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A hybrid measurement approach for archaeological site modelling and monitoring: the case study of Mas D'Is, Penàguila

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ABSTRACT

There are several methodologies for obtaining and processing geospatial data with the aim of generating 3D models that represent reality. Thus, it is necessary to analyse the performance and capabilities of each methodology and its integration into archaeological heritage documentation. This paper analyses and compares the generation of 3D archaeological site models through the integration of aerial photogrammetry from an unmanned aerial vehicle, terrestrial photogrammetry and laser scanning. This process is carried out for two different excavation campaigns to monitor the sites based on dimensional analysis. Finally, a hybrid 3D model is generated by merging the three methodologies into a true orthophoto of the archaeological site for each campaign. One of the most relevant aspects of the model is the integration of multiple geo-technologies, which requires establishing a rigorous methodology for geo-referencing different data and equipment that is supported by the use of a dual geodesic coordinate system. The results obtained confirm that the geo-technologies proposed for integration are perfectly complementary, providing high quality and thorough models of archaeological sites.

1. Introduction

Knowledge of the topographic features of an archaeological site is essential for its full documentation. Methodologies such as terrestrial laser scanning (TLS) and terrestrial and aerial photogrammetry, the latter from unmanned aerial vehicles (UAVs), have been used to document archaeological sites, each showing great potential separately. Terrestrial photogrammetry offers a low-cost, highly flexible alternative by allowing automated methods, and it opens procedures to all users for performing dimensional analyses and even reconstructing simplified models from images taken with any type of camera (Tokmakidis and Skarlatos, 2002). In addition, the recent emergence of UAV technology has allowed these principles to be extrapolated to aerial photogrammetric imagery with spatial and temporal resolution impossible to achieve with standard satellite procedures (Gomez-Lahoz and Gonzalez-Aguilera, 2009). At an archaeological site, because it is a great advantage to have vertical and oblique bird's eye view images without any obstacles and from a unique perspective, UAV photogrammetry has emerged as a technology of great interest to the scientific archaeological community. However, one of the biggest drawbacks of both terrestrial and UAV photogrammetry lies in the difficulty of modelling and treating complex non-parametric geometries. Lately, laser scanning technology is being applied to the recording and 3D modelling of highly complex archaeological sites, for example, archaeological sites and/or underground caves where the complexity of the shapes and object sizes necessitates non-destructive techniques for documentation and reconstruction (González-Aguilera et al., 2011a,b). However, one of the major drawbacks in its lone application resides in the lack of semantic information in the resulting point clouds, which is vital in the process of archaeological interpretation.

Therefore, various authors have chosen to integrate different geo-technologies in order to make use of hybrid synergy and obtain more complete and competitive products. Eisenbeiss et al. (2007),

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Lambers et al. (2007) and Remondino et al. (2009) use aerial photogrammetry taken by UAV, terrestrial photogrammetry and TLS to obtain digital terrain models (DTMs) of archaeological settlements. They combine information from different sensors and methodologies to obtain a DTM that overcomes the deficiencies of the individual methodologies.

In an attempt to merge satellite data, Patias et al. (2009) use a UAV-helicopter, TLS and QuickBird satellite images to carry out the documentation of archaeological sites. In this case, the satellite images provide added value because they allow geolocation and a general representation of the whole environment.

Although all of the cited works have integrated geotechnologies, none of them have developed a thorough georeferencing methodology capable of guaranteeing high precision and enabling automation in the registration process of all the data and sensors. This aspect is crucial in archaeological campaigns where numerous sensors are used and the data obtained correspond to different methods. A proper georeferencing system would allow adaptive hybridization of the models so that redundant information is removed in common areas and extra information is provided in shadow areas. Furthermore, the registration of images from UAV and terrestrial photogrammetry incorporates breaklines through stereoscopic restitution processes, providing higher quality and authenticity to the final model, two key aspects in the generation of a true-orthophoto.

This paper describes how three capture techniques: aerial photogrammetry from UAVs, laser scanning and terrestrial photogrammetry, can be integrated to generate hybrid archaeological products: a three-dimensional model and a true orthophoto, allowing archaeological site monitoring to quantify the degree of progress at a site. The development of a rigorous geo-referencing method will be of great utility for future archaeological works, making it possible to obtain better results while establishing a basis for automated sensor registration.

The modelling methodology used here allows the generation of a three-dimensional hybrid model with its corresponding true orthophoto. To demonstrate the added value of hybridization methods in 3D modelling, a series of comparisons (quantitative and qualitative) are made in order to evaluate and quantify the advantages and disadvantages of each methodology separately and together. Finally, the variable of time is incorporated to monitor the degree of evolution of the site. More specifically, we propose to perform a dimensional analysis to assess the excavation volume and identify areas most affected in two different campaigns.

2. Materials

2.1. Site description

Placed in the municipality of Penàguila (Alicante, Spain), the archaeological site of Mas D'Is is set in the location known as “Les Puntes”, close to the Penàguila River. The site proves to be in flat terrain in an agricultural area. This is why the terracing under the crop fields is hidden. This site holds great interest for the archaeological scientific community, offering a new image of the Neolithic communities in the Mediterranean area of the Iberian Peninsula. In contrast to the traditional view, which considered some continuity between habitat sites of Mesolithic and Neolithic groups with a preferential use of caves, recent data suggests the development of sedentary villages in the locational strategies of the early farming groups (Bernabeu Aubán et al., 2003) (see Fig. 1).

Several geometrical shapes and various irregular reliefs can be found in the settlement of Mas D'Is. The former are related to human presence, whereas the latter correspond to the morphology of the terrain. These characteristics provide the site great complexity,

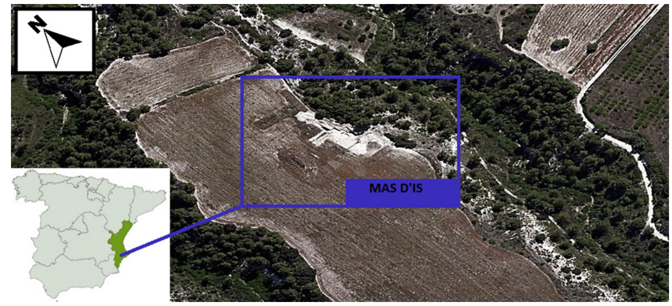

Fig. 1. Aerial image of the archaeological settlement.

so it is important for them to be recorded and reconstructed by hybrid approaches and models. On the other hand, factors such as vegetation and the depth of excavations create added drawbacks in terms of shadows and matching errors, seriously affecting the final product if they are not carefully filtered.

2.2. Instruments for reference system definition

The instruments used for establishing a reference frame (Fig. 2) include a total station, Topcon Imaging Station, a high-accuracy GPS type RTK GNSS Leica System 1200 and several artificial targets for geo-referencing the dataset acquired from each sensor. A complete description of each instrument is detailed below.

2.2.1. Total station

To obtain the coordinates of the points that enclose the common framework of the work equipment is used that ensures precise topographic observations (Fig. 2). Total Station Imaging Station 2 allows the measurement of points without a prism reflector from a distance of 250 m to 2000 m. Moreover, with the use of a prism the range can be extended up to 3000 m. Prism measurements can be performed by a single operator using the robotic tracking receiver RC-3. The range precision for that instrument is ± 2 mm + 2 ppm for distances with prism measurements and ± 3 mm for reflectorless measurements. It also has dual axis compensator ± 6 ' accuracy. The minimum angular reading is 1 mgon and since the maximum working distance is approximately 40 m, all this translates into accuracy in determining the position of better than 0.01 m.

2.2.2. High accuracy GPS

The linkage of this work to a cartographic reference system is performed by GPS sensors (Fig. 2). Leica System 1200 receptors works with the L1 and L2 frequencies emitted by the constellation satellites GPS and GLONASS. This allows measurement in real time kinematic (RTK) mode while static observations are recorded in the base receiver. In the subsequent post-processing step, the coordinates of the measured points are obtained in a global system with centimetre accuracy. To minimise the possibility of recording false coordinates, this equipment updates its position with a frequency of 20 Hz (0.05 s). Absolute positioning, when points were surveyed in static mode, provided accuracy of 5 mm + 0.5 ppm in horizontal and 10 mm + 0.5 ppm in vertical, and 10 mm + 1 ppm in horizontal and 20 mm + 1 ppm in vertical when points were surveyed in cinematic mode.

2.2.3. Targets for geo-referencing the obtained models

The need to integrate all the data captured by each of the sensors under the same coordinate reference system requires that targets be of different types depending on their use. Stakes with a nail in the centre were used for installing the base of the GPS,

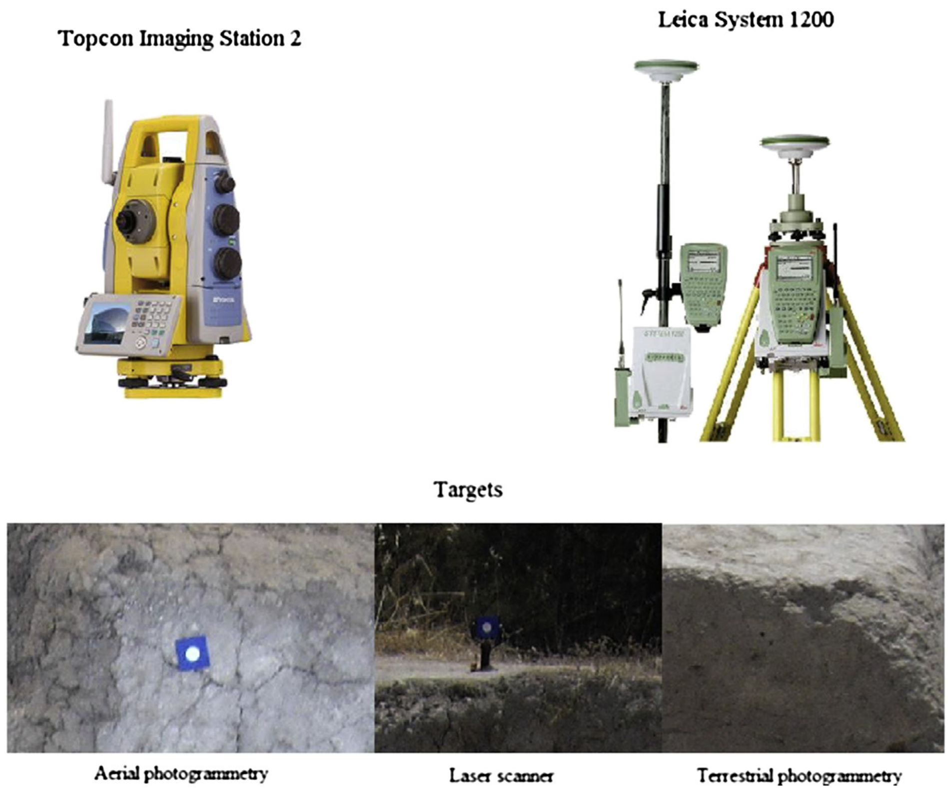

Fig. 2. Topographic equipment used in this work (Above). The different types of targets used in the archaeological survey (Below).

targets with blue background and a 3-cm diameter white circle were used for aerial photogrammetry and laser scanning, and targets made of black acetate with a 1.5-cm diameter circumference were used for terrestrial photogrammetry (Fig. 2). The choice of this latter type of target for use in terrestrial photogrammetry is based on the shorter distance to the object, so that the spatial resolution is increased. Therefore, with these targets the visual impact on the texturing of 3D models obtained by terrestrial photogrammetry can be minimised. In addition, these targets were surveyed from a single station in order to minimise error propagation, guaranteeing a relative precision of 0.005 m.

2.3. *Instruments for image acquisition*

The instruments for image acquisition include an UAV of the quadracopter (Microdrones, md4-200) type, a Pentax Optio A40 compact digital camera and a Leica ScanStation 2 laser scanner (Fig. 3). The equipment meets the needs for carrying out this work. A complete description of each instrument is provided.

2.3.1. *Unmanned aerial vehicle*

Different types of model aircraft have different capabilities, with advantages or disadvantages depending on purpose (Hunt et al., 2005). Compromises must be made between ease of flying, stability in wind, handling flight failures, distance covered, and take-off/landing requirements. In this study, a Microdrone md-400 (Microdrones, Inc., Kreuztal/Germany) was utilised. It is a vertical take-off and landing (VTOL) quadracopter aircraft (Fig. 3). The acronym VTOL denotes the capability of a flight vehicle to take off and land in the vertical direction without the need of a runway. It employs four rotors or propellers on vertical shafts mounted on one level of the bodywork. The advantage of this concept is the movement of the UAV body can be controlled in three directions by a simple variation in thrust (and therefore torque) of each of the four propellers, if the direction of rotation for each of them has been appropriately selected. Each 24-pole motor has a gross weight of 40 g and a diameter of 48 mm. A brushless external rotor motor has 18 slots and 24 magnets and has fully synchronised commutation. Each of the motors is supplemented with three Hall–sensors, which relay the momentary position and turning speed of the magnets to the control electronics. Integrated control of the motors is mediated via a Controller–Area–Network (CAN–bus) with each motor having a unique address. The joint operation of all components creates a closed control loop at a dynamic fast enough to

Fig. 3. Sensors used in this work.

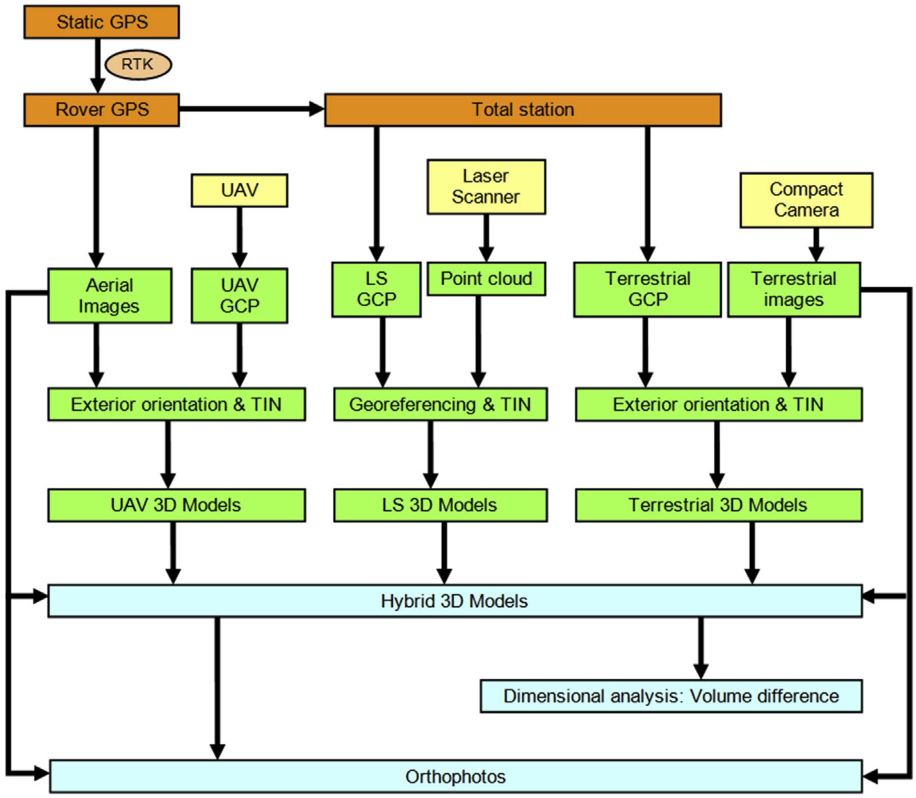

Fig. 4. Scheme of the workflow performed in the hybridization of geo-technologies for modelling and monitoring the Mas D'Is Penàguila archaeological site.

enable accurate and rapid control of each motor's momentum and thereby stabilise the aircraft.

The core component of the electronics is the IMU (Inertial Measurement Unit) module, which includes a bearing fixture and barometric altitude stabilization. This device comprises a set of mutual communicating sensors that are combined in a Kalman filter. A 32-bit embedded controller calculates the requested control vectors in millisecond intervals. This type of generic control allows for basic stabilization of the drone's position and bearing during flight and facilitates the manual control tasks of the pilot.

Heading retrieval, an accelerometer and a baroaltimeter for heading and altitude control are also installed in the IMU-module. The flight controller (FC) permits user interpretation of the radio controlled (RC) commands including a mixer, safety features and motor management, among others. A Global Positioning System (GPS) U-Blox 6 is also installed for reporting and controlling the location of the aircraft.

2.3.2. *Terrestrial laser scanner*

To perform laser scanning surveying, Leica ScanStation 2 equipment was used based on the time of flight (ToF) principle with a scanning speed up to 50,000 points per second. This laser scanner has a 360° × 270° – Horizontal × Vertical-field of view, with an angular resolution of 0.0023° in horizontal/vertical and a precision in angular measurement of 0.0034°. The laser beam diameter is 6 mm for 50 m and works in the visible green electromagnetic spectrum with a wavelength of 532 nm. The measurement distance ranges from 30 cm to 300 m, and the precision of a simple measurement goes from 4 mm to 50 mm. Although in this work the images obtained with the Pentax camera have been used for the mapping texture process, the Leica ScanStation 2 incorporates an integrated 1 megapixel camera. The intensity values are registered with 12 bit radiometric resolution. It also includes a dual-axis compensator with a precision of 0.00015°. The spatial resolution used was 5 mm at 20 m distance.

2.3.3. *Conventional RGB compact digital camera*

A Pentax Optio A40 digital camera (PENTAXTM, Golden, Colorado, USA) was utilised to obtain images in the visible spectrum. The main characteristics of the camera for this study are:

- Sensor: 1/1.7” type CCD, 12.0 million effective pixels and pixel size of 0.0018 mm.
- Image size: 4000 x 3000 (columns × rows).
- Lens: 37–111 mm (35 mm), 3x optical zoom, Focal of 2.8–5.4.
- Focal length: 7.9 mm
- Pixel size: 0.0018 mm
- ISO sensitivity: ISO 50–ISO 1600.
- Internal memory (21 Mb) and SD memory card.

3. Methods

The method developed can be observed in Fig. 4. Due to the role of the different sensors used, the first step establishes a common reference frame based on the use of different artificial targets that perform as ground control points. The high precision of the surveying equipment together with the rigour of the reference system definition guarantees that data based on aerial images (UAV), point clouds (TLS) and terrestrial images (digital camera) can be integrated. After data have been acquired with each technology, the information is processed in order to generate hybrid geomatic products. Finally, the assessment of the results obtained and their monitoring over time allow us to derive conclusions about the evolution of the archaeological settlement.

3.1. Reference system definition

The definition of the reference system with the geo-referencing methodology is a key factor enabling the results of different methodologies to be merged and compared. To do this, a reference system together with its common and proper coordinates must be chosen, establishing a homogenous network of control and check points that allow us to geo-reference the different datasets acquired by different sensors. The targets aimed at in aerial photogrammetry are located in horizontal planes, while those for terrestrial photogrammetry and laser scanning are placed in vertical planes. Then, the GPS base is placed and the coordinates are surveyed in static mode. This process is intended to bind all the measurements in the correct places after processing the observations. At the same time, all the station bases and the control points for aerial photogrammetry are surveyed by GPS in real time kinematic (RTK) mode. Two bifrequency GPS units were used in order to establish rigour in the surveying of control points, and a relative precision of 0.02 m was obtained. Then, the targets for terrestrial photogrammetry and laser scanning are surveyed by the total station.

One of the most relevant aspects proposed in this paper involves the choice of an appropriate reference and coordinate system. According to ISO 191111, a coordinate reference system (CRS) can be geodesic or local. Ideally, for archaeological work, a local CRS would be desirable because the work area is small and all coordinates in metres are small in magnitude, avoiding problems related to the generation of certain model formats (e.g., VRML, OBJ, PLY) when cartographic CRS coordinates are used such as UTM.

However, the requirement for correct geo-referencing in geomatics products is strong due to the convenience of having overlapping information from different sources and to the need to publish the products into globalised systems like Google Earth. In this sense, the methodology proposed in this paper aims to take advantage of both CRS types, taking the easy way in the management of local CRSs and addressing the possibility of geo-referencing geodetic CRSs. The geodetic reference system used in this work is the ETRS89 (European Terrestrial Reference System 1989), an official reference system in Spain since 2007. The local system used, LGCSPA (Local Geodetic Coordinate System for Anchor Point), is the local geodetic system linked to the anchor point, which is supported by the GPS base and whose position is determined with high accuracy after post processing with two Spanish global navigation satellite system (GNSS) stations. This coordinate system is realised as: origin: point itself; *Z* axis: according to the geodesic vertical in the anchor point; *Y* axis: according to the direction of geodetic north and an *X* axis completing a right-handed triplet. To avoid negative coordinates in planimetry, the origin has been moved 100 m in each coordinate axis. In order for heights to be orthometric a translation in the *Z* axis is considered, HPA (height of anchor point), obtained as the coordinates of the anchor point: (100, 100, HPA).

To ensure that all work is referenced to LGCSPA the following methodology is defined:

1. Get the coordinates of the points measured by GPS-RTK. This includes the total station bases and the targets that are the control points for UAV photogrammetry.
2. Calculate the points surveyed by the total station in this LGCSPA system. This group of points includes the targets that are control points for the terrestrial photogrammetry and laser scanning.

The main advantage of working with this LGCSPS system compared to the UTM coordinate system, from a geodetic point of view, is that operations such as passing from terrain to ellipsoid and projecting the ellipse's measurements onto the UTM plane can be avoided, resulting in better quality archaeological site data. However, if the final products, DTM and the true orthophoto, require a cartographic projection, it is possible to get these models into the UTM coordinate system by applying a simple rotation and scaling translation.

3.2. Data acquisition

In this section the data acquisition process is described, which consists of 1) aerial image acquisition, 2) laser scanner data acquisition and finally 3) ground image acquisition.

3.2.1. Aerial imagery

Before executing a flight, flight planning should be performed in such a manner that permits implementing the photogrammetric algorithms, mainly with respect to overlap, verticality and image scale. To do so, the authors developed the MFlip software (Hernandez-Lopez et al., 2013) (Fig. 5), which was awarded the ASPRS (American Society of Photogrammetry and Remote Sensing) John I. Davidson President's Award. On the first day of data acquisition, the planned flight height was approximately 60 m, which resulted in a GSD of approximately 0.014 m. In this case, two

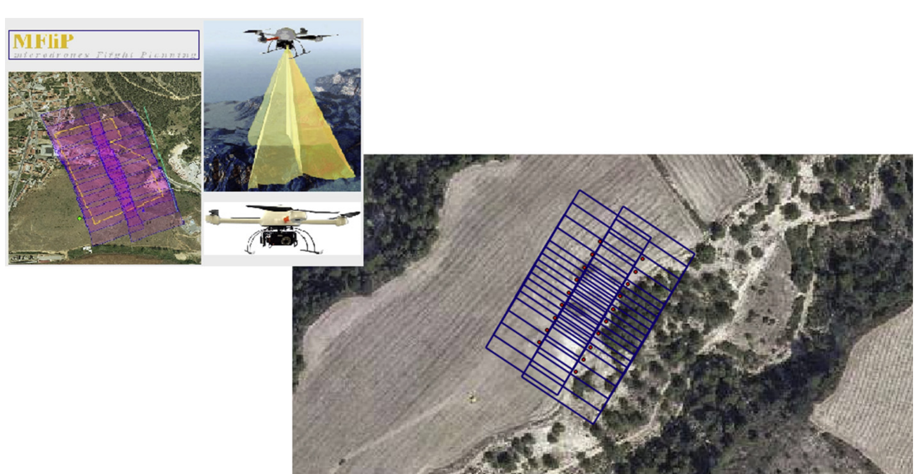

Fig. 5. Flight planning software used for the UAV survey of the archaeological settlement.

parallel flights were necessary. On the second day the flight plan consisted of performing three parallel flights at a height of approximately 40 m, resulting in a GSD of approximately 9 mm. For both flights the forward overlap between images was 60% while the side overlap was 30%. The flight parameters defined for the UAV were the following: 1) a horizontal speed of 4 m/s, 2) vertical speed of 2 m/s, 3) landing speed of 2 m/s. Two shots of the camera were programmed for each image acquisition point to ensure sharpness (the best image was selected during the processing work). In particular, the images were taken with a short fixed focal length using a diaphragm aperture of f/2.8, exposure time 1/1000 s and ISO 100. The parameters defined for each flight plan were written in an ascii file that was saved in a SD card incorporated into the UAV, which permitted the flight to be performed automatically (only take-off and landing were manual).

3.2.2. Laser scanner data

After flying the UAV, laser scanner data acquisition was performed. It was necessary to perform three scans from different locations on each of the days to acquire data from the entire site. The above-described targets were located across the site to align the point clouds generated at each base. The spatial resolution was established for the worst case at 5 mm, considering that the maximum scan distance would be less than 20 m. Thus, for closer objects, the spatial resolution was even higher than 5 mm.

3.2.3. Terrestrial imagery

Terrestrial image acquisition was performed with a camera that was mounted in the UAV with the objective of improving the texture of the vertical planes. Several images were obtained, which allowed the whole archaeological site to be covered. The images were captured according to a photogrammetric procedure (Hanke and Grussenmeyer, 2002). The distance to the object was approximately 6 m. Thus, the images were captured within a distance of 2 m, maintaining a base/distance to the object ratio of 1/3, which is adequate for photogrammetric purposes. The whole site was covered with a GSD of 3 mm by 36 images. In addition, the terrestrial images were taken with a short fixed focal length with a diaphragm aperture of f/8, exposure time 1/500 s and ISO 100.

3.3. Data processing

The information processing was carried out in two steps. Firstly, data were processed from each of the separate methodologies (aerial imagery, terrestrial imagery and laser scanning). Thus, three DTMs in TIN format (triangular irregular network) were obtained. After evaluating and analysing all the models for discrepancies, errors were detected, classified and evaluated. As a result, a single DTM was developed that considers for each area the model that best represents that portion of space. The DTM is textured with the highest quality images, using the aerial images for the horizontal planes and terrestrial images for vertical planes. Thus, a hybrid 3D model that best represents the archaeological site was obtained. In order to accurately process all this information, it is necessary to calibrate the camera and the laser scanner. If the images are oriented and the laser point clouds are aligned, a DTM can be developed. In a further step, the hybrid model and the true orthophoto are generated.

3.3.1. Calibration

Using the camera as a measurement instrument requires previous modelling of the physical and geometric parameters that define the behaviour of the optical components. In this case laboratory calibration was performed with *Image Master Calib* software. Taking images of a known pattern from different positions and orientations, it is possible to determine the focal length (f), optical centre coordinates (x_{ppa}, y_{ppa}), radial distortion according to the Gaussian model (k_1, k_2) (Brown, 1971) and tangential distortion (p_1, p_2). Because the same camera is used for all photogrammetric processes, only one calibration is required.

Likewise, and although not as standardised, the use of a laser scanning system requires, in the interest of higher quality results, to have its internal parameters calibrated and its systematic errors modelled. To do this, we have made use of an existing calibration field placed in the Higher Polytechnic School of Ávila (Spain) that has allows us to work with a total of 21 internal orientation parameters divided into: 9 parameters for measuring distance (ρ), 7 parameters for the horizontal angle (Θ) and 5 parameters for the elevation angle (α). Some of these parameters refer to classic systematic errors of topographic equipment, while many others were obtained through tests and empirical evidence (González-Aguilera et al., 2011a,b).

3.3.2. Orientation

The coordinates of the control points and the calibration parameters of the camera are the inputs that allow the orientation of the terrestrial and aerial images. This process comprises two phases. The first involves extraction and an automatic feature-matching algorithm that is performed by ASIFT (Affine Scale Invariant Feature Transform) developed by Morel and Yu (2009). The reason for using ASIFT lies in its robust performance with images that show marked differences in scale and rotation. In the second step, the points found by ASIFT are matched with the manually measured ground control points to compute the absolute positioning and orientation of the images based on bundle adjustment. This adjustment consists of an iterative least square process with collinearity equations (Kraus, 1993). The calculation and adjustment of the absolute orientation of the images is carried out with the Image Master® Pro software, taking as input the automatic correspondence of interest points extracted by ASIFT. The method employed, known as blunder adjustment, is the least squares resolution of a redundant system generated from the collinearity equations. In this system, the input data are the image coordinates of the control and matching points, the calibrated focal length, the coordinates of the optical centre and the geometrical distortion parameters. Furthermore, the unknowns are the position (X_L, Y_L, Z_L) and orientation (ω, φ, χ) of the camera at the instant of the image's acquisition and the ground coordinates of the matching points (X, Y, Z).

3.3.3. Alignment

In order to completely register the archaeological site and due to its geometry and dimensions, scans were performed from different locations. From each scan a point cloud was obtained, which was aligned, geo-referenced and debugged. Alignment and geo-referencing processes were performed with Leica Cyclone® software. To do so, four of the above-described targets were located around the site. The targets were scanned from each of the basements of the scans and the coordinates of the targets were calculated by topographic methods.

3.3.4. Integration

Placed on rock, the study site presents complex geometry, so the best representation of the surface is generated by the combination of TLS and photogrammetry; thus the regular surfaces are described by a three-dimensional model generated by photogrammetry. This model is obtained from point clouds by automatic correlation with a spatial resolution of 2 cm, and it has the great advantage of incorporating digitalised breaklines from stereoscopic restitution of the aerial and terrestrial images. Moreover, the point cloud obtained by TLS is used for irregular areas with non-parametric surfaces, where breaklines are not required, obtaining a resolution of 3 mm. The complementarity of these two models is evident, the shadowed areas generated by TLS are supplemented by photogrammetry.

The meshing strategy employed is Delaunay triangulation based on the incremental method (Bourke, 1989) and enhanced with the addition of breaklines as geometric constraints. More specifically, significant features related to edges and slope changes of the field lines (essentially vertical walls) are restored from the oriented UAV images, using for this the combination of the collinearity conditions with the internal and external orientations of the images.

Finally, the generation of the hybrid 3D model resulting from the integration of independent 3D models consists of three basic operations: (1) the identification and marking of informationless areas due to occlusions and/or shadows corresponding to each model, (2) superposition of the 3D models, and (3) the removal of redundant and overlapping areas.

After obtaining the 3D hybrid model resulting from the integration of the three geo-technologies, we will be able to generate a true orthopohoto. Removing shadows and occlusions in hybrid DTM allows us to implement a process of adaptive true orthorectification that incorporates two novel steps compared with the classical process of generating orthophotos (Kraus, 1993): (1) the integration process of orthoprojection using the different images taken by the UAV (2) determining the visible and occluded parts of each image.

4. Results

The results were obtained based on two field campaigns performed on 27th May 2010 and 2nd July 2010. The goal of using two different campaigns was two-fold: on one hand, the different technologies and approaches can be compared, and on the other hand, the archaeological settlement can be monitored in terms of the material extracted through a dimensional analysis of volumes. Although each technique allows us to obtain a detailed description of the settlement, none is able to provide an integral reconstruction of the site in terms of completeness. Through the method presented in this paper each technology is reinforced by the integration of others, and thus the results guarantee the best quality in terms of precision, reliability and completeness, minimizing economic and temporal costs.

4.1. Comparison of geo-technologies

The utilised geo-technologies were compared to ascertain the precision of each technique (Fig. 6) and to deeply analyse the strengths and weaknesses of each method from data acquisition to final model development (Table 1). Because the positioning was performed with a mixed methodology (total station and GPS), the absolute precision in the position of each model is 1.6 cm in planimetry and 2.3 cm in height. A sketch with the positions of the sensor stations and control points is shown (Fig. 7).

The different DTMs obtained were compared from a quantitative point of view. The areas affected by gross errors are discarded, only taking into account the overlap areas. In these areas a

Table 1
Comparison of geo-technologies: differences between DSM (in metres) obtained along vertical direction (Z).

DSM comparison	Minimum	Maximum	Average
Laser scanner vs. terrestrial photogrammetry	0.001	0.021	0.006
Laser scanner vs. aerial photogrammetry	0.002	0.032	0.008
Terrestrial photogrammetry vs. aerial photogrammetry	0.001	0.020	0.004

dimensional analysis based on discrepancies along the vertical (Z) direction is performed. The different resolutions obtained by the different geotechnologies together with their georeferencering systems provide discrepancies between MDTs of around several centimetres. The larger discrepancies are obtained in those areas that are especially unfavourable (i.e., horizontal planes obtained for terrestrial photogrammetry or vertical planes modelled from aerial images). The results are show in Table 1.

From a qualitative point of view (Table 2), an initial visual analysis of the models allows us to confirm that there is no single geo-technology that provides a complete model of the site. Occlusions and shadows in the case of laser scanning, viewpoint limitations in photogrammetry and low quality of the vertical walls inside the model in the case of UAV photogrammetry all lead to a lack of information for a specific area. It should be noted that the correct representation of the deeper areas inside the site does not appear in the DTM made by terrestrial photogrammetry. This area does not appear in the DTM made by TLS due to problems related to the shadow areas and the obliquity of the scan angles.

The model obtained by UAV photogrammetry covers the whole archaeological site, highlighting the speed and simplicity of this method. However, this method implies lower geometric resolution, with a point each 5 cm. On the other hand, the models obtained by terrestrial photogrammetry and TLS show the best resolution values, with 2 cm and 5 mm, respectively, which is significant in defining the breaklines. In addition, there are difficulties related to the representation of vertical planes, obtaining overly sharp triangles, as well as shadow zones. These vertical areas represent a complicated matching process that generates ambiguities and therefore an erroneous representation of the surface.

By contrast, in the terrestrial photogrammetry the error associated with the representation of vertical planes disappears, giving rise to the same error, in this case, expressed in horizontal planes. The complementarity of the two methodologies is apparent. On the other hand, the disadvantage resulting from shadow generation in the photographs remains, as well as dealing with complex non-parametric geometries. That is why those shadow areas are represented by TLS. However, TLS also carries a number of associated errors such as lack of information in hidden areas, excess of information outside the study area and lower quality due to the obliquity of the scan and the increment of beam divergence.

4.2. Hybrid products: DTM and true orthophoto

The hybrid products obtained (DTMs and true orthophotos) correspond to two different excavation campaigns and have

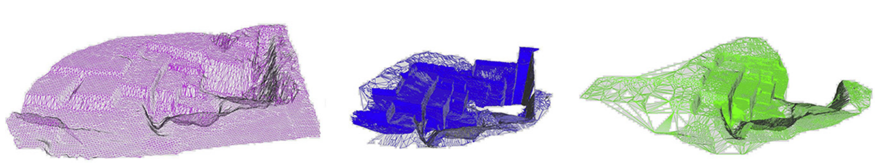

Fig. 6. DTMs obtained via: (left) aerial photogrammetry, (centre) ground photogrammetry, and (right) laser scanning.

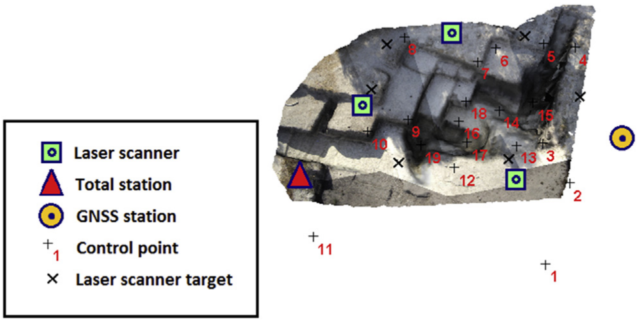

Fig. 7. Sketch showing the positions of sensor stations and control points.

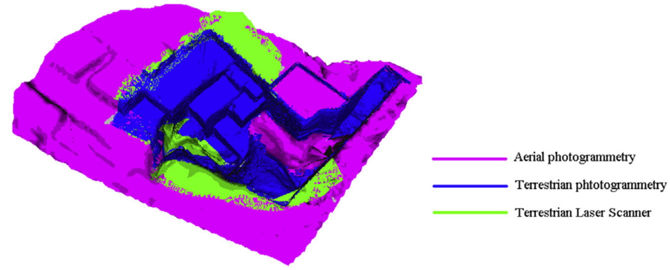

Fig. 8. The hybrid DTM corresponding to the second excavation campaign.

different characteristics. More specifically, for the creation of the first DTM, aerial photogrammetry and laser scanning were used, obtaining a DTM with 520,705 points and 24 breaklines, of which 206,116 points correspond to TLS, whereas the rest were found from the UAV photogrammetry by using automatic image matching. A similar DTM was generated for the second excavation campaign, with the exception of the addition of terrestrial photogrammetry (Fig. 8). In this case there were 30 breaklines and 889,450 points, of which 138,047 points were obtained by TLS and 751,403 points by automatic matching using aerial and terrestrial photographs.

Due to the fact that hybrid and integral DTM are available for the whole archaeological settlement of both excavation campaigns, another hybrid product can be created, the true orthophoto. The images taken by the UAV are used to generate both orthophotos, and since both were taken during a low-altitude flight, it is possible to generate a high-resolution orthophoto with a GSD of 2 cm (Fig. 9). The output size was 1020 × 1560 pixels and the GeoTIFF format was chosen in order to preserve the geo-referencing, enabling its geographical information system (GIS) integration.

4.3. Monitoring: dimensional analysis

During the excavation work in an archaeological site, there are amounts of dug material that would be interesting to analyse dimensionally, sometimes to consider and study associated expenses, to foresee future excavation ratios or for other reasons.

Throughout, between the two existing volumes subtracted from the corresponding DTMs obtained at different stages of the excavation, a variation of 11.5 m^3 was observed. This was to be expected considering that only extraction works were carried out and there was no ground-fill involved. In Table 3, the excavation depth values can be observed.

Fig. 9. The true-orthophoto for the second excavation campaign: GSD 2 cm.

Table 2
Qualitative summary comparison for the three proposed geo-technologies.

		Laser scanning	UAV photogrammetry	Terrestrial photogrammetry
Cost	Data acquisition	8–16 h/man Two person working simultaneously	1–2 h/man Two person working simultaneously	0–1 h/man
	Point cloud	Nothing	Average (min-h), depend on the number of photos and CPU processor used.	Average (min-h), depend on the number of photos and CPU processor used
	Technology	(10,000–130,000 Euros)	(3000–30,000 Euros)	(100–500 Euros)
Automation level		Manual intervention in the filtering and cleaning process.	Manual intervention in the definition of control points.	Manual intervention in the definition of control points.
Space requirement		1–2 Gb point cloud per campaign	1–100 Mb point cloud per campaign. Images of 0.1–1 Gb per campaign	1–100 Mb point cloud per campaign. Images of 0.1–1 Gb per campaign
Accuracy/Resolution		Very high/5 mm	High/5 cm	High/2 cm
Photo alignment with the point cloud model		Manual	Automatic	Automatic
Need for training to operate		Yes	No	No

Table 3
Monitoring: dimensional analysis resulting from both campaigns (in metres).

Monitoring	Minimum depth	Maximum depth	Average depth
Fist excavation campaign	0.000	5.121	0.733
Second excavation campaign	0.000	6.325	1.864
Difference	0.000	−1.204	−1.131

5. Conclusions and future work

The integrated geo-technologies proposed in this paper offer an accurate and rapid assessment of the as-built status of an archaeological site, providing the opportunity to easily and quickly understand, analyse and identify discrepancies in the current state of the settlement. Considering the current status of the various geo-technologies, it is clear that no single geo-technology solves all the needs of archaeological surveying such as reconstructing as-built models and monitoring the advance of a settlement. In this sense, photogrammetric and laser scanning technologies are complementary when used in combination, providing added value through hybrid products: MDT and true orthophotos. Last but not least, the generation of hybrid products requires correct and rigorous geo-referencing, and thus the geo-referencing method proposed in this paper contributes to this aim. The accuracy attained by this method proves to be of paramount value to the employment of this kind of model for the study and measurement of excavation sites. In this case, differences of mere centimetres have been found; this is only possible thanks to the precise methods of geo-referencing.

With regard to future perspectives some avenues to future work remain open, for instance the automatic incorporation of breaklines into DTMs based on vectorization processes and the automatic registration of sensors based on the proposed geo-referencing method.

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