

Workflow for high definition documentation of the roman archaeological site of Herrera (Seville)

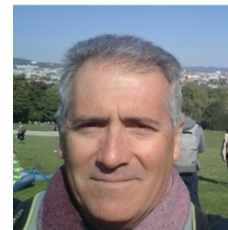
Structure from Motion (SfM) photogrammetry has become in the last years one of the most used methodologies for three-dimensional recording in many scientific fields thanks to its great precision, low cost and speed. The aim of this paper is to present a workflow methodology to obtain precise results for the graphical documentation of an archaeological site with complex structures (Rouco & Benavides, 2023)

The improvement of photogrammetric hardware and software has provided us with a tool of great value for archaeological research and survey. SfM photogrammetry has been widely applied to cultural heritage studies in a variety of ways, such as digitizing historical buildings, archaeological sites and artefacts. Improvement in UAV-mounted camera technology and calibration methods of non-metric cameras have expanded the use of photogrammetric modelling to non-professional and semi-professional users (Westoby et al. 2012). Although the potential of SfM photogrammetry allows obtaining 3D models with a very good graphic appearance using almost any type

of camera, these models need certain calibration and adjustment processes in order to achieve enough precision for professional use.

This paper focuses on discussing some important data capture workflow recommendations, as well as the new processing workflows implemented in Agisoft Metashape version 2.0, which improve 3D digital reconstruction and graphical documentation to make it complete and precise.

The Herrera Roman Baths site offers an excellent opportunity to explore the complex casuistry in the record of cultural heritage due to the complexity in the registration of the structures and the high degree of precision and graphic resolution that the project required for the tasks of restoration of decorative elements. The existence of a roof structure that protects them has forced us to carry out a manual flight with a UAV at a very low altitude (4m), and to develop different modeling strategies to guarantee metric precision and a high level of detail.



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UAV ; SfM photogrammetry ; point cloud ;
3D model ; orthophotography.

INTRODUCTION

Currently, photogrammetry and 3D digital reconstructions can be done with any type of camera, but these products do not have sufficient precision to be used in professional work, requiring knowledge of classical photogrammetry concepts for their precise adjustment. It is necessary to control the geometric and radiometric variables of the images, the resolution of the image in ground units, "GSD", percentages of overlap between longitudinal and transversal images or the number and distribution of control points on the ground, among others.

The use of SfM (Structure from Motion) methodology has been widely noted as a fundamental tool for the documentation, research and dissemination of architectural and archaeological heritage (Verhoeven, 2011; Kersten et al., 2012; Rodriguez-Navarro, 2012; Pereira Uzal, 2013; Remondino et al., 2017; Novakovi et al., 2017; Benavides et al., 2020). The data obtained provide a complete and objective representation of the object of study, achieving greater precision and detail than with classical surveys, providing data even in those places where physical access is not possible. Its purpose is to create a 3D virtual model of the object of study with high-resolution quantitative and qualitative data. The aim of our study is the application of SfM methodology in a high-definition and high-precision graphic documentation in the Roman site of Herrera (Sevilla, Spain). This is a thermal complex dated of the end of 2nd century b.C. (Romo y Vargas, 1990). The complex is linked to a villa, partially destroyed (Buzón y Carrasco, 2014; Vera, 2014). The thermae were documented in an emergency excavation in 1990, finding fifteen rooms. These included a good part of the thermal circuit, with the frigidarium, caldarium, apoditerium, etc. All have signs of having been richly decorated with stuccoes, marbles and mosaics. Among these we can highlight the exedra, showing one scene of two pugilist fighting and a detailed scene of the goddess Venus capturing a galley (Figure 17) (Buzón y Carrasco, 2014; Vera, 2010 y 2014)

However, the several phases of the excavations carried out since the 90's by different teams in the site have resulted in the loss or decontextualization of part of the excavated materials due to different methodologies and the storage system of the recovered artefacts

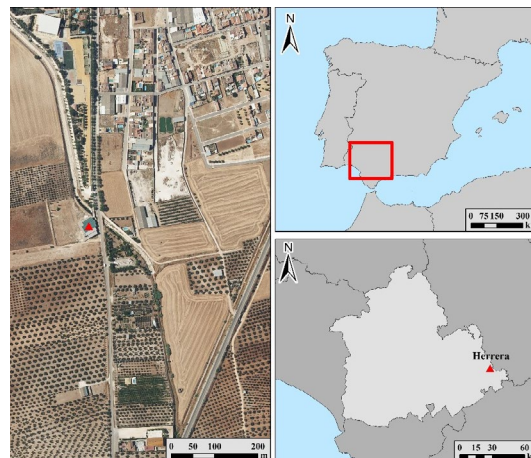


Fig. 1 - Location.

(Buzón y Carrasco, 2014). This problem shows again the importance and the necessity of a good graphic record simultaneous to the excavation process, in order to minimize the loss of data. For this reason, precise documentation of the preserved remains of the baths has been carried out.

METHODOLOGY

The high resolution and precision of the graphic documentation required by the project demanded careful planning in data acquisition and processing. The reliability of the entire workflow was ensured by evenly distributed ground control point (GCP) measurements on the archaeological site and a good capture of images. Data processing through the new version of Agisoft Metashape 2.0 allows highly automated photogrammetry showing great potential in terms of spatial resolution, accuracy and graphic quality. Metashape tends

to produce extra point clouds, which are of almost the same density, if not denser, as LIDAR point clouds.

WORKFLOWS IN THE DATA CAPTURING

The comprehensive record of a heritage site requires prior planning, for both the image capture and the location of the control points in order to optimize data capture to achieve a homogeneous and complete result.

In this phase we must control, among others, the necessary equipment (GNSS, Total Station, UAV, camera on pole, etc.), accessibility to the work site, risk assessment, obstacles that may hinder the capture (e.g. movement of people or vehicles) or flight. In addition, we must be aware of environmental conditions such as lighting (may be needed to schedule the hours of capture to avoid shadows and areas with too much sunlight).

In the particular case of UAV photogrammetry, it is also necessary to organize the operational coordination in compliance with current legislation and planning the flight following the technical requisites according to the height of the structures and the topography of the site.

PLACEMENT OF GROUND CONTROL POINTS AND TOPOGRAPHIC SURVEY

Prior to image capture, the Ground Control Points (GCP) must be placed on the ground and walls with targets of different sizes (Figures 3 and 5). The placement of the targets should consider the good vision from the point which they will be measured by the topographic equipment and avoid placing them in areas with poor visibility during the capture like vegetation, objects, buildings, etc. An adequate distribution of the GCP and the measurement of these with high precision instruments is essential for the proper indirect referencing of the images, as well as for the correct calibration of

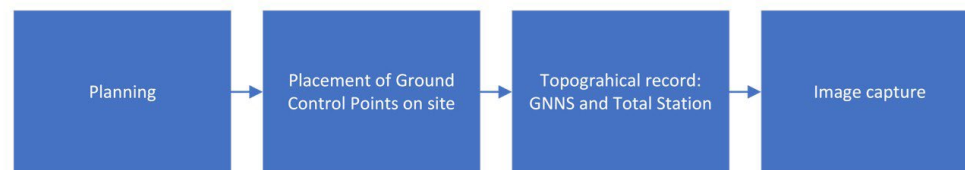


Fig. 2 - Planning.



Fig. 3 - General view of the roman site "Roman baths of Herrera".
the lens (Tahar et al, 2013; Sanz-Ablanedo et al, 2018). In our case study, 10 targets were homogeneously distributed through the site, placing some of them outside the structures for subsequent georeferencing in the official system for Spain UTM30-ETRS89. The targets inside the site have been measured by radiation from a single station point with a Total Station Leica TS06 with infrared distance meter and mini prism, using an arbitrary reference system and obtaining an estimated RMS (Root Mean Square) of the targets of 3 mm. For the georeferencing of the site four GCPs outside the structures have been measured through a GNSS-RTK EMLID REACH RS connected in real time to the RAP (Andalusian Positioning Network), which provides us the coordinates in a world coordinate system (UTM30-ETRS89). This way, we georeferenced the relative coordinates measured with the Total Station with those universal coordinates obtained with GNSS. In this regard, it is important to highlight the differentiation between the "plane" coordinates measured by the total station using reference plane (X, Y) and the "spherical or geographic" coordinates (angular measures of latitude and longitude on the ellipsoid) measured by topographic GNSS equipment and the GNSS receivers of the UAVs. We must also bear in mind that UAVS recorded altitude is referred to the ellipsoid and therefore do not correspond to orthometric heights referred to the geoid (Figure 4).

Both projection systems are different and must not be combined when adjusting and processing the GCPs on Agisoft Metashape or other photogrammetry soft-

ware. The use of a unique reference system that includes both types of data forces us to transform the UTM coordinates to topographic coordinates by calculating the grid scale factor.

At this point, we must indicate that there are UAV equipment that allow direct georeferencing through advanced systems, incorporating receivers high precision GNSS-RTK (+- 1-2 cm) that determine the position (lat, long, height elip) of the optical center of each of the pictures and inertial sensors that measures their angular orientation (yaw, pitch, roll) in the moment of each capture. But several research have shown that obtaining a 3D model by direct referencing of RTK images does not guarantee adequate accuracy of the model since the absence of GCP prevents the correction of systematic errors due to non-calibration of the lens, positioning errors of the UAV equipment or errors in the adjustment of the aerial-triangulation (Forlani, G et al, 2018; Sanz-Ablanedo et al, 2018).

IMAGE CAPTURE

As a general rule, image capture requires the following considerations:

- a.- Planning the flight with an extension greater than the area of interest so that we have enough external passes that help to adjust the aerial triangulation, improving the precision in the registration of the perimeter areas under study.
- b.- Use cameras with a fixed focal lens and mechanical shutter: They provide greater accuracy and precision than varifocal lenses and allow for

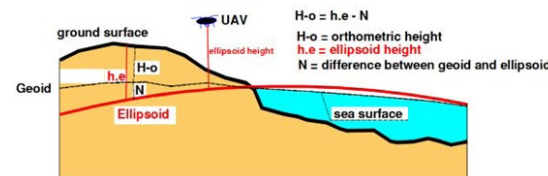


Fig. 4 - GNSS and UAV systems record their location in geographic coordinates (longitude, latitude) and the height referred to the ellipsoid. Knowing geoid models (that are located on the website of Agisoft Metashape), ellipsoid heights can be transformed into orthometric heights. .

better camera calibration (Shortis et al, 2006; Mosbrucker et al, 2017).

c.- Adequate sharpness and radiometric adjustment of the images: The SFM photogrammetric process is based on the quality of the images. Images that are not very sharp or out of focus produce noise and errors in the final result and therefore should be discarded. We recommend performing a hyperfocal focus, placing the diaphragm opening at an intermediate value, called sweet spot (eg: for camera aperture values between f/2.8 to f/11 we recommend the mean value f/6) and setting a very fast shutter speed (1/1000' ' or higher). The ISO value will depend on the amount of existing lighting (values 100, 200 or 400 are acceptable). In UAV image capture, very low movement speeds are recommended for avoiding motion blur. This blur is directly proportional to the speed of the aircraft and inversely proportional to its height. Some studies show a strong correlation between image quality and model accuracy (Turner et al, 2012).

d.- programming the UAV flight through specific apps (Map Pilot, UGCS, Pix4D capture, etc) optimize the number of passes and the good capture of images, establishing an optimal speed of movement depending on the height of the flight and the longitudinal overlap of images, depending on the type of camera.

In our case study, the existence of a roof structure that protects the archaeological site has greatly conditioned the capture of images. The low height of the



Fig. 5- Measurement of GCP through total station and mini prism to achieve high precision. RMS <3mm. .

flight (4 m) and the non-availability of GNSS coverage under this cover, which prevents the programmed flight, make it necessary to carry out a manual flight and with very small displacements between images to achieve sufficient overlap. The use of the Hasselblad 24mm fixed-lens camera mounted on the DJI Mavic 3 equipment (CMOS 4/3, Effective pixels: 20 MP and ISO 100-6400 range) provides extremely high quality images. On the other hand, insufficient interior lighting has forced the aperture to f/2.8 and set an ISO 200 to obtain an optimal shooting speed of 1/800". To avoid motion blur, the images have been captured with the UAV in a stationary position. On the other hand, certain areas with direct sunlight produced strong contrasts in the images, which made it necessary to delay the flight by one hour to ensure constant illumination.

Guaranteeing the complete record from a manual flight at such a low altitude requires a high overlap. Capture of nadiral images causes missing of definition of the vertical elements (walls) being necessary the additional capture of oblique images. In addition, the inclusion of oblique images considerably strengthens the fit of the aero-triangulation block. In total, 1263 images have been captured (879 nadiral and 384 oblique). Another thing to take into account is the resolution of the images in ground units (GSD). The height flight (4 m) and the capture with the camera Hasselblad programmed at f:24 mm CMOS 4/3', size 5280x3956 px, provides a GSD of 1.0 mm.

Where:

$$GSD = \frac{AS * H * 100}{dF * nPixel}$$

AS = Sensor width (mm)
H = flight height or distance to the object (m)
dF = Focal Distance (mm)
nPixel = number of pixels in the width of the sensor

WORKFLOWS IN DATA PROCESSING

There is a wide variety of commercial and open source SfM software, but practically all of them have the same base and a similar workflow although they provide unique features. The new version 2.02 of Agisoft Metashape incorporates new functions from the already known general workflow, such as scanner data import, aerial Lidar and depth maps can be reused for different processes, as well as allowing functions to be

1. Loading data (images).
2. Aligning images or scans and building the sparse point cloud.
3. Building dense point cloud.
4. Building mesh 3D.
5. Generating texture.
6. Building tiled model.
7. Building digital elevation model.
8. Building orthomosaic.
9. Exporting results.

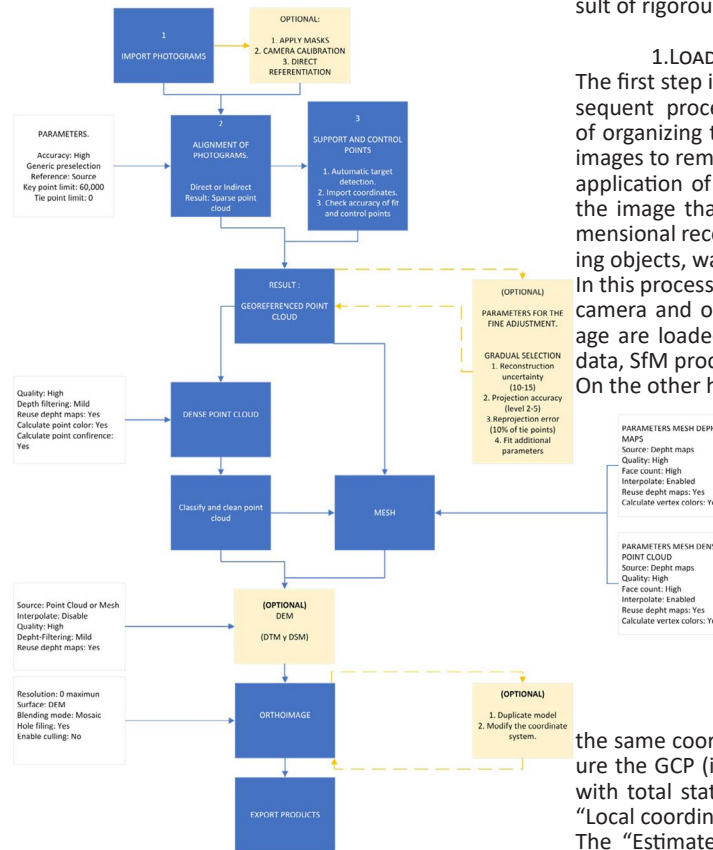


Fig. 6 - Schematic diagram summarizing the workflow of our research.

programmed using Python or JavaScript. Summary the main steps in the processing workflow in photogrammetry:

The main objective of our research has been the creation of a specific workflow for the object of study and the adaptation of the parameters to improve results in terms of precision and graphic quality. The methodological contributions presented in this article are based on sound photogrammetric principles and are the result of rigorous testing.

1. LOADIN DATA:IMAGE AND LASER SCAN

The first step is to import the images. To facilitate subsequent processes, Metashape gives the possibility of organizing them into groups and inspecting loaded images to remove unnecessary images. Optionally, the application of masks allows you to limit the areas of the image that you do not want to use for three-dimensional reconstruction, like a people, vehicles, moving objects, water, sky, etc.

In this process, the EXIF metadata (internal orientation camera and optionally position) included in each image are loaded into Agisoft Metashape. Without this data, SfM processing is not possible.

On the other hand, to be able to process the images in

the same coordinate system as the one used to measure the GCP (in our case plane coordinates measured with total station), you must choose in configuration "Local coordinates"

The "Estimate Image Quality" function allows us to automatically evaluate the quality of the images and eliminate those blurred. Values close to 1 are optimal, and images less than 0.7 should be replaced or deleted.

2. ALIGNING IMAGES AND BUILDING THE SPARSE POINT CLOUD.

The algorithms used in SfM photogrammetry have been highly tested, allowing them to run with a high degree of automation and require few operator decisions beyond the degree of resolution. Aligning and orienting the images in the same relative position in which they were captured has been and continues to be the fundamental problem of photogrammetry. This process called relative orientation is carried out in two steps using algorithms related to computer vision. The first step of the SfM approach is to search for thousands of specific feature points in the image, called “key points”, using the principle of the SIFT algorithm (Lowe, D. 1999). In the second step, it determines the position and relative orientation of each image by adjusting the homologous points of pairs of “tie point” images using the Bundle algorithm (Cefalu, Haala, & Fritsch, 2017). (Figure 7)

As we already mentioned, the cover structure has caused some images to not have a geographic location (external orientation parameters), which causes alignment errors in the aerial triangulation process between images with and without coordinates. In these cases, we recommend eliminating the location of all the images, proceeding to a new aerial triangulation that only takes into account the correlation of images from the “tie points”, achieving success in the complete alignment as long as we have enough overlapping points. Some software applications enable determination of a maximum number of key points and tie points in order to speed up this registration process.

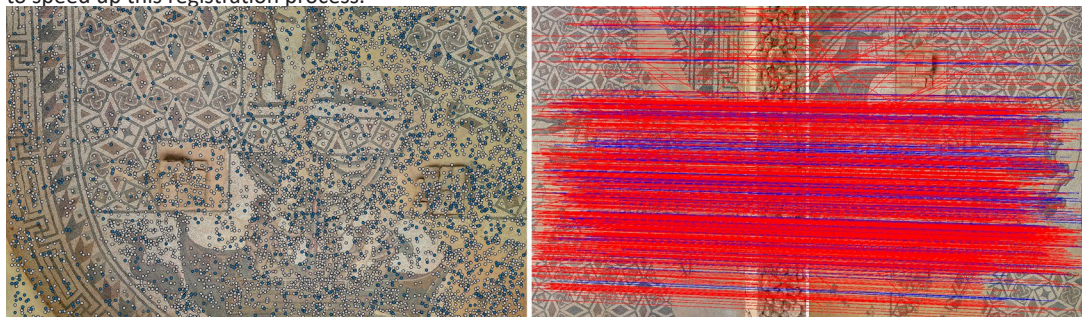


Fig. 7 - (a) Images with key-point (grey color) and tie-point (blue color). (b) Matching tie point between two images (red: invalid and blue: valid)

- **Accuracy:** At High accuracy, Agisoft Metashape uses the full resolution photo. (Medium use the 50% and Low accuracy at 25% resolution) (Agisoft Metashape User Manual Professional Edition, Version 2.0, 2023). Choosing High accuracy is not necessary when there are many images because the processing times increase significantly.
- **Generic preselection:** When this option is selected, images are preliminarily matched using the lower accuracy (down sampled) setting to find overlapping pairs of images before a second pass at the accuracy set in the dialog. This substantially speeds up the process but returns fewer overall tie-points. (Agisoft Metashape User Manual Professional Edition, Version 2.0, 2023)
- **Key point limit:** this parameter depends on the overlap between images and their quality. Agisoft Metashape advises in most cases a value of 40,000. Increasing this value too much can result in the creation of poor quality points. In our case study we will increase the value to 60,000.
- **Tie point:** a value of 0 implies using all tie-points for a better adjustment and clearing of these tie-points we use the “gradual selection” command from the “model” menu.

The result of this step is a sparse point cloud that represents the object’s geometry. Sparse point cloud may in some cases contain a lot of noisy points resulting from a high re-projection. This first adjustment does not take into account the calibration of the lens.

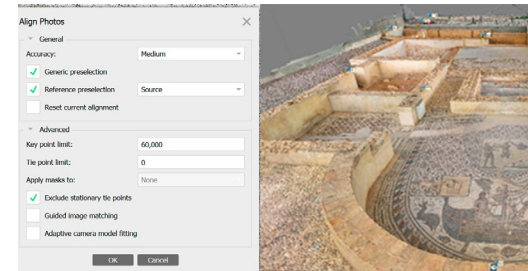


Fig. 8 - Sparse point cloud obtained by the correlation of images by the SHIFT and BUDGET algorithm with the software Agisoft Metashape v.2.02.

3. REFERENCING AND OPTIMIZATION

One of the most important parts of the photogrammetric process consists of referencing and adjusting the precision of the model.

In a first step, the precise parameters of the camera are automatically estimated in the least squares iteration during the aerial triangulation process based on the adjustment of the tie-points, but this relative orientation is not precise. Using support points (GCP) captured in the images and measured on the ground allow us a double function. a.- locate the 3D model in the same coordinate system in the topographic survey allowing to fix position, orientation and scale of 3D-model and b.- optimize the accuracy camera parameters for a better fit. It is advisable to use GCP-targets that are automatically identifiable by the software, whether they are coded or not. In this way, systematic errors from a visual and manual identification of GCPs by the operator are eliminated (Garcia & Oliveira, 2021). After many experiments, the best results have been obtained using non-coded targets: white circle on a black background (Figure 5). The software is able to identify the geometric center of the white circle (Tools – Markers – Detects Markers).

1. **Import of coordinates:** this process consists of assigning the topographic coordinates to the targets identified in Metashape. To do this it is necessary to place the same label of the GCP and target. After importing the GCP coordinates, it is necessary



Fig. 12 - Parameters used in the research to obtain the dense point cloud.

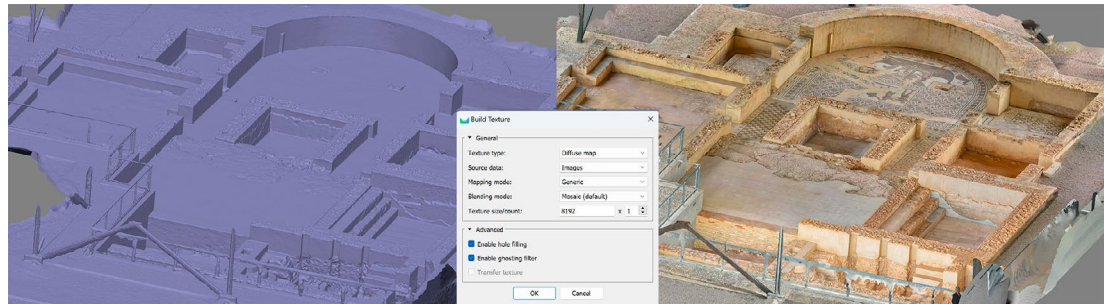


Fig. 14 -3d mesh, (a) solid mesh (b) texture mesh.

Once the dense cloud has been created, it generally needs to be edited to remove noise. There are multiple ways to observe, delete, or classify poor-quality points before continuing in the workflow.

“Filter by confidence” command provides an important tool to observe, remove or classify bad quality points before continuing with the workflow. On a scale from 0 to 255, values closer to 0 have fewer depth maps involved in generating points and therefore more noise. In this process we must be careful not to delete points that are part of the model even if they have a low level, about this it is advisable to classify them as noise points, instead of eliminating them, in this way they can always be restored.

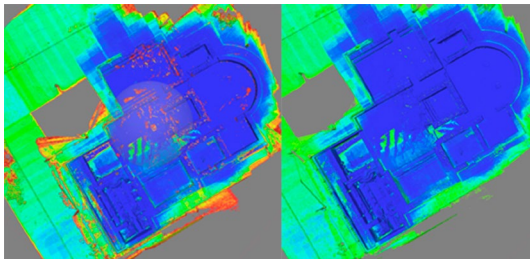


Fig. 13 - Low-confidence point cloud filtering allows you to remove or classify noisy points. (a) before, (b) after.

4. MESH

The creation of meshes using the point cloud triangulation algorithm is an extremely complex, automatic process that allows obtaining a more efficient and realistic model by applying textures and obtaining orthoimages for graphic documentation. In the new version of Metashape 2.0 the 3D model can also be generated from the depth maps which reduces the processing time.

5. ORTOMOSAIC

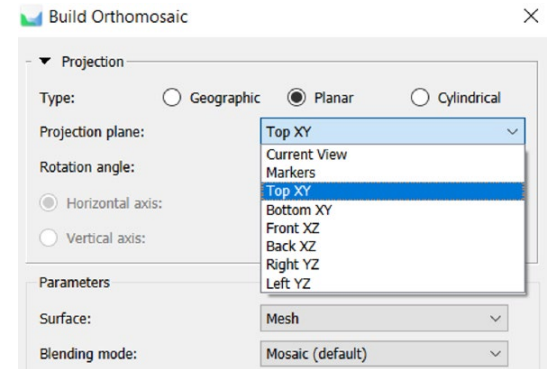
The last product that usually generated in the workflow is the orthophoto. An orthophoto is an image that has been projected orthogonally on the 3D model (mesh, DEM or Depth map) and therefore taking into account the volume of the objects, the distortion of the lens and the inclination of the camera. The result is an orthogonal metric view with the actual texture of the objects.

Lower altitudes allow for more detailed images, which means that the final map will contain more visual information, but for an orthomosaic to have a homogeneous resolution, the images must be made, whenever possible, at the same distance from the object, which forces change height. Generally, the geometric resolution of orthophotography depends on the resolution of the image in GSD.

The orthophoto needs to be transformed in the selected projection: Geographic, Planar or Cylindrical. The geographic projection serves the more typical task of creating an orthomosaic for a large site in a geographic coordinate system. Planar projection allows you to select arbitrary orientation of the projection

plane, which is useful for architecture or archeology projects, such as elevations, plans, or other surfaces. To obtain orthophotographs according to a choose projection plane we recommend duplicating the chunk and modifying in CAD the orientation of the GCP (Figure 15-a) so that the floors plant or elevations are oriented with respect to X, Y, Z select (Figure 15-b) and we import the coordinates of the reference system again. In this way the generation of orthophotographs is faster and more accurate according to the predefined views: Top XY, Front XZ, etc. As a great advantage, orthoimages exported in Tiff format have metadata with position and scale.

If lighting conditions have changed significantly during scene capture, it is recommended that you use the Calibrate Colors option from the Tools menu prior to the Build orthomosaic procedure.



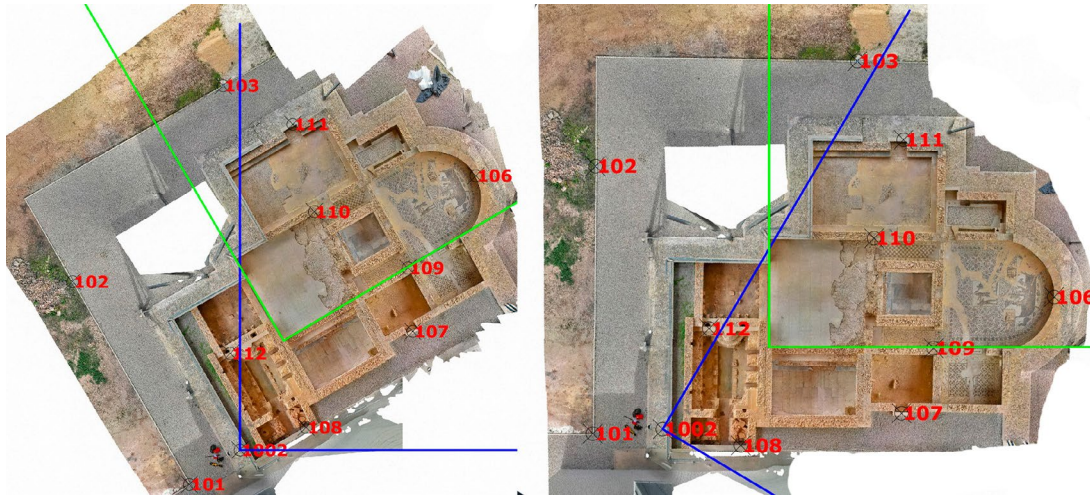


Fig. 15 - (a) GCP points in topographic coordinates and (b) GCP rotated to get new projection referent system (c) Defined views for orthomosaic construction

vation and dissemination of this archaeological site. Among others, we highlight the geometric analysis carried out on the musivarius pavements, as a fundamental element in Roman domestic and public architecture. After a detailed analysis, we observe that although there is a wide and complex compositional design adapted to each room, the SQUARE is the fundamental element on which the geometric layouts are articulated. (Figure 18)



Fig. 17 - Orthomosaics of sections A-A' and B-B'.

RESULTS

The results obtained through the application of the workflow proposed in the research have allowed a significant increase in the precision in the adjustment of the aero-triangulation which results in a better final product.

The systematic capture of the entire site (1263 images) allows a complete and homogeneous record of all structures and decorative elements with a pixel resolution of 1.2 mm. The SFM workflow allows easy addition of data (images) to complete those zones without registration.

The evaluation of the 3D model of the Roman site of Herrera using SFM photogrammetric techniques has proven to be an important means for heritage documentation. The considerable reduction of time in data collection, the ability and precision to capture complex shapes or the hyperrealist representation of textures are proof of this. (Figures 15 - 16)

From HD orthophotographs we have developed different investigations aimed at understanding, conser-

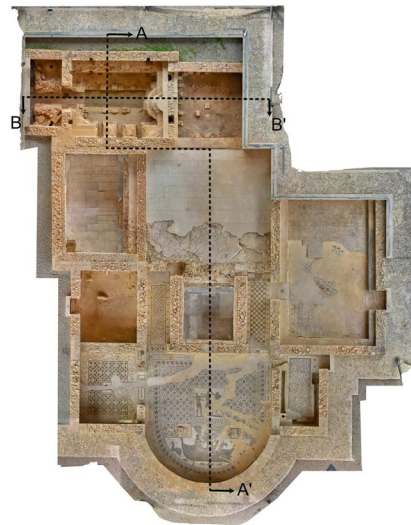


Fig. 16 - Orthophotography in plan of the Roman baths of Herrera.

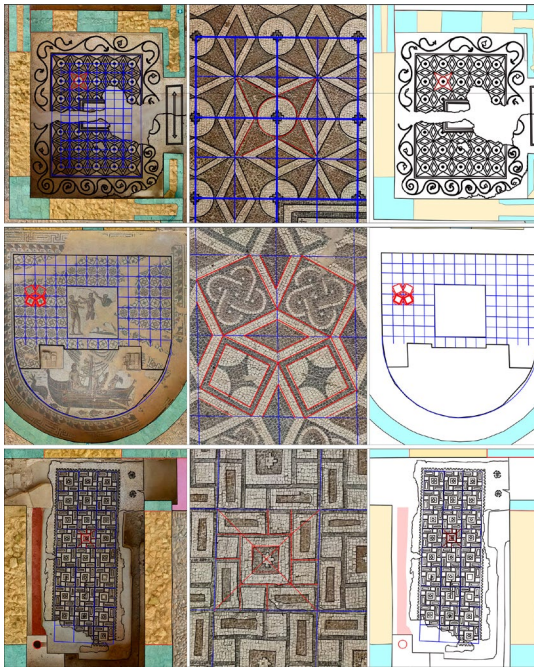


Fig. 18 - Details analysis pavements.

On the other hand, as support for the archaeological study, an analysis of the materials and construction techniques used in this site has been carried out, identifying by means of a color map that facilitate their interpretation the different stratigraphic units and their interrelationships. (Figure 19).

CONCLUSIONS

Digital technological development has completely modified the methodology of registration and documentation of architectural and archaeological heritage, making it much more efficient and accurate, but it requires significant technical specialization for the results to be adequate. The generation of 3D digital models of historic buildings considerably improves data collection and subsequent management. Graphic documentation is a fundamental tool to capture the morphology of the structures and the typology

of the materials or even to analyze their pathologies to determine their causes (Benavides et al, 2020). The combination of camera locations by block adjustment and ground control points allow to obtain professional quality products (mainly 3D model and orthorectified images). An adequate distribution of the GCP and the measurement of these with high precision instruments is essential for the proper indirect referencing of the images, as well as for the correct calibration of the lens. The results of our study show a strong correlation between image quality and model accuracy. The speed and effectiveness of SfM processing allows a fast and simultaneous registration to the excavation which avoids the loss of data and a complete record of archaeological findings. The superimposition of different 3D models on the same reference system allows the

contextualized registration of the artifacts found. The differentiation of the plane and geographical reference systems used in the GCP measurement phase and in image capture is an important data for the adjustment and processing so that the results are optimal. The documentation of architectural and archaeological heritage from orthophotographs is the most effective means of knowledge by combining image and graphic analysis in the same document. The realism and precision of its shapes and textures allow us to analyze without subjectivity the object of study, the processes of alteration and degradation that affect it. The geometric analysis of the pavements of the archaeological site of Herrera show us the great creativity and metric rigor of the artisans (tessellarius or musearius), generating very complex and different artistic compositional designs from a simple grid of squares.

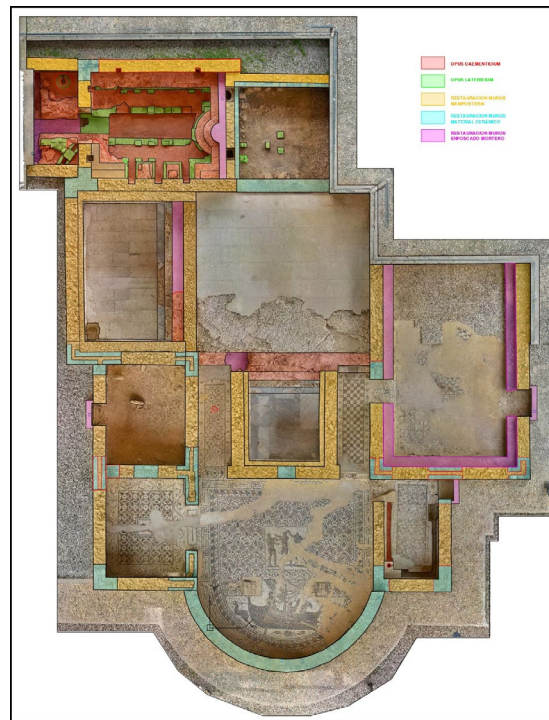


Fig. 19 - Analysis of materials and construction techniques.

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