawing on tablets see e.g. Forte, 2014; for directly in 3D Dell’Unto et al., 2017). Such a procedure in itself would also call for a well-considered workflow of data and quality control as well as raise issues such as digital annotation, as already acknowledged by others (e.g. De Reu et al., 2014: 261). The use of

tablets is often suggested for further annotation of orthophotos and/or 3D models, and workflows towards integration with GIS and databases are currently being tested. An approach that could prove versatile is to work with a tablet that allows pen drawing, i.e. freehand drawing, directly in GIS. Such a workflow would accommodate using the orthophoto/3D model information, avoid breaking the standardized GIS processing and still approach the physical process of producing a hand drawing. Obviously that would require some additional GIS processing, i.e. converting freehand drawn lines into polygons with identifiers, but that is a process that could largely be automated. It should be stressed however, that a valid issue here is one shouldn’t be limited by the affordances of a tablet (Morgan and Wright, 2018), and probably the handiness of a tablet still leaves much to desire in comparison to paper and pencil.

Finally, an often mentioned problem in the context of 3D data recording is that of data storage, accessibility and preservation (cf. Bevan, 2015), although these surely need careful thought, at least for an approach such as this, with less than 200 photos and three resulting models (2D ortho, DEM, 3D mesh), totaling to maximum of 4GB on a daily basis, this is unlikely to become an insurmountable problem. Given that the project takes the conventional responsibility for producing professional level meta-info and reports, as well as tries to adhere to open standards, the accessibility of content and software should remain acceptable. The fast pace of decreasing costs of storage will render the daily production of a couple of GB of data a minor issue. Online scientific data sharing solutions will greatly ease all three areas, storage, accessibility and preservation, in the near future.

8. Conclusions

The aim of this project was to contribute to the developing implementation of UASs and photogrammetrical methods in the primary archaeological fieldwork process. Although 3D recording will not substitute 2D technical handmade drawings in most excavations on the short run, they can be effectively embedded in the primary process. As such, the proposed method is a new approach combining both techniques in an efficient, well-defined, transparent and standardized workflow for archaeological excavations. The result is a specified workflow that allows for the daily production of a 3D model and 2D orthomosaic that retains geometrical accuracy at a high resolution with a modest investment of resources. In this way, the 3D model and 2D orthomosaic facilitate field drawing and building a 3D archive of the ongoing excavations on a 24 h iteration, allowing reassessment of observations. The outcomes impart clear benefits for the process of scientific data collection in the field, and are thereby a useful addition to the production of knowledge during fieldwork.

Materials

UAS

- DJI Phantom 3 Standard

Specifications UAS camera

- Sensor: 1/2.3" CMOS; Effective Pixels 12 M
- Lens: FOV 94° 20 mm (35 mm format equivalent) f/2.8
- ISO Range: 100–1600
- Electronic Shutter Speed: 8–1/8000 s
- Image Size: 4000 × 3000

Software

- Agisoft PhotoScan Professional v. 1.3.2 build 4205 (64bit)
- DJI Go; Go Creative app 3.1.1
- CloudCompare 2.9.1 (64bit)

Workstation

- Chipset: Intel® Core™ i7-5500U CPU @ 2.5GHz (quadcore)
- Internal Memory: 16 GB DDR3 RAM
- OS: Windows 8 64bit
- GPU: AMD Radeon R7 M270 1 GB DDR3

Conflicts of interest

None.

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References

- Agisoft LLC, 2017. Agisoft PhotoScan User Manual: Professional Edition. Agisoft LLC Version 1.3.
- Barsanti, S.G., Remondino, F., Visintini, D., 2012. Photogrammetry and laser scanning for archaeological site 3D modeling e some critical issues. In: In: Fozzati, L., Roberto, V. (Eds.), NTA-2012. The New Technologies for Aquileia. Proceedings of the 2nd Workshop on the New Technologies for Aquileia. Aquileia, Italy, June 25, 2012. CEUR Workshop Proceedings, vol. 948. CEUR-WS, pp. B1–B10.
- Bevan, A., 2015. The data deluge. *Antiquity* 89, 1473–1484. <https://doi.org/10.15184/aqy.2015.102>.
- Brenningmeyer, T., Kourelis, K., Katsaros, M., 2015. The Lidoriki project: low altitude, aerial photography, GIS, and traditional survey in rural Greece. In: Campana, S., Scopigno, R., Carpentier, G., Cirillo, M. (Eds.), CAA2015, Keep the Revolution Going. Proceedings of the 43rd Annual Conference on Computer Applications and Quantitative Methods in Archaeology, Università di Siena, Italy (March 30–April 3, 2015). Archaeopress, Oxford, pp. 979–988.
- Campana, S., 2014. 3D modeling in archaeology and cultural heritage – theory and best practice. In: Remondino, F., Campana, S. (Eds.), 3D Surveying and Modeling in Archaeology and Cultural Heritage Theory and Best Practices. BAR International Series. BAR Publishing, Oxford, pp. 7–12.
- Campana, S., 2017. Drones in archaeology. State-of-the-art and future perspectives. *Archaeol. Prospect.* <https://doi.org/10.1002/arp.1569>. 1099–0763.
- Caraher, W., 2016. Slow archaeology: technology, efficiency, and archaeological work. In: Averett, E.W., Gordon, J.M., Counts, D.B. (Eds.), 2016. Mobilizing the Past for a Digital Future, the Potential of Digital Archaeology. The Digital Press at the University of North Dakota, Grand Forks, ND, pp. 421–441. <https://doi.org/10.17613/M6ZG8P>.
- Carandini, A., 1981. *Storie Dalla Terra. Manuale Dello Scavo Archeologico*. Einaudi, Bari.
- Caro, J.L., Jiménez-Jáimez, V., Márquez-Romero, J.E., 2016. Using digital photogrammetry to produce 3D models at prehistoric ditched enclosures: perdigões as a case study. In: Kamermans, H., de Neef, W., Piccoli, C., Posluschny, A.G., Scopigno, R. (Eds.), 2016. The Three Dimensions of Archaeology, Proceedings of the XVII UISPP World Congress (1–7 September, Burgos, Spain). Volume 7/Sessions A4b and A12. Archaeopress, Leiden, pp. 61–72. <https://doi.org/10.5281/zenodo.260320>.
- De Reu, J., Plets, G., Verhoeven, G., De Smedt, P., Bats, M., Cherretté, B., De Maeyer, W., Deconynck, J., Herremans, D., Laloo, P., Van Meirvenne, M., De Clercq, W., 2013. Towards a three-dimensional cost-effective registration of the archaeological heritage. *J. Archaeol. Sci.* 40 (2), 1108–1121. <https://doi.org/10.1016/j.jas.2012.08.040>.
- De Reu, J., De Smedt, P., Herremans, D., Van Meirvenne, M., Laloo, P., De Clercq, W., 2014. On introducing an image-based 3D reconstruction method in archaeological excavation practice. *J. Archaeol. Sci.* 41, 251–262. <https://doi.org/10.1016/j.jas.2013.08.020>.
- Dell'Unto, N., Landeschi, G., Apel, J., Poggi, G., 2017. 4D recording at the trowel's edge: using three-dimensional simulation platforms to support field interpretation. *J. Archaeol. Sci.: For. Rep.* 12, 632–645. <https://doi.org/10.1016/j.jasrep.2017.03.011>.
- Dell'Unto, N., 2014. The use of 3D models for intra-site investigation in archaeology. In: Remondino, F., Campana, S. (Eds.), 3D Surveying and Modeling in Archaeology and Cultural Heritage Theory and Best Practices. BAR International Series. BAR Publishing, Oxford, pp. 151–158.
- Dellepiane, M., Dell'Unto, N., Callieri, M., Lindgren, S., Scopigno, R., 2012. Archeological excavation monitoring using dense stereo matching techniques. *J. Cult. Herit.* 14 (3), 201–210.
- Doneus, M., Verhoeven, G., Fera, M., Briese, C., Kucera, M., Neubauer, W., 2011. From deposit to point cloud – a study of low-cost computer vision approaches for the straightforward documentation of archaeological excavations. In: In: Čepék, A. (Ed.), XXIIIrd International CIPA Symposium, Prague, 12–16 September 2011, Geoinformatics, vol. 6. Faculty of Civil Engineering, Czech Technical University, Prague, pp. 81–88. <https://doi.org/10.14311/gi.6.11>.
- Fernández-Hernandez, J., González-Aguilera, D., Rodríguez-González, P., Mancera-Taboada, J., 2015. Image-based modelling from unmanned aerial vehicle (UAV) photogrammetry: an effective, low-cost tool for archaeological applications. *Archaeometry* 57, 128–145. <https://doi.org/10.1111/arcm.12078>.
- Forte, M., 2014. 3D archaeology: new perspectives and challenges—the example of Çatalhöyük. *J. East. Mediterr. Archaeol. Herit. Stud.* 2, 1–29. <https://doi.org/10.13140/2.1.3285.0568>.
- Gnade, M., 2002. Satricum in the Post-Archaic Period. A Case Study of the Interpretation of Archaeological Remains as Indicators of Ethno-cultural Identity. Leuven, Peeters.
- Gnade, M., 2013. Satricum. In: In: Bagnall, R.S., Brodersen, K., Champion, C.B., Erskine, A.E., Huebner, S.R. (Eds.), The Encyclopedia of Ancient History, vol. 11. Wiley, pp. 6060–6061. Chichester [etc.].
- Gnade, M., 2014. Gli scavi archeologici a Satricum. In: Arnaldi, V. (Ed.), Roma 1914: Storie Della Città. Maretti editore, Rome, pp. 9–11.
- Gordon, J.M., Averett, E.W., Counts, D.B., 2016. Mobile computing in archaeology: exploring and interpreting current practices. In: Averett, E.W., Gordon, J.M., Counts, D.B. (Eds.), 2016. Mobilizing the Past for a Digital Future, the Potential of Digital Archaeology. The Digital Press at the University of North Dakota, Grand Forks, ND, pp. 1–30.
- Green, S., Bevan, A., Shapland, M., 2014. A comparative assessment of structure from motion methods for archaeological research. *J. Archaeol. Sci.* 46, 173–181. <https://doi.org/10.1016/j.jas.2014.02.030>.
- Howland, M.D., Kuester, F., Levy, T., 2014. Photogrammetry in the field: documenting, recording, and presenting archaeology. *Mediterr. Archaeol. Archaeometry* 14, 101–108.
- James, M.R., Robson, S., 2012. Straightforward reconstruction of 3D surfaces and topography with a camera: accuracy and geoscience application. *J. Geophys. Res.* 117, 1–17. <https://doi.org/10.1029/2011JF002289>.
- Kersel, M.M., 2016. Response: living a semi-digital kind life. In: Averett, E.W., Gordon, J.M., Counts, D.B. (Eds.), 2016. Mobilizing the Past for a Digital Future, the Potential of Digital Archaeology. The Digital Press at the University of North Dakota, Grand Forks, ND, pp. 475–492.
- Lambers, K., Eisenbeiss, H., Sauerbier, M., Kupferschmidt, D., Gaisecker, T., Sotoodeh, S., Hanusch, T., 2007. Combining photogrammetry and laser scanning for the recording and modelling of the late intermediate period site of pinchango alto, palpa, Peru. *J. Archaeol. Sci.* 34, 1702–1712. <https://dx.doi.org/10.1016/j.jas.2006.12.008>.
- Lang, M., Behrens, T., Schmidt, K., Svoboda, D., Schmidt, C., 2015. A fully integrated UAV system for semi-automated archaeological prospection. In: Campana, S., Scopigno, R., Carpentier, G., Cirillo, M. (Eds.), CAA2015, Keep the Revolution Going. Proceedings of the 43rd Annual Conference on Computer Applications and Quantitative Methods in Archaeology, Università di Siena, Italy (March 30–April 3, 2015). Archaeopress, Oxford, pp. 989–996.
- Limp, W.F., 2016. Measuring the face of the past and facing the measurement. In: Forte, M., Campana, S. (Eds.), Digital Methods and Remote Sensing in Archaeology, Archaeology in the Age of Sensing. Quantitative Methods in the Social Sciences. Springer, pp. 349–370. <http://www.springer.com/series/11748>.
- Morgan, C., Wright, H., 2018. Pencils and pixels: drawing and digital media in archaeological field recording. *J. Field Archaeol.* 43 (2), 136–151. <https://doi.org/10.1080/>

- 00934690.2018.1428488.
- Olson, B.R., Placchetti, R.A., Quartermaine, J., Killebrew, A.E., 2013. The Tel Akko total archaeology project (Akko, Israel): assessing the suitability of multi-scale 3D field recording in archaeology. *J. Field Archaeol.* 38 (3), 244–262. <https://doi.org/10.1179/0093469013Z.00000000056>.
- Ostrowski, W., Hanus, K., 2016. Budget UAV systems for the prospection of small- and medium-scale archaeological sites. *Int. Arch. Photogram. Rem. Sens. Spatial Inf. Sci.* 41-B1, 971–977. <https://doi.org/10.5194/isprs-archives-XLI-B1-971-2016>.
- Powlesland, D., 2016. 3Di – enhancing the record, extending the returns, 3D imaging from free range photography and its application during excavation. In: Kamermans, H., de Neef, W., Piccoli, C., Posluschny, A.G., Scopigno, R. (Eds.), 2016. The Three Dimensions of Archaeology, Proceedings of the XVII UISPP World Congress (1–7 September, Burgos, Spain). Volume 7/Sessions A4b and A12. Archaeopress, Leiden, pp. 13–32. <https://doi.org/10.5281/zenodo.260320>.
- Prins, A.B., Adams, M.J., Homsher, R.S., Ashley, M., 2014. Digital archaeological field-work and the jezreel valley regional project, Israel. Near east. Near E. *Archaeol.* 77–3, 192–197. <https://doi.org/10.5615/neareastarch.77.3.0192>. Special Issue: Cyber-Archaeology.
- Remondino, F., Barazzetti, L., Nex, F., Scaioni, M., Sarazzi, D., 2011. UAV photogrammetry for mapping and 3D modelling – current status and future perspectives. In: Eisenbeiss, H., Kunz, M., Ingensand, H. (Eds.), 2011. International Conference on Unmanned Aerial Vehicle in Geomatics (UAV-g) XXXVIII-1/C22, ISPRS Workshop, 14–16 September 2011, Zurich. *Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci.* XXXVIII-1/C22. pp. 25–31. <https://doi.org/10.5194/isprsarchives-XXXVIII-1-C22-25-201>.
- Rinaudo, F., Chiabrand, F., Lingua, A., Spanò, A., 2012. Archaeological site monitoring: UAV photogrammetry could be an answer. In: Shortis, M., Mills, J. (Eds.), 2012. XXII ISPRS Congress, Technical Commission V XXXIX-b5, 25 August – 01 September 2012, Melbourne, Australia. *Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci.* XXXIX-B5. pp. 583–588. <https://doi.org/10.5194/isprsarchives-XXXIX-B5-589-2012>.
- Roosevelt, C.H., Cobb, P., Moss, E., Olson, B.R., Ünlüsoy, S., 2015. Excavation is destruction digitization: advances in archaeological practice. *J. Field Archaeol.* 40–3, 325–346. <https://doi.org/10.1179/2042458215Y.0000000004>.
- Sapirstein, P., 2016. Accurate measurement with photogrammetry at large sites. *J. Archaeol. Sci.* 66, 137–145. <https://doi.org/10.1016/j.jas.2016.01.002>.
- Sapirstein, P., Murray, S., 2017. Establishing best practices for photogrammetric recording during archaeological fieldwork. *J. Field Archaeol.* 42 (4), 337–350. <https://doi.org/10.1080/00934690.2017.1338513>.
- Sauerbier, M., Eisenbeiss, H., 2010. UAVs for the documentation of archaeological excavations. In: Mills, J.P., Barber, D.M., Miller, P.E., Newton, I. (Eds.), 2010. Proceedings of the ISPRS Commission V Mid-term Symposium 'Close Range Image Measurement Techniques' XXXVIII - Part 5, 21–24 June 2010, Newcastle upon Tyne, United Kingdom. *Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci.* XXXVIII – Part 5. pp. 526–531.
- Sordini, M., Brogi, F., Campana, S., 2016. 3D Recording of archaeological excavation: the case study of Santa Marta, Tuscany, Italy. In: Campana, S., Scopigno, R., Carpentiero, G., Cirillo, M. (Eds.), CAA2015, Keep the Revolution Going. Proceedings of the 43rd Annual Conference on Computer Applications and Quantitative Methods in Archaeology, Università di Siena, Italy (March 30–April 3, 2015). Archaeopress, Oxford, pp. 383–391.
- Stek, T.D., 2016. Drones over Mediterranean landscapes. The potential of small UAV's (drones) for site detection and heritage management in archaeological survey projects: a case study from Le Piane in the Tappino Valley, Molise (Italy). *J. Cult. Herit.* 22, 1066–1071. <https://doi.org/10.1016/j.culher.2016.06.006>.
- Verhoeven, G., 2009. Providing an archaeological bird's-eye view. An overall picture of ground-based means to execute low-altitude aerial photography (LAAP) in archaeology. *Archaeol. Prospect.* 16, 233–249. <https://doi.org/10.1002/arp.354>.
- Verhoeven, G., Taelman, D., Vermeulen, F., 2012. Computer vision-based orthophoto mapping of complex archaeological sites: the ancient quarry of Pitaranha (Portugal-Spain). *Archaeometry* 54 (6), 1114–1129. <https://doi.org/10.1111/j.1475-4754.2012.00667.x>.
- Wernke, S.A., Hernández, C., Marcone, G., Ore, G., Rodriguez, A., Traslaviña, A., 2016. Beyond the basemap: multiscalar survey through aerial photogrammetry in the andes. In: Averett, E.W., Gordon, J.M., Counts, D.B. (Eds.), 2016. Mobilizing the Past for a Digital Future, the Potential of Digital Archaeology. The Digital Press at the University of North Dakota, Grand Forks, ND, pp. 251–278.
- Willemsen, S., Seubers, J., 2015. Toegevoegde waarde of waardeloze toevoeging? Ervaringen met 3D-documentatie in het veld. *Paleo-aktueel* 26, 37–46.