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Combining terrestrial stereophotogrammetry, DGPS and GIS-based 3D voxel modelling in the volumetric recording of archaeological features

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Abstract: Archaeological recording of structures and excavations in high mountain areas is greatly hindered by the scarce availability of both space, to transport material, and time. The Madriu-Perafita-Claror, InterAmbAr and PCR Mont Lozère high mountain projects have documented hundreds of archaeological structures and carried out many archaeological excavations. These projects required the development of a technique which could record both structures and the process of an archaeological excavation in a fast and reliable manner.

The combination of DGPS, close-range terrestrial stereophotogrammetry and voxel based GIS modelling offered a perfect solution since it helped in developing a strategy which would obtain all the required data on-site fast and with a high degree of precision. These data are treated off-site to obtain georeferenced orthoimages covering both the structures and the excavation process from which site and excavation plans can be created. The proposed workflow outputs also include digital surface models and volumetric models of the excavated areas from which topography and archaeological profiles were obtained by voxel-based GIS procedures. In this way, all the graphic recording required by standard archaeological practices was met.

Keywords: Terrestrial, Stereoscopic, GIS, GPS, Recording, Archaeology, Orthoimage, DSM

1. Introduction

While aerial photogrammetry has a long tradition in its application to the recording and analysis of archaeological landscapes (Poidebard, 1939; Newcomb, 1971; Fant and Loy, 1972; Mattiseck, 1980 and, more recently, Reindel and Grün, 2006; Brenningmeyer and Begg, 2007; Orengo and Palet, 2010; Orengo et al., 2010), terrestrial photogrammetry has been mainly applied to the recording of standing buildings, or structures, or archaeological objects (Grün et al., 2004; Bryan, 2006; El-Hakim et al., 2008). Few examples of the application of terrestrial photogrammetry to the recording of archaeological excavations can be encountered (Whittlesey, 1966; Fant and Loy, 1972 and, more recently, Barceló and Vicente, 2004; Tschauner and Siveroni, 2007; Orengo, 2010).

This is chiefly due to the high investment required in both equipment and training the personnel for its application, which are not usually available in archaeological projects. Nonetheless, the appearance of new easy-to-use software and the significant decrease in price of both computing hardware and software and geomatics equipment has rendered these technologies more accessible and a ready increase in their archaeological application is expected during the next years. Not in vain, photogrammetric modelling has been regarded as the most complete, cheap, portable, flexible and widely used approach for the 3D reconstruction of heritage and archaeological features (Remondino and El-Hakim, 2006: p. 299).

The use of photogrammetrical techniques in high mountain archaeological projects such as the Madriu-Perafita-Claror, the InterAmbAr and PCR Mont Lozère projects was chosen in accordance with the limitations posed by the scarcity of time and resources available to record archaeological features and excavations. These international research projects were aimed at studying the long-term human-driven landscape changes of high mountain areas. In order to do so it was necessary to locate all human structures in the study areas and, subsequently, dig archaeological test pits within them so their typology and chronology could be assessed. Four-hundred and twenty-one archaeological structures were located during the Madriu-Perafita-Claror and 317 in the InterAmbAr field surveying campaigns. Fifty-seven test pits of 1 x 2 m were excavated in 55 different archaeological structures in the Madriu-Peraftia-Claror valley. The application of these techniques in the InterAmbAr and PCR Mont Lozère projects is still in progress.

Work on these high mountain areas was greatly hindered by their geographical setting which includes heights of between 2000 and 2600 m a.s.l. These areas are covered in snow for most of the year, being accessible only during the summer months. Since there were no roads which permitted access to these areas, the transport of personnel, material and food had to be done by helicopter. This circumstance hindered the development of long campaigns which had to be reduced to two 10 days-long campaigns per year (food preservation issues prevented longer stays). Besides, the teams had to be reduced in size and they usually comprised eight to ten archaeologists. Lack of electrical sources also posed a problem since the use of surveying and photogrammetric material was limited by the amount of batteries available.

Archaeological recording is today a standard procedure that requires much precision and care. It includes the recording of all materials recovered, usually carried out off-site, but also the drawing of site plans, archaeological strata plans and profiles. The later procedures involve a large amount of time which may easily equal the time required in the actual test-pit excavation.

It soon became evident that these standards could have not been achieved with the time and human resources available by employing traditional on-site drawing techniques.

2. Material and methods

Due to the scarce amount of time and resources available, and the extent of archaeological structures under investigation, a methodology that allowed for a fast and reliable recording of structures and test pit excavations needed to be developed. This methodology had to be able to produce both georeferenced plans of the structures and 3D data from which the test pit profiles could be derived.

The methodology followed integrated differential Global Positioning System (DGPS) measurements, terrestrial stereophotogrammetry and geographic information systems (GIS) based volumetric modelling. The workflow followed five stages (Fig. 1):

2.1. Ground control point (GCP) identification and DGPS measurement

This was carried out by marking and numbering with a pen marker the GCPs in the structures. Then the points were measured with a survey-grade Topcon HiperPro DGPS+ with a RTK base station. The data collector, a Topcon FC-100 incorporated the program Topcon TopSURV v. 6.04 which numbered each control point according to the numbers assigned to the GCP. This program allowed the exporting of georeferenced files which could be loaded directly into commercial GIS and photogrammetrical packages. Apart from the projected XYZ coordinates, the files incorporated attributes such as structure number and GCP number which greatly facilitated data classification. The use of a Global Navigation Satellite System GNSS receiver was preferred due to its ability to record the GCPs in a much faster fashion than total station sys- tem without significantly losing the spatial accuracy necessary to conduct subsequent photogrammetrical analysis. It also provided georeferenced measurements avoiding thus further georeferencing work. The projected coordinate systems employed were, in the case of the Madriu-Perafita-Claror and InterAmbAr projects, European Datum 1950, UTM 31 N and, in the case of PCR Mont Lozère, Lambert Conformal Conic, France II.

2.2. Acquisition of photographic stereo pairs

The camera employed to obtain the structures and test pit images was a consumer-grade Canon PowerShot Pro 1 digital compact camera. The inner camera geometry was previously calibrated in a laboratory environment using Topcon Camera Calibration Software v. 2.10. The Canon PowerShot Pro 1 presented a series of advantages. Its small size and resilience made it especially useful for fieldwork. It also presents semi-professional Canon ‘L series’ optics and an 8 mega-pixels objective which permitted the

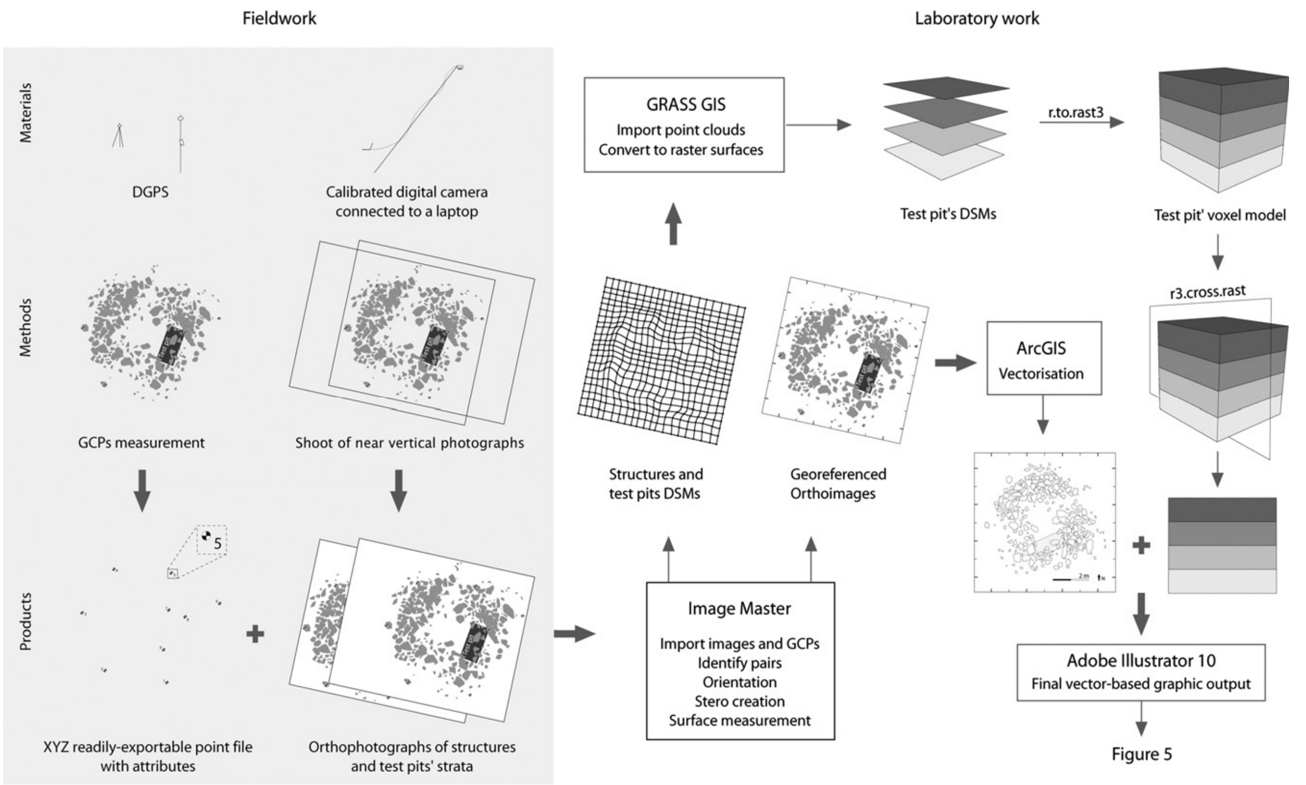

Fig. 1. Graphical scheme of the workflow.

Fig. 2. Image illustrating the process of image acquisition.

acquisition of quality images. Another advantage is that it can be remotely operated.

A simple system was developed: the camera was attached to a 4 meters long extensible pole. Then, the camera was connected via a USB cable to a computer from which the pictures could be taken from a distance by using remote capture software integrated in Canon's ZoomBrowser EX package. The use of this software also al- lowed the on-site classification of photographs according to the number of structures being documented. This was an important feature since more than two thousand pictures were taken (Fig. 2) with no other indication to identify as to which structure they belonged to than the GCPs depicted on them. This picture classification could have taken many hours in the laboratory.

Two types of elements had to be recorded. First, the whole structure under analysis had to be documented. This was done by reducing the structure shape to a simple geometrical frame composed with as few straight lines as possible. Sequential near vertical photographs of the structure were taken while walking on these lines. These photographs had a minimum of a 66% overlap between them. Each single photograph depicted a minimum of eight control points. It was not intended to use all of them in the photogrammetric processing but to have as many references as possible.

The second type of element to be recorded was the test pit exca- vations. Rather than a single picture of the excavated area, it was necessary to take a series of overlapped near vertical photographs covering the whole test pit for each excavated archaeological layer or stratum as they may represent different chronologies and uses of the structure. Each layer's photographic strip depicted a mini- mum of three fixed DGPS positioned GCPs which could later be employed in the photogrammetrical process. The use of near vertical photographs and stereophotogrammetric recording was considered as the most adequate methodology since the object of interest was the archaeological layer which is usually a near horizontal surface. Two other factor were also considered important in the choice of vertical stereophotogrammetry. Firstly, since the excavation process had to stop to allow photogrammetric recording of every archaeological layer. This process had to be done as fast as possible so, the excavation could continue with little loss of time. Secondly, the limited amount of batteries suggested shooting as few photographs as possible for each archaeological layer.

These two initial phases composed the data acquisition phase, which was developed on-site. The next stages in the workflow were developed in the laboratory and they were centred in the processing of these data and the production of final graphic output.

2.3. Development of georeferenced photogrammetric DSMs and orthoimages

Topcon Image Master v. 1.4 (formerly PI-3000) was employed to develop both orthoimages and phototextured DSMs. The application of this software to the recording of archaeological complex irregular surfaces had been evaluated before with satisfactory results (Chandler et al., 2007; Masinton, 2008). The first stage in the registration process was importing the GCPs coordinates previously downloaded from the DGPS. Secondly, the photographs were incorporated. The camera calibration parameters were included by importing the previously created file from the Camera Calibration Software. Thirdly, each stereophotographic pair was defined.

Image master requires the orientation of each individual stereo pair individually. The orientation process started by linking the GCPs obtained with the DGPS to the numbered GCP marks present at the photographs. Once the six best distributed control points were measured, the stereo pairs went through a bundle adjustment process. This method is subject to few restrictions as regards the placement of the control points. It also allows the precision of the data measured in each of the stereo images to be uniform and it is therefore appropriate for dealing with photographs taken with- out a fixed photographic distance at base length. Another advantage of employing bundle adjustment is all stereo images and the GCPs can be employed in conjunction in the surface generation process highly improving thus the accuracy of the measurements. All these characteristics were adequate for dealing with the data gathered on-site, where the pole-attached camera did not guarantee strict verticality, equal photographic distance or equal orientation in taking the photographs.

Once the different stereo pairs of a single structure were oriented, they were all used to create a 3D surface by employing Image Master 'Auto Surface Measurement Batch Processing' which automatically measures a surface that extends over multiple stereo images. For all the structures' DSMs, a mesh interval of 2 cm was applied. For the smaller test pit' DSMs the resolution was increased to a 0.5 cm mesh interval. Common GPCs were employed for the photogrammetric reconstruction of the various layers excavated in a single structure. Accordingly the DSMs spatial match was highly accurate. The areas covered by the DSMs were constricted to the archaeological strata tracing a stereo-matched poly-line. This process provides a highly reliable TIN which can be used to automatically generate orthoimages and can be exported for its use in other geospatial software.

2.4. Development of volumetric models

Voxels, acronym for volume pixels, are the volumetric expression of pixels. That is, they are cubes of equal sides which can be clustered to form volumetric 3D models. Developing volumetric models of the excavated test pits was deemed interesting to automatically produce profiles of the excavated strata. Although this paper will only deal with the automated profile extraction process, volumetric models have many, if still undeveloped, archaeological applications. Voxel-based models can be used to calculate statistics on the volume of soil excavated, to analyse sedimentation and

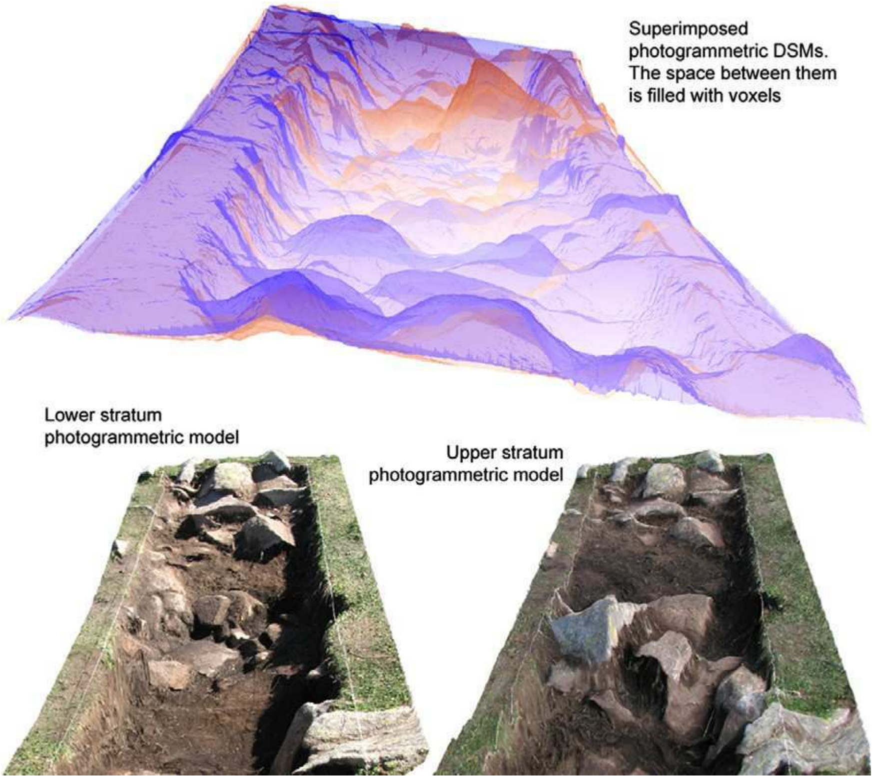

Fig. 3. Creation of a volumetric model from two photogrammetry-based DSMs.

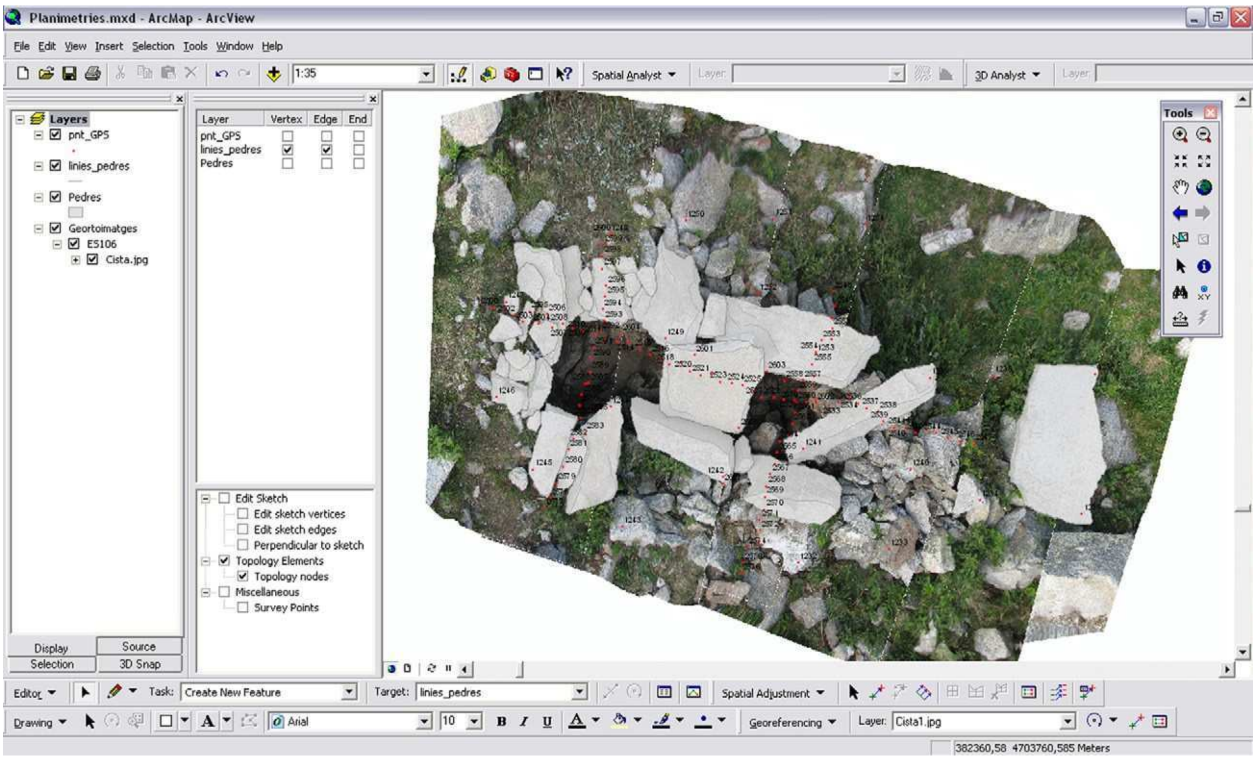

Fig. 4. Vectorisation of an archaeological structure in ArcGIS 9.2.

erosion processes in a 3D environment or, simply, to take measurements in an Euclidean space (Lieberwirth, 2008a: pp. 92–93). Their multiple applications have made them routinely employed in geological and medical 3D imaging.

Two strategies are implemented in GRASS SIG to develop voxel models: direct interpolation between 3D vector points and the so-called ''flood-filling'' algorithm (Lieberwirth, 2008a,b). The former, implemented into GRASS through the module ''v.vol.rst'', interpolates voxels of a given resolution between the 3D points employing the vector points' attribute field (in this case corresponding to the layer number) to define the value of the voxels. This was not considered adequate to develop a volumentric representation of the excavation' stratigraphy since the 3D vector points were representing the surface of each layer and an interpolation between them would have resulted in the estimation of intermediate values for each stratum. The flood-filling algorithm, on the contrary, creates a discrete volumetric representation of each stratum by filling with voxels the space between overlapping 2D raster-based DSMs. This second strategy was preferred since it kept the integrity of the strata. The TINs developed in Image Master for every archaeological stratum were imported into GRASS GIS 6.4 as cloud points and interpolated into raster maps. For each test pit, a series of DSM raster maps depicting each of the excavated layers was generated. These were later employed to develop ''flood-filling'' volumetric models of the excavations by using the module 'r.to.rast3' (Fig. 3). The small voxel size required for accurate volumetric representations may result in the absorption of many system resources.

2.4. Generation of plans and profiles of both structures and test pits

The georeferenced orthoimages were imported into ArcGIS 9.2' where the structures were vectorised to create the site plans (Fig. 4). The test pit profiles were created using the GRASS module 'r3.cross.rast', which created a 2D cross section from the volumetric models previously developed.

The last step consisted in joining the structure plans and the test pit profiles in a single graphical output suitable for archaeological presentation (Fig. 5) using a standard vector-based drawing program, in this case Adobe Illustrator 10. In this environment, plans and profiles were associated and relevant information, such as strata numbers or radiocarbon dates, were added.

3. Results

This recording strategy permitted the recording of 52 structures that ranged from 2 to 230 m^2. From all these structures, orthoimages, 3D DSMs, site plans and topographies were obtained. Volumetric recording was executed in the ten most interesting excavations. The time employed on-site to record the structures ranged from 5 min for the smallest structures to 2 h for the biggest ones. Post-excavation process and generation of the different digital products involved a time investment four to six times higher than on-site recording. The time cost was dependent on the technician's experience.

The spatial accuracy of the derived plans and profiles was significantly higher than those typical of traditional archaeological drawing. The DGPS recorded GCPs presented a static accuracy of 0.003 m in the horizontal plane and 0.005 m in the vertical plane. The archaeological layers' photogrammetric models presented a

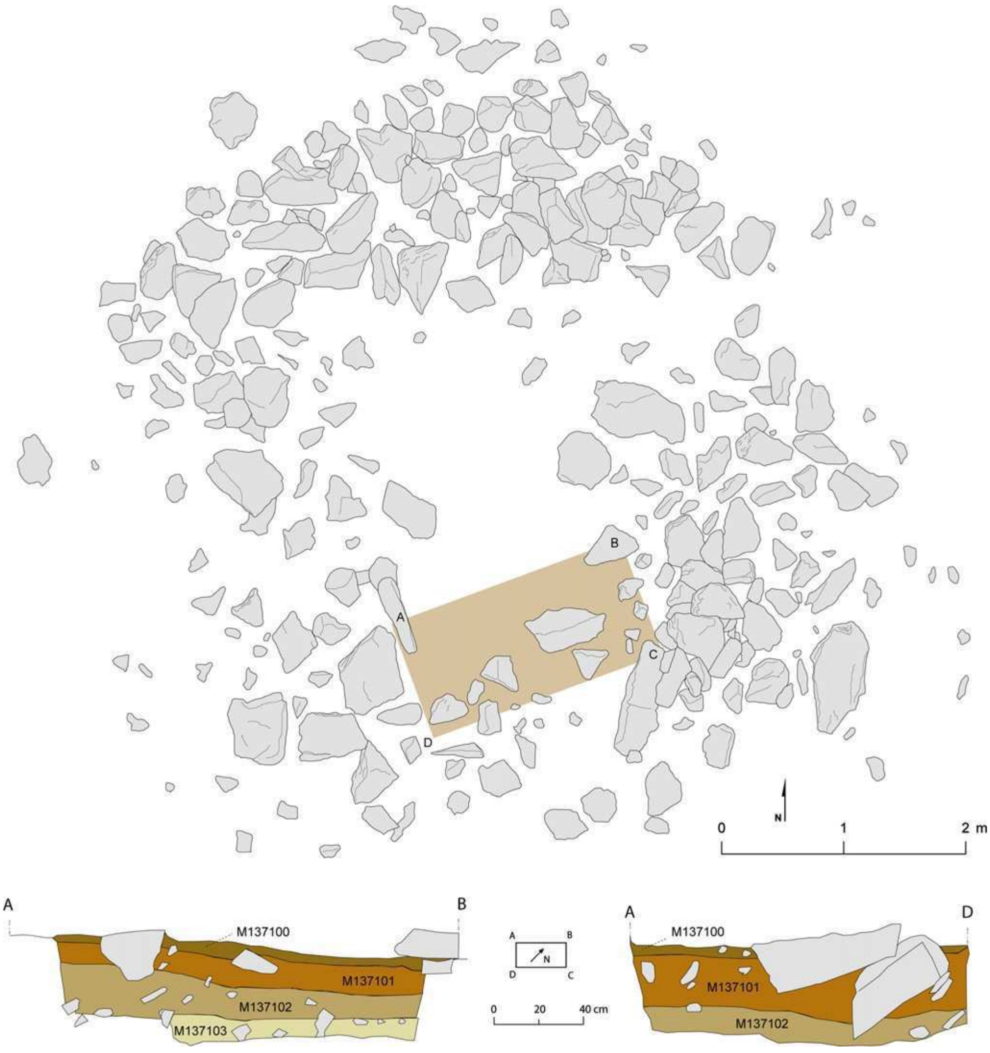

Fig. 5. Archaeological illustration joining the different data products.

minimum plane ground resolution of 0.0016 m and a maximum plane ground resolution of 0.001 m. Vertical ground resolution presented a minimum value of 0.0024 m and a maximum of 0.0077 m. Orthoimages generated from the structures' photogrammetric models and employed to develop site plans presented a plane maximum ground resolution of 0.0015 m and a minimum of 0.0193 m.

4. Discussion

The work process combining DGPS, photogrammetry and voxel-based GIS presented in the previous sections has proven advantageous in many aspects. The material employed to conduct the on-site data recording was light and easily transportable and, therefore, adequate for high mountain archaeological recording. Another advantage was the reduced time necessary to conduct the recording process. Compared to previous experience in archaeological recording it can be up to 10 times faster and, at the same time, much more accurate. Normal deviation in traditional archaeological drawing can range from five to fifteen centimetres depending on the size of the structure and the use of auxiliary surveying material. The digital products generated by this process are also georeferenced, which cuts out the need to orientate and scale the drawings.

This combination of techniques is not only cost effective and time efficient, but it goes beyond the sole drawing of the structure and the archaeological strata to record the full process of archaeological excavation by taking two or more vertical photographs after digging each archaeological stratum. In this way and by employing this process, all aspects of the archaeological graphic register can be managed.

Generated products not only include plan drawings and sections as can be expected in traditional archaeological drawing but georeferenced high definition digital orthoimages, 3D digital surface models (DSM) and volumetric models. All these data can be readily integrated into GIS or CAD software facilitating their post-processing and production of final archaeological illustrations. Although, not many geospatial packages today can handle voxel models, GRASS GIS can export voxel data to VTK or Vis5D formats. Alternatively voxel models can also be exported to 3D ASCII. These can be imported to specialised scientific data visualisation open source software such as VTK Toolkit, ParaView, Mayavi, or Vis5D+ where they can be explored and analysed in detail.

Although, the application of these techniques provides numerous advantages, some drawbacks must also be noted. The material employed is heavier than that used in typical archaeological field drawing. This material can include surveying stations or DGPSs but does not usually include on-site computers or extensive poles. Another significant problem in the application of these techniques is the need for experienced professionals. This work-flow joins DGPS, digital stereophotogrammetry and voxel-based GIS modelling. Each of these techniques involves accurate knowledge of data acquisition procedure and data processing which is not widespread within the archaeological community. The application of these techniques may be hindered also by the price of these materials. Digital cameras, computers and surveying material is rather affordable but digital photogrammetric software is used more rarely and, although much cheaper than before, still requires extra investment which not many archaeological teams can afford.

Although these techniques are time saving on-site, they require considerable post-processing time. The generation of orthoimages and DSMs, an integrated procedure in Image Master, is only part of the process. The orthoimages have to be imported into a vector-based program to create plans and the DSMs have to be imported into a voxel-based GIS to develop volumetric models from which sections can be created. Traditional post-excavation archaeological drawing also employs vector-based software to digitise on-site hand-made drawings but it does not devote time to orthoimage production or GIS modelling.

Finally, these techniques have proven useful in reconstructing the test pit excavation process since their reduced size allowed the recording of each stratum by a single orthophoto pair. However, when extensive larger excavations are involved, this procedure may not be entirely adequate since it would require the shooting of hundreds of photographs and the investment of large amounts of time in their post-processing. In this case, low altitude high definition digital orthophotographs should be employed.

5. Conclusions

This work procedure enabled the fast and reliable register of structures and excavation processes in extreme conditions. The integration of the different techniques simplified post-excavation data processing, making it possible to treat raw on-site recorded data to produce the whole range of archaeological graphic products. Its use made it possible to go beyond the pure drawing of site plans and excavation plans and profiles by generating sites' 3D models and excavation volumetric models. The nature of archaeological excavations implies the destruction of the object under study. This methodology permitted a thorough recording of this process, which could be used for further visualisation and in depth analysis.

The incorporation of stereophotogrammetric techniques in the recording of archaeological features and excavations offers a tool that is especially useful when available time is scarce. This may include rescue excavations (the most common type of excavation conducted at present), which would largely benefit from the implementation of such procedures.

In order to introduce these techniques into the archaeological community, it will be necessary to train specialised technicians and invest in software and hardware. In this sense, if one does not take into account the frequent system crashes, Image Master photogrammetry software provides a cheap and easy to use tool that can be combined with surveying stations and post-processing software within a simple workflow.

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References

Barceló, J.A., Vicente, O., 2004. Some problems in archaeological excavation 3D modelling. In: der Stadt Wien, Magistrat, Kulturelles Erbe, Referat, Wien, Stadtarchäologie (Eds.), The E-way into the Four Dimensions of Cultural Heritage. CAA 2003. Computer Applications and Quantitative Methods in Archaeology, Proceedings of the 31st Conference, Vienna, Austria, April 2003. Archaeopress, Oxford, pp. 400–404 (Enter the Past).

Brenningmeyer, T., Begg, D.J.I., 2007. Reconstructing tebtunis: assembling a site model using archived aerial photography. In: Clark, J.T., Hagemeister, E.M. (Eds.), Digital Discovery. Exploring New Frontiers in Human Heritage. CAA2006. Computer Applications and Quantitative Methods in Archaeology. Proceedings of the 34th Conference, Fargo, United States, April 2006. Archaeolingua, Budapest, pp. 313–318.

Bryan, P., 2006. The role of photogrammetry in understanding, enhancing and enjoying England's historic environment. In: Baltsavias, E., Gruen, A., Van Gool, L., Pateraki, M. (Eds.), Recording, Modeling and Visualization of Cultural Heritage. Taylor and Francis, London, pp. 77–386.

Chandler, J.H., Bryan, P., Fryer, J.G., 2007. The development and application of a simple methodology for recording rock art using consumer-grade digital cameras. The Photogrammetric Record 22 (117), 10–21.

El-Hakim, S.F., Remondino, F., Gonzo, L., Voltolini, F., 2008. Effective high resolution 3D geometric reconstruction of heritage and archaeological sites from images. In: Posluschny, A., Lambers, K., Herzog, I. (Eds.), Layers of Perception. Proceedings of the 35th International Conference on Computer applications and Quantitative Methods in Archaeology (CAA). Berlin, Germany, April 2–6, 2007. Dr. Rudolf Habelt GmbH, Bonn, pp. 43–50.

Fant, J.E., Loy, W.G., 1972. Surveying and mapping. In: McDonald, W.A., Rapp, G.R. (Eds.), The Minnesota Messenia Expedition. Reconstructing a Bronze Age Regional Environment. The University of Minnesota Press, Minneapolis.

Grün, A., Remondino, F., Zhang, L., 2004. Photogrammetric reconstruction of the Great Buddha of Bamiyan, Afghanistan. The Photogrammetric Record 19 (107), 177–199.

Lieberwirth, U., 2008a. Voxel-based 3D GIS: modelling and analysis of archaeological stratigraphy. In: Frischer, B., Dakouri-Hild, A. (Eds.), Beyond Illustration: 2D and 3D Digital Technologies as Tools for Discovery in Archaeology. Archaeopress, Oxford, pp. 85–94.

Lieberwirth, U., 2008b. 3D GIS voxel-based model building in archaeology. In: Posluschny, A., Lambers, K., Herzog, I. (Eds.), Layers of Perception. Proceedings of the 35th International Conference on Computer Applications and Quantitative Methods in Archaeology (CAA), Berlin, Germany, April 2–, 2007, Kolloquien zur Vor- und Frühgeschichte, vol. 10. Habelt, Bonn, p. 8.

Masinton, A., 2008. Review of ImageMaster Close-range Photogrammetry Software by Topcon. Internet Archaeology 25, <http://intarch.ac.uk/journal/issue25/reviews/masinton.html>.

Mattiseck, K., 1980. Vermessungswesen und Archäologie. Nachrichten aus dem öffentlichen Vermessungsdienst Nordrhein–Westfalen 13 (2), 84–112.

Newcomb, R.M., 1971. Celtic fields in Himmerland, Denmark, as revealed by vertical photography at a scale of 1:25,000. Photogrammetria 27 (3), 101–113.

Orengo, H.A., 2010. Arqueología de un paisaje cultural pirenaico de alta montaña. Dinámicas de ocupación del valle del Madriu-Perafita-Claror (Andorra). Unpublished Ph.D. thesis, Rovira i Virgili University, Tarragona.

Orengo, H.A., Palet, J.M., 2010. Methodological insights into the study of centuriated field systems: a landscape archaeology perspective. Agri Centuriati 6, 171–185.

Orengo, H.A., Ejarque, A., Albiach, R., 2010. Remote Sensing and GIS applied to the study of an Iberian Iron Age oppidum's hinterland: La Carència project (Valencia, Spain). In: Frischer, B. (Ed.), Making History Interactive. Proceedings of the 37th annual international conference on Computer Applications and Quantitative Methods in Archaeology, Williamsburg, Virginia, <http://www.caa2009.org/articles/Orengo_Contribution303_c%20(1).pdf>.

Poidebard, A., 1939. Un grand port disparu, Tyr. Recherches aériennes et sous-marines, 1934–1936. Librairie Orientaliste Paul Geuthner, Paris.

Reindel, M., Grün, A., 2006. The Nasca-Palpa Project: a cooperative approach of archaeology, archaeometry and photogrammetry. In: Baltsavias, E., Gruen, A., Van Gool, L., Pateraki, M. (Eds.), Recording, Modeling and Visualization of Cultural Heritage. Taylor and Francis, London, pp. 21–32.

Remondino, F., El-Hakim, S., 2006. A critical overview of image-based 3D modeling. In: Baltsavias, E., Gruen, A., Van Gool, L., Pateraki, M. (Eds.), Recording, Modeling and Visualization of Cultural Heritage. Taylor and Francis, London, pp. 299–313.

Tschauner, H., Siveroni, V., 2007. Stratigraphic modeling and 3D spatial analysis using photogrammetry and octree spatial decomposition. In: Clark, J.T., Hagemeister, E.M. (Eds.), Digital Discovery. Exploring New Frontiers in Human Heritage. CAA2006. Computer Applications and Quantitative Methods in Archaeology. Proceedings of the 34th Conference, Fargo, United States, April 2006. Archaeolingua, Budapest, pp. 257–270.

Whittlesey, J., 1966. Photogrammetry for the excavator. Archaeology 19 (4), 273–276.