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UAV PHOTOGRAMMETRY FOR ARCHAEOLOGICAL SITE SURVEY. 3D MODELS AT THE HIERAPOLIS IN PHRYGIA (TURKEY)

FOTOGRAMETRÍA UAV EN APOYO DEL LEVANTAMIENTO DE UN SITIO ARQUEOLÓGICO. MODELOS 3D EN LA HIERÁPOLIS DE FRIGIA (TURQUÍA)

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Highlights:

- The paper aims to validate UAV photogrammetry as a very flexible tool for archaeological areas; a fix wing eBee device by Sensefly is tested.
- Derived DSM and aerial orthoimages in complex areas with different formal traits are discussed, targeting high mansory ruins and collapsed parts.
- Up to 2 cm accuracy and high resolution 3D models are convenient to extract morphological data.

Abstract:

Unmanned aerial vehicle (UAV) photogrammetry has shown a very rapid development in many fields, especially in archaeological excavation areas and architectural complexes, where it offers a detailed generation of three-dimensional (3D) data including the possibility of updating over time. It also proves to be a very flexible tool applicable to many types of complex areas with a variety of different features. The use of aerial acquisition provides highly effective results, adding to both rapid capture and lower costs. In fact, today in the field of archaeological research, great efforts are invested in the generation of very large-scale models and orthophotos, and the technology seems to promise further future developments, not only from the terrestrial (orthogonal) point of view, but also from the nadiral direction from a low altitude, as a preferential and often optimal point of view. Here an effective workflow for photogrammetric product generation is presented for selected case studies in some monumental areas of ancient Hierapolis in Phrygia (Turkey), in which the Italian Archaeological Mission of Hierapolis (MAIER) has been working since the 1960s. The recent experiences achieved by UAV photogrammetry are quite innovative. The variety and complexity of the buildings, as well as the height of their ruins, offer numerous challenges, which are interesting to deal with. The 3D aerial survey was performed for multiple purposes with the eBee system by Sensefly. Specific attention was paid to the digital surface model (DSM) and aerial orthoimages of three test areas: the Plutonium area; the Thermal Bath-Church; and the Necropolis. Starting from the same technical approach, a comparative assesment among the three sites was carried out, taking into account the specific goals, the type of the structure and the terrain conformation.

Keywords: unmanned aerial vehicle (UAV); digital surface model (DSM); aerial photogrammetry; archaeological heritage; 3D modelling; data integration

Resumen:

La fotogrametría con vehículos aéresos no tripulados (Unmanned Aerial vehicle, UAV) ha mostrado un desarrollo muy rápido en muchos campos, especialmente en áreas de excavación arqueológica y complejos arquitectónicos, donde ofrece una detallada generación de datos tridimensionales (3D), junto con su actualización en el tiempo. También demuestra ser una herramienta muy flexible aplicable en muchos tipos de áreas complejas, con diferentes características formales. El uso de la toma aérea proporciona hoy resultados altamente efectivos, lo que aumenta la rapidez de adquisición y menores costes. De hecho, hoy en día en el campo de la investigación arqueológica, se invierten grandes esfuerzos a la hora de generar modelos y ortoimágenes a grandes escalas, y parece prometer más desarrollos futuros, no sólo desde el punto de vista terrestre (ortogonal), sino también con dirección nadiral, desde baja altitud, como punto de vista preferencial y óptimo. Aquí se presenta un flujo de trabajo eficaz que permite generar productos fotogramétricos en varios casos de estudio en áreas monumentales de la antigua Hierápolis de Frigia (Turquía), donde la Misión Arqueológica Italiana de Hierápolis (MAIER) ha estado funcionando desde los años 1960. Estas experiencias logradas con la fotogrametría UAV son bastante innovadoras. La variedad y la complejidad de los edificios, así como la altura de sus ruinas ofrecen numerosos puntos problemáticos que son interesantes de tratar. El levantamiento aéreo 3D se realizó con múltiples propósitos por medio del sistema eBee de Sensefly. Se prestó especial atención al Modelo Digital de Superficie (MDS) y a las ortoimágenes aéreas en tres áreas de prueba: el área de Plutonio; la Iglesia-Baño Termal; y la

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Necrópolis. Partiendo del mismo enfoque técnico, se ofreció una evaluación comparativa de los tres sitios, teniendo en cuenta los objetivos específicos, el tipo de estructura y la configuración del terreno.

Palabras clave: vehículo aéreo no tripulado (UAV); modelo digital de superficie (MDS); fotogrametría aérea; patrimonio arqueológico; modelización 3D; integración de datos

1. Introduction

The heritage preservation process and its dynamics are typical of the archaeological contexts, which has always been and will always be, as such due to its same consistency, prone to environmental and human risks. Safeguards values and dedicated investments have steadily to feed this continuous process of monitoring and to keep under control by careful documentation, as an essential and perpetual practice over several years. 3D information derived from survey data with different sensors –due to them being a part of the same spatial system– can be integrated to create a multi-scale detailed model as well as a multi-resolution one according to time and space (Kersten & Lindstaedt, 2012; Moussa, Abdel-Wahab & Fritsch, 2012; Sabina, Valle, Ruiz, García & Laguna, 2015). These models are a complete and detailed reproduction of reality, and provide a powerful database of information for the world of digital 3D perception that may be instantly used and queried to obtain multiple three- and two-dimensional representations, as well as the fourth dimension (time) modelling and interpretation, and based on which multidisciplinary analysis and monitoring over time can be conducted. Geomatics approach, efficiently integrating aerial and terrestrial points of view, tries to answer every day better by providing techniques refinements for purposes coming from archaeological topics.

The development of technical capacity and potentialities of geomatics techniques for site excavation monitoring is presented in this experience. Here some results of many documentation projects that involved the Laboratory of Geomatics for Cultural Heritage of Politecnico di Torino; they took place with the MAIER (Italian Archaeological Mission of Hierapolis) during many years of its ongoing activity in Pamukkale (Turkey).

In fact, the MAIER operates in the ancient city of Hierapolis in Pamukkale since long time, up from the 1960s and it is still active. It was directed for the first tens of years by Politecnico di Torino, Prof. Verzone and Prof. De Bernardi; then in early 2000s by Università del Salento with Prof. Francesco D'Andria as the head of MAIER and since 2016 with Prof. Grazia Semeraro.

Here the site magnitude of the archaeological area and the large number of continuing archaeological investigations, together with the stratification of the monumental complexes require ad hoc solution for their different demands. The UAV devices for mapping some of the monumental complexes in Hierapolis (Pammukkale, TK), have been employed in order to study and evaluate applicability of this technique in different featured excavation areas (Chiabrando, D'Andria, Sammartano & Spanò, 2016).

Some useful themes derived from these applications are the integration of UAV data and terrestrial Light Detection and Ranging (LiDAR) surveys, the production of surface models (DSM) from aerial sensors for terrain analysis and high-scale representations of the current state of the site for updating spatial information (Chiabrando, Sammartano, Spanò & Teppati Losè, 2017). All this is a part of the continuous documentation processes and communication projects. These days, this worthy endeavour has become increasingly crucial for acquiring the characteristics of completeness that is needed in a multidisciplinary context, as is the archaeological one. 3D models, from this point of view, can be frequently useful for navigation in archaeological and stratigraphic studies, and in reconstructions, structural analyses, and studies of materials and decay (Fiorillo, Fernández-Palacios, Remondino & Barba, 2013).

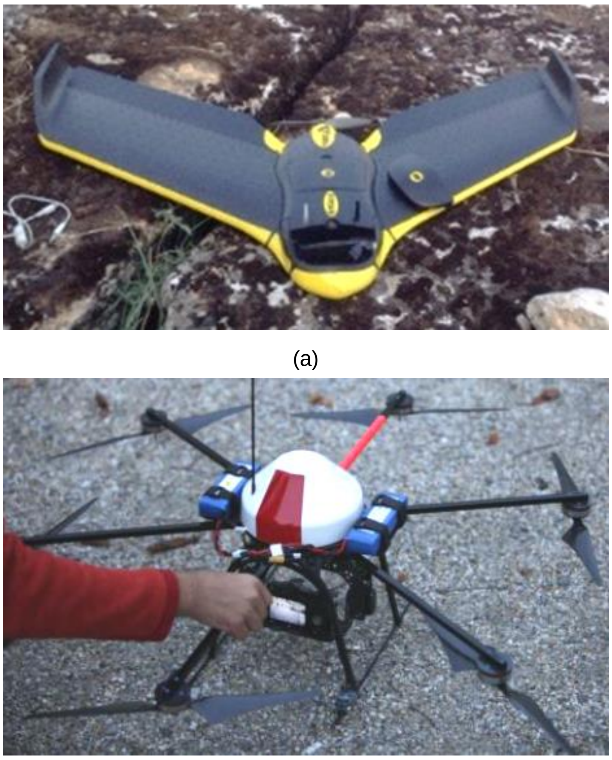
2. UAV photogrammetry and the eBee aerial platform

In order to obtain a correct UAV survey, the metric approach that needs to be followed concerns the data acquisition: the images, the coordinates, and the altitude of the camera centre. These can be calculated either through a traditional photogrammetric approach, using terrestrial topographic ground control points (GCPs) or by means of direct camera georeferencing (using the measures derived from the on-board sensors GNSS and IMU). In these last few years, many platforms have been developed to produce, update and integrate various geospatial information systems, and they are available according to different technical features, equipments, and flights organisation (Colomina & Molina, 2014; Sauerbier & Eisenbeiss, 2010; Themistocleous, Ioannides, Agapiou & Hadjimitsis, 2015).

Several updates and technological refinements in the remotely piloted aerial system (RPAS) are being taken on by researchers, both from the point of view of the hardware component (instrument that acquires images) and the software (programs for data processing).

The platforms mostly employed in different types of areas and applications (Figure 1) can be generally divided into many categories –by outfit, flight type, sensors, range, and height. We can resume two categories of aircrafts according to their tuning: the fixed-wing UAV and the multicopter ones. They differ primarily in their wing kits and in the parameters on which their behaviour depends. Briefly, a hexacopter can fly at the lowest height with more stability, but lacks autonomy in terms of the flying time. On the contrary, fixed-wing UAV flies up to 50 minutes and can reach greater heights, but needs a continuous flying trend.

One of the recently updated and cost-effective platforms is a product of the SenseFly company (technical details are available at the SenseFly Company https://www.sensefly.com/drones/eBee.html and with MENCI Software http://www.menci.com/sensefly), namely the eBee autonomous flying drone. The eBee is a fully automatic UAV platform with a central body where all the electronics and main communication hardware are incorporated. These include the data link antenna, pilot probe, battery and camera compartment on the top face, ground sensor and camera hole on the bottom face, the wing servo connection along the side and the propeller in the backside. According to the SenseFly specification, the height of the platform with the embedded camera is



(a)

(b)

Figure 1: Examples of equipped RPAS for aerial mapping: a) fixed-wing from eBee by Sensfly, b) hexacopter customized by Politecnico di Torino from Mikrokopter.

about 0.69 kg and its wingspan is 96 cm. From an operational point of view, the main characteristics are the following: a maximum flight time of 50 minutes, a flight speed between 11 m/s–25 m/s, radio link range of 3 km, and a minimum flying height of 50 m. The system is connected to a ground control station (GCS), which is able to define all the characteristics of the flight and allows the supervision of the platform during the flights in real time. During the data acquisition, different sensors tailored to the system and provided by SenseFly can equip the UAV eBee: the Canon PowerShot S110 RGB, Canon S110 NIR, and Canon S110 RE that allow the acquisition of the images in the red edge band. Besides these, a Radio Tracker can also be used, togheter with MultiSPEC 4C, a multispectral camera that acquires multi-spectral images (green, red, red-edge and near infrared), and ThermoMAP, a thermocamera that produces grey scale images and video with high pixel density and thermal resolution. SenseFly manages the eBee platform using all the information about the flight plan through the eMotion software. This program is based on an automatic photogrammetric approach: the first parameter to be set up is the one related to the area of interest, the ground sample distance (GSD) and the overlapping percentages among the images (sidelap and endlap). Once these parameters are set (Fig. 2), the software automatically calculates the number of strips required to cover the area of interest as well as the flying height. The second planning step is focused on the take-off and landing settings: this step is obviously crucial in case of an automatic platform since is strictly necessary a take-off and landing area without vertical obstacles in a certain range. The eBee performance during the landing phase is excellent, considering that by exploiting the on-board GNSS and the proximity sensors composed of a high-speed optical sensor and lens assembly, the platform is able to land in a predefined area with an accuracy of about 5 m (when the terrain is quite flat, more difficulties occur in tilted areas). Figure 2 shows a screenshot of the flight planning.

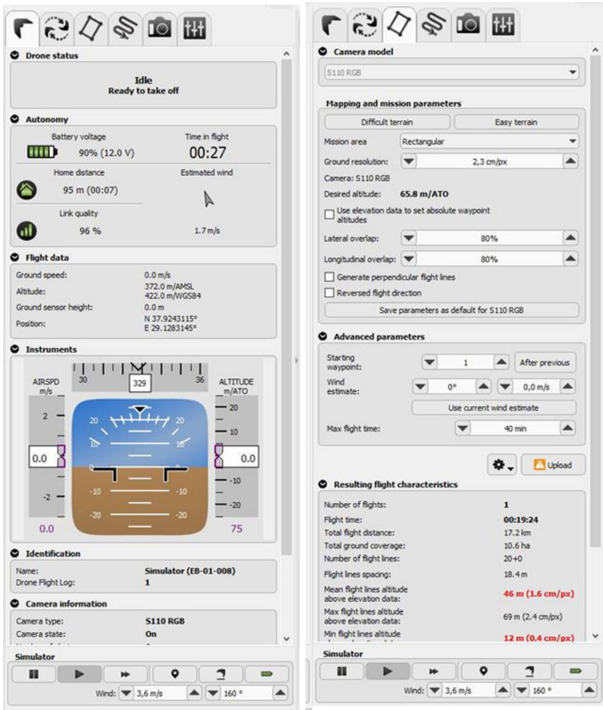


Figure 2: The parameter inputs of the flight plan in three samples of the eMotion interface software: drone status, mapping, and mission parameters.

This platform is able to acquire the GNSS/IMU data during the flight as well. The position/attitude measurements –made according to the characteristics of the on-board sensor (U-Blox chipset)– allow the definition of the position of the shooting with an accuracy of a couple of meters in the east and north directions, and almost double in Z. These sensors provide a position based on the Coarse/Acquisition (C/A) code at 1 Hz (no raw code data is recorded), and an altitude sensor, which provides three attitude angles (roll, pitch, and heading). Certainly, for large mapping (1:200-1:100) purposes, this accuracy is not sufficient. As a consequence, a suitable number of GCPs –well-distributed and materialized on the terrain– need to be collected using accurate topographic measurements by GNSS or Total Station for the image orientation.

3. The test site: Hierapolis of Phrygia

The ancient city of Hierapolis in Phrygia is founded on a calcareous shelf, and is rich in springs emerging from subterranean galleries. Ancient citizens evoked the city as "*πότνια Νυμφῶν, νάμασιν ἀγλαΐησι κεκασμένη*" ("Lady of the Nymphs, adorned by wonderful springs"), as stated in the inscription carved on a travertine wall of the diazoma in the theatre (Ritti, 1985, p. 114). The geological context of the site conditioned the ancient and current arrangement of the city, which is characterised by frequent destructive earthquakes and marked by the extraordinary concretions known as "white falls", thereby giving the Turkish village Pamukkale its name, which means "cotton castle". The site is located in the north-eastern and seismically active side of the Denizli Basin, which is a 70 km long graben (Alcicek, 2007).

During the last years, the MAIER's activities have led to the identification of two very important monumental buildings. In 2011, the church built upon the tomb attributed to the apostle Philip was brought to light. The following year, the famous Ploutonion cave –which was considered to be the entrance to hell– was discovered with a dedicatory inscription to the underground world god Pluto and his wife Kore. Starting from 2008, several large-scale restoration activities have been carried out through Turkish or foreign funding. Among them is the reassembling of the monumental theatre's façade, which is a relevant example of richly decorated Severian-age architecture. Other restoration activities have been concerned with the St. Philip Church and the visiting routes accessing the oriental hill where the St. Philip Church and the Martyrium of St. Philip stand, adding to the excavation of the main road of the northern Necropolis (D'Andria, 2016).

4. Aerial documentation: A sample autonomous flight

4.1. Data acquisition

For the data acquisition, the fixed-wing autonomous eBee drone was used (Fig. 3). During the data acquisition, the UAV was equipped with two different sensors. The Canon PowerShot S110 RGB is a 12 MPixel Commercial Off-the-Shelf (COTS) camera (with a tailored dial lock), which is able to acquire regular image data in the visible spectrum (Fig. 4); the Canon PowerShot S110 NIR is the same camera with a modified filter (long-pass filter) that allows the acquisition of data in the near-infrared band.

(a)

(b)

Figure 3: The eBee flight: a) Take-off phase; b) Setting up of the eBee platform with the customised camera.

The S110 (CCD size 7.44 x 5.58 mm, pixel pitch 1.86 µm, and focal length 5.20 mm) allows the manual setting up of the exposure parameters and can also provide RAW format image files as output.

As the main goal of the present paper was the realisation of orthoimages and 3D models, only the RGB data were

Figure 4: eBee Canon images. A zoomed RGB view of the Martyrium of San Filippo.

processed in order to evaluate all the eBee processing steps, from the flight plan, up to the data extraction. According to Turkey's UAV regulations (http://uavcoach.com/drone-laws-in-turkey), a platform with a weight under 4 kg can fly without any authorisation, with a flying height below 100 m.

Furthermore, pursuant to the aims of the project, the GSD was set up at 2 cm in order to obtain suitable information for very accurate large map documentation. In Figure 5, a sample screenshot of the planned flight is shown.

Figure 5: One of the flight plan in an eMotion screenshot.

In the analysed areas of Hierapolis, a set of targets were generated using black and white painted cardboards – positioned and finally measured as the GCP using a Real Time Kinematik (RTK) GPS survey (Fig. 6). For the survey operations, two GPS Leica System 500 were employed; the first one (used as reference) was positioned on the main vertex of the topographic network of the Hierapolis area (Astori et al., 2004) and the second one was used as rover, using the radio communication between the two receivers for the transmission of the real time correction. As expected, the coordinates of the GCPs were measured with a horizontal accuracy of 0.02 m and a vertical accuracy of about 0.04 m.

Figure 6: A view of the GPS RTK survey in the Necropolis areas.

4.2. Data processing

The employed software (Strecha, 2014) comprises three main steps: initial processing, point cloud densification, and DSM and orthomosaic generation.

The initial processing of the images extracts the interior and exterior camera orientation, and carries out a sparse model using features tracked along and across multiple photos. In this part of the process, the images are positioned using the data extracted by the on-board GPS, and then the Tie Points (TPs) are computed. TPs are prominent features that provide an efficient tracking across images, such as those measured using the Scale-Invariant Feature Transform (SIFT) algorithm. The sets of extracted points are correspondences identified by using image coordinates in as many photos as they appear. An automatic aerial triangulation and a bundle block adjustment are used to create the first projective reconstruction or 'sparse model'. This first projective reconstruction does not have a known coordinate system (usually the sparse point cloud is performed through a relative orientation). The user can manually adjust the results by introducing known real world coordinates of several points (targets) positioned and measured before the flight. The software contains a tie point/manual GCP editor, which allows the user to import the coordinates of the targets and to identify them in photos for the model reoptimization, and their consequent transformation to real world coordinates. Initial processing creates the base model so that the densification process can be achieved via projective reconstruction, which takes groups of individual pixel correspondences as input and generates 3D locations as output. The Root Mean Squared Error (RMSE) was calculated as well as the reprojection error for the manual GCPs (Strecha, 2014).

Once the results of the first part were checked, it was possible to move to the second step –the densification process. The process known as dense matching, which uses the sparse model and the initial estimation of the camera orientation to reproject individual pixels in the real coordinate space, typically performs this part. Point cloud densification using Pix4D is generally performed using a minimum of three matching points for each solved 3D pixel location and it is recommended the densification with the setting of half scale images for use in project areas that do not exhibit very high contrast with many sharp features. In the present project, in order to obtain a very accurate 3D point cloud, the images were not scaled (1/1). Moreover, the textured mesh could also be generated at this step. The final step in the Pix4D workflow was the production of the DSM and a complete true orthomosaic. True orthophotos are a common end product obtained from DSMs where the aerial images are rectified from perspective to orthographic projection using an underlying DSM; the single orthoimages are automatically clustered in the software.

5. Three flights for three goals

Three very important areas of the ancient city were selected for the present study (Fig. 7), thanks to their peculiar charachteristics and in order to demonstrate the various application possibilities and the relative descriptive abilities of the aerial acquisitions. The central city areas pertaining to the Plutonium (A) next to the Apollo sanctuary in the Sacred area; the massive masonry building of the so-called Terme-Chiesa (B); and the Northern Necropolis area (C). It is interesting how it is possible to conduct experiments that are very similar from a technical point of view and obtain objectives suitable to the individual requirements of the study areas. The next few paragraphs are intended precisely to highlight this particular versatility of the method. The final summary comparative (Table 1) will show among other data, some technical information characterising the experiences by putting them in close comparison.

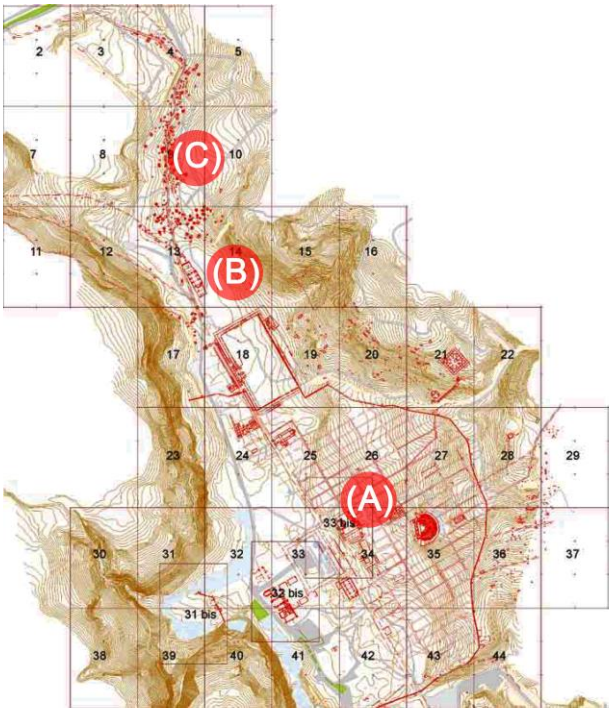


Figure 7: Hierapolis ancient city union framework (original scale 1:10000), Atlante of Hierapolis (D'Andria, Scardozzi &Spanò, 2008).

The Plutonium area (0.11 km^2), for example, was covered in about 10 minutes (80% sidelap and 80% endlap) by performing 14 flight lines at an altitude of 57.2 m. The test area of the so-called Terme-Chiesa, which extends to the monumental gate of the city (the Frontinus gate), is of a comparable size and the flight details were very similar. The area of the overflown Necropolis is wider and the flight altitude was higher. The topographical measurements performed before the flights allowed the collection of around 18 GCPs in the Necropolis area (0.23 km^2), 22 GCPs in the Thermal Bath Church (0.12 km^2), and 20 GCPs in the Plutonium area (0.11 km^2). As we can observe, the measured points were much more than ten points in a square kilometre, which is a suggested good compromise for photogrammetric flights (Krauss, 1997; McGlone et al., 2004).

5.1. (A) The Plutonium area for updating intents

The sanctuary built in the central area of the city is dedicated to Apollo, whose oracular cult has been documented by inscriptions discovered during the excavations.

The sacred area –changed to a monumental layout in the Augustan age, but just in use in the Hellenistic period– is organised upon three terraces sloping towards the west, near a huge fault from which concentrations of carbon dioxide pour out. After the excavations in the 1960s, which had led to the identification of the so-called "Building A" interpreted as the Temple, the resumption of research in 2001 enabled the identification of two other buildings ("B" &"C") and clarified many aspects related to the sacred practices previously held in these enclosures (D'Andria, 2013; Semeraro, 2016). The main place of worship, the Temple of Apollo, is to be found in Building B, identified thanks to the traces of foundation cables. It had indeed been destroyed in a systematic and radical way in the 5th century AD during a phase of strong Christianity affirmation. The excavation data analysis allows the reconstruction of a hexastyle temple in the Ionic order as it appears in the Hierapolis coins (Semeraro, 2012). Since 2008, the excavations in the area to the south of the Sanctuary of Apollo have uncovered a vast monumental complex. In 2012, the discovery of the dedicatory inscription to Pluto and Kore allowed the definitive identification of the famous Ploutonion cave of Hierapolis (Fig. 9), which is alluded by the testimonies of several ancient writers (Panarelli, 2016; D'Andria, 2013). Remarkable among all authors, Strabo (XIII, 4, 14) which refers to a cave from which poisonous vapours come out for approaching animals. Opposite the entrance of the cavity, the bulls were sacrified by suffocation, with the participation of the eunuchs, the priests of Cybele.

Dio Cassius (LXVIII, 27) also points out the presence of a theatron, built over the cave. The Hades Sanctuary covers about 2500 m^2 around the cave that opens along the fractures of the fault line running through the city's N–S axis at a rock jump of about 2 m.

From the cave exit gases, with carbon dioxide in high concentration, and thermal water flowing forcefully to one of the most active hot spring sources of the area.

The general orthophoto in Figure 8, like the zoomed ones shown in Figures 9 and 10, and the related textured DSM (Fig. 11), show how it is very important to have an overall map, in the form of an image that captures a precise

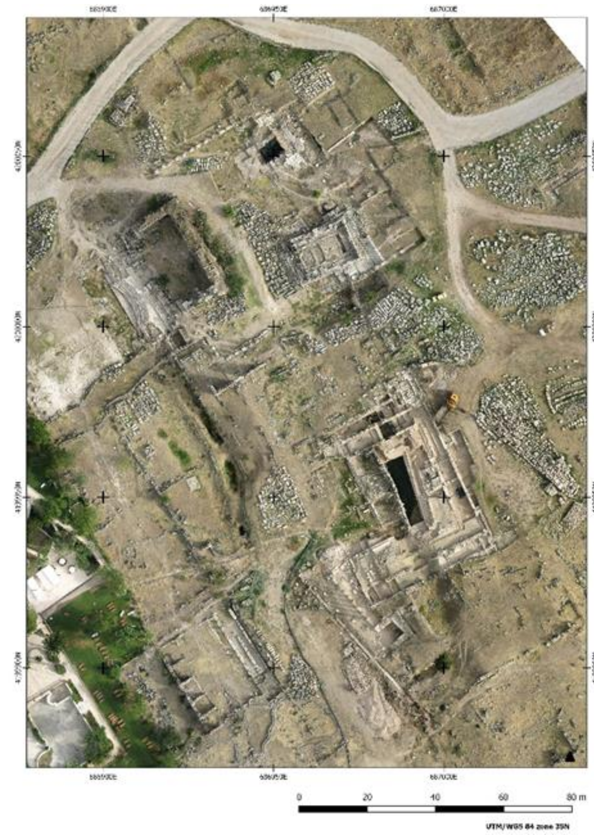


Figure 8: Othophoto of the Apollo sanctuary and Plutonium excavation area.

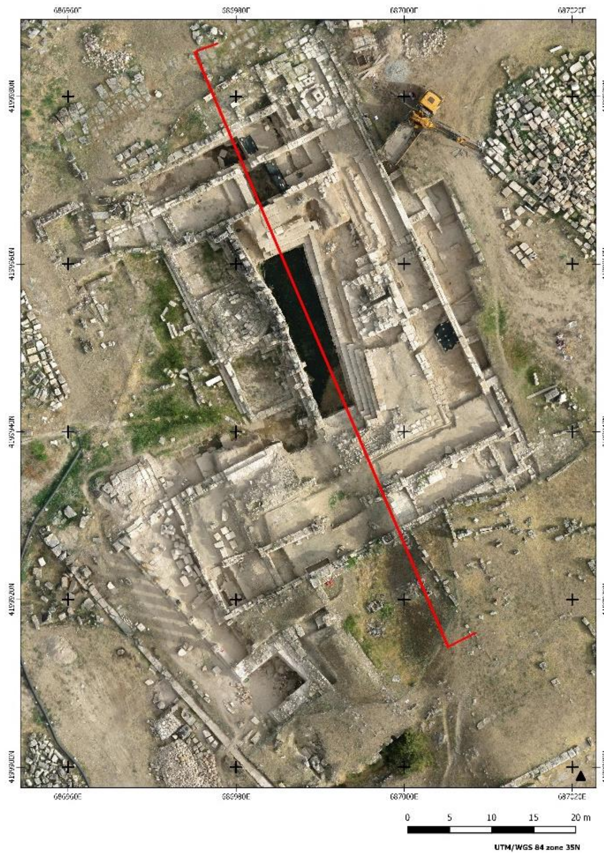


Figure 9: Excerpt orthophoto of the Plutonium area with Section profile (1).

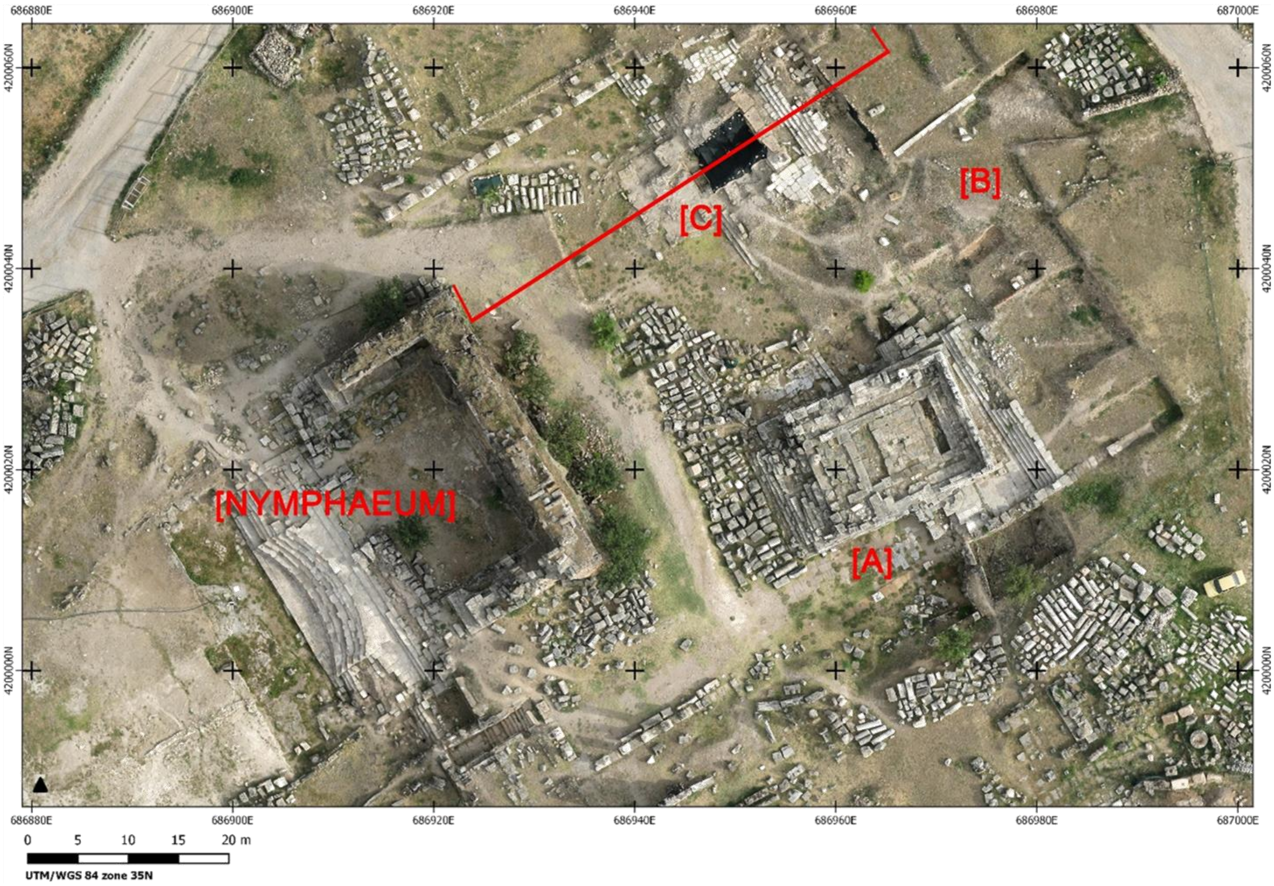
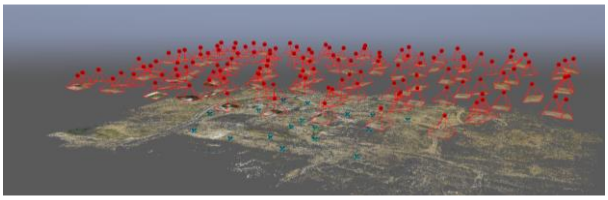


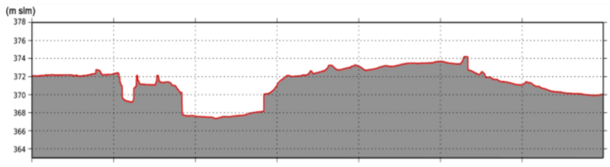
Figure 10: Excerpt orthophoto of the Apollo sanctuary and Nymphaeum area with Section profile (2).



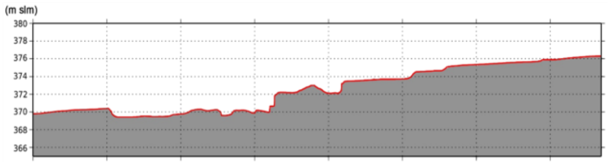
(a)

(b)

Figure 11: a) Camera positions of the photogrammetric flight with sparse point cloud and GCPs; b) view of the textured DSM.



(a)

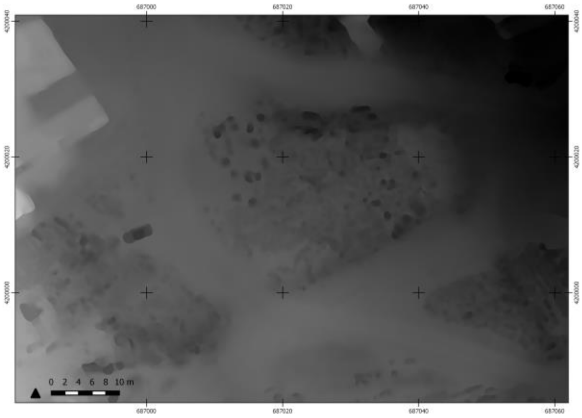


(b)

Figure 12: Profile sections on the Apollo Sanctuary: a) on the Ploutonion cave; b) on the Building C.

moment of the excavation and modelling works, with accurate metric and texture information. It allows experts to explore precise spatial relationship among all the excavation areas and help investigating their historical evolution and connexion too. Using orthophotos, it is possible to examine the changes in the area's condition until 2015, as well as analyse altimetric variations (Fig. 12) and support spatial catalogation of archaeological findings during excavation and accommodation phases (Fig. 13). This part of the city has been the most excavated in recent years, and the UAV results (Fig. 11) also allow us to relate specifically the two areas, the sanctuary with their terraces and the Ploutonion cave (see altimetric levels in Figure 12), so dense of layered structures in time. A 2 cm resolution and a less than 2 cm metric accuracy show that these products are key elements for the geometric documentation and updating process in archaeological contexts.

(a)



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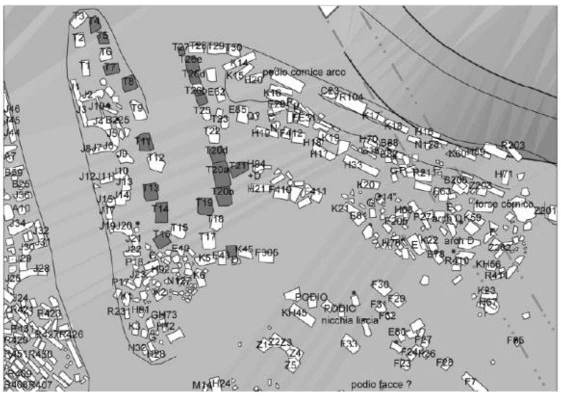


(c)

Figure 13: Spatial catalogation of archaeological findings from photogrammetry during excavation and accommodation phases: a) View of orthoimage; b) DSM; and c) example of spatial findings catalogation in a geographic information system (GIS).

5.2. (B) Improving the Ancient Terme Chiesa LiDAR model

The building is located along the northern limit of the Hierapolis, and certainly was one of the centres of urban enlargement in the Antonine age, along with the giant North Agora and the North theatre. The complex of the so-called Thermal Bath Church is characterised by structures in travertine blocks, retained for a considerable height and marked by crashes, injuries, fractures, gaps, and out-of-plumb walls, which were caused by earthquakes –especially those in the 2nd half of the 7th century AD– leading to the abandonment of the building that had been converted into a church (D'Andria, 2015).

The complex is particularly in danger due to the damage accumulated from several seismic events over the past centuries. In order to assess the present condition and properly formulate hypotheses for the necessary interventions, a combined laser surveying and Finite Element Modelling (FEM) procedure was set up (Invernizzi, Spanò & Alferi, 2014).

The walls of the Roman bath are entirely composed of large squared travertine blocks, basically placed without mortar in order to make a dry-stone wall with only sporadic and very thin plaster joints. The wall covering is completely lost, and the aim of the documentation performed using the LiDAR technique was to deepen the geometrical description of the serious alteration of the walls and vaults, and their widespread risky instabilities. The terrestrial technique is able to provide models describing the peculiarities of each travertine block. They are, for example, the roughness, the breaks and the micro-breaks, and in the structural assessment project, the geometry of almost each masonry block, that was explicitly accounted for and converted to be used as the input of a FEM program (Spanò et al., 2016).

The model shown in Figure 14a,b,d,e,g,j has been derived from 43 laser scanning positions placed as following:

- 22 scans from the ground level, along the outer limit of the building;
- 16 scans from the ground level, inside *calidarium*;
- 5 scans from the top of some areas of the collapsed walls, or from the top of the easily reachable walls, in order to obtain an almost complete scan covering.

Considering the time needed for the recording, registration, filtering, and decimation of the LiDAR point clouds, as well as the construction of the 3D mesh, the LiDAR technique provides extremely detailed and accurate outputs, but it is definitely heavy and less sustainable in relation to photogrammetry; in fact, it is used when it is strictly necessary.

On the other hand, drone surveys and the resulting products such as orthophotos (Fig. 15) and the DSM (Figs. 16 and 17) cannot be compared to the extremely detailed models offered by terrestrial laser surveys, particularly for the vertical portions of the structure, which are not achieved in the most effective manner by projecting rays, as visible in comparisons in Fig. 14c,f,h,i. It is important, however, to consider that all the elevated parts of the structure, including the top surface of the large bumpy cylindrical vaults, are difficult to measure from the ground. This integration of terrestrial and aerial survey by drone has not yet been performed on the Hierapolis data, but has been effectively accomplished on other occasions (Aicardi et al, 2015; Bastonero, Donadio, Chiabrando & Spanò, 2014). Another important opportunity is the capacity of a drone survey to document the areas of collapse, which can actually be well-documented from a nadir point of view. The images of Figure 18 report the volume calculation of a segmented portion of the model pertaining to the collapse of the apse area of the church. The processing has been performed with 3DReshaper software (v. 2016 MR1) by Technodigit.

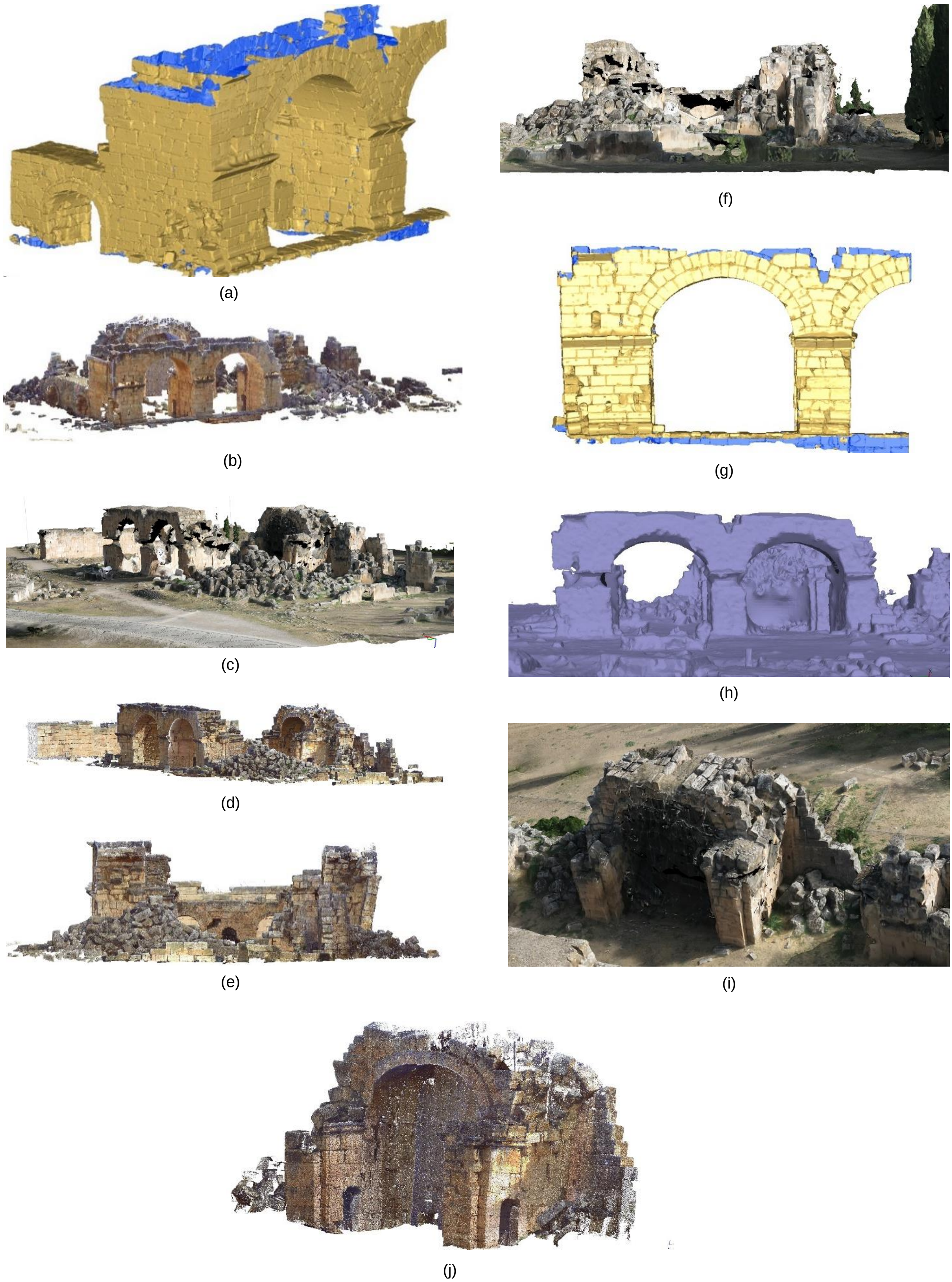


Figure 14: A sequence of similar views about the terrestrial LiDAR and the drone models (very deficient in case of the upstanding walls). The north-west corner of the Bath-Church (a–b); the south-west corner (c–d); the apse in the south (e–f); the west façade (g–h); and the inner front in the eastern side of the building (i–j).

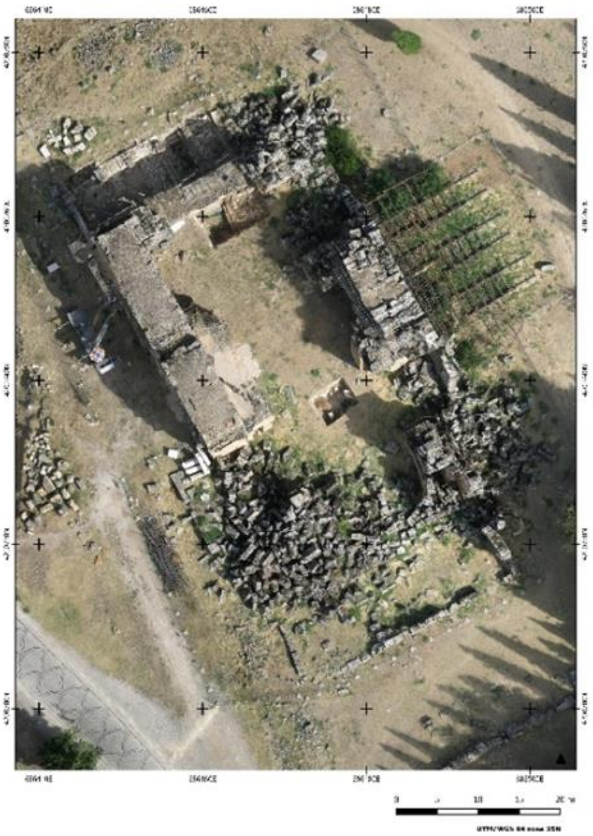


Figure 15: Orthophoto of the so-called Terme-Chiesa.

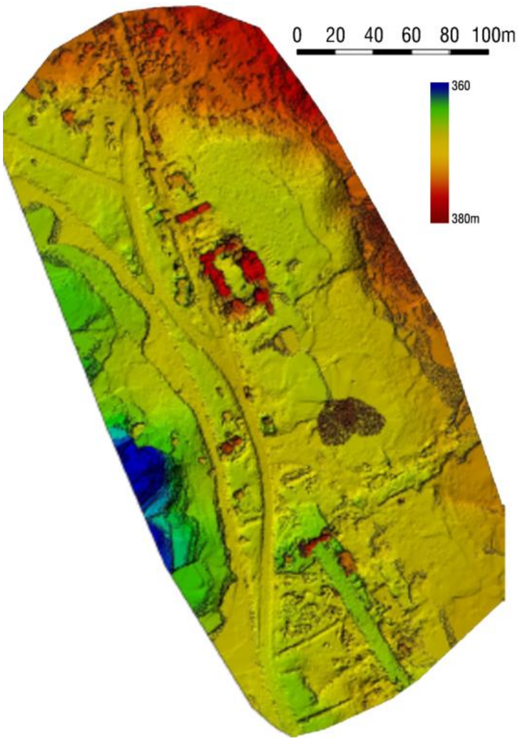
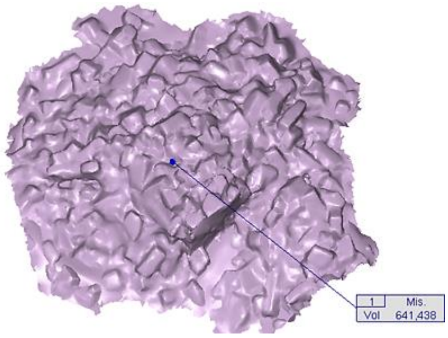


Figure 16: DSM of the northern portion of the city surrounding the ancient Bath-Church, between the northern Necropolis, in the north, and the northern Agorà, in the south.

Figure 17: A 3D view of the textured DSM processed from the Terme-Chiesa flight.

(a)



(b)

Figure 18: The apse area of the church: a) aerial image of the collapse blocks; b) 3D model used to compute its area and volume.

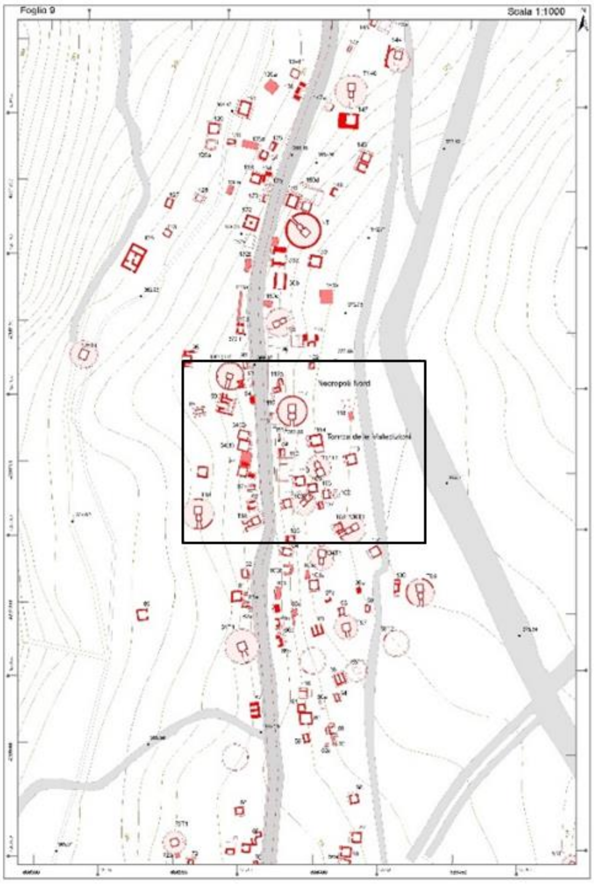
5.3. (C) The levels of paths in Necropolis

The stretch of the road to Tripolis affected by the 2015 drone flights is flanked by funerary areas that extend into the first rung of the hill to the east and into the flat area and the gentle slope to the edge of the west travertine terrace. The occupation of the area started as early as the 2nd century BC, and it developed until the end of the 3rd century AD, starting from the mounds and ending with the reorganisation of the road elevations. The mounds, which are particularly common in this stretch, represent the oldest burial site (between the 2nd and 1st centuries BC). At a later stage, from the end of the 1st century AD, some burial structure was built, arranged along the main street and along the internal lines. Tombs at newsstands with their pediments and underground rooms in collapse, but readable in the system and in the upstanding structures, are placed in succession on the side of the road or emerge on the first step of the hill (Ronchetta, 2015).

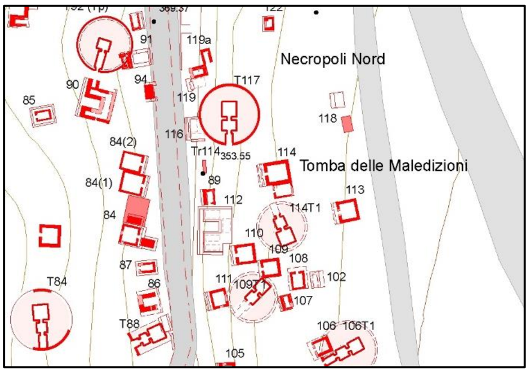
A principle of organisation of the space can be pinpointed through the aggregation of some complexes (Figure 19a).

This principle is shown (Figure 19b) for concentrated groups of tombs (108, 109, 110, 111), or in the continuity of facing of the structures in support of coffins (119), or with the creation of masonry fences with access to the monument's portals (112), or with the presence, along the path, of parking areas defined by exedras to seat (147a).

In 2013, after the modern road had been moved to the Necropolis valley, a large stretch of the old pavement was again highlighted. The road's axis is 6 m wide on an average, and up to 8 m in some places. It consists of twomargins in parallelepipeds of travertine blocks arranged according to the length, which delimit the paving stone made up of compacted limestone. Following the detailed campaign for the updating process of the



(a)

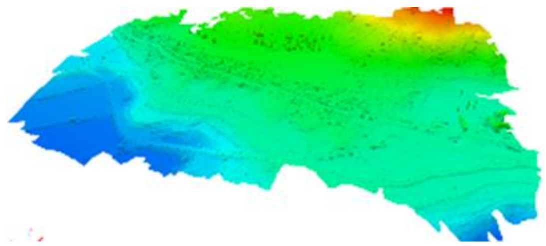


(b)

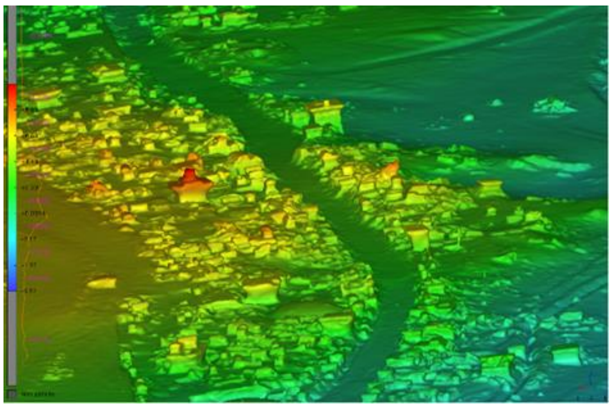
Figure 19: The necropolis planimetric map enabling the formulation of the principle of the tombs' organisation: a) The sheet No. 9 of the Atlante of Hierapolis (D'Andria, Scardozzi & Spanò, 2008); b) An excerpt of an area of precise space organisation.

Figure 20: Orthophoto of the covered necropolis area in 2015.

(a)



(b)



(c)

Figure 21: Some visualisations of the model: a) Range colour and b) textured DSM pertaining to the Necropolis; c) A view of the model with levels represented by colours in the scale levels.

Necropolis map, which has positioned a large number of sarcophagi (Scardozzi & Ahrens, 2015) essential to understand the organisation and temporal succession of the graves, the drone survey has provided a very substantial completion (Fig. 20). In Fig. 22 some singular aerial view of the central road and the sarcophagi are displayed.

The important contribution of the drone survey was definitely the provision of a highly-detailed terrain model (Fig. 21) that affects the tissue of the whole Necropolis and its domestic routes. Up until now, these data were not available and we believe that the ability to measure, on a digital model, every possible level or height difference within the Necropolis' points is an important opportunity for future studies and analysis.

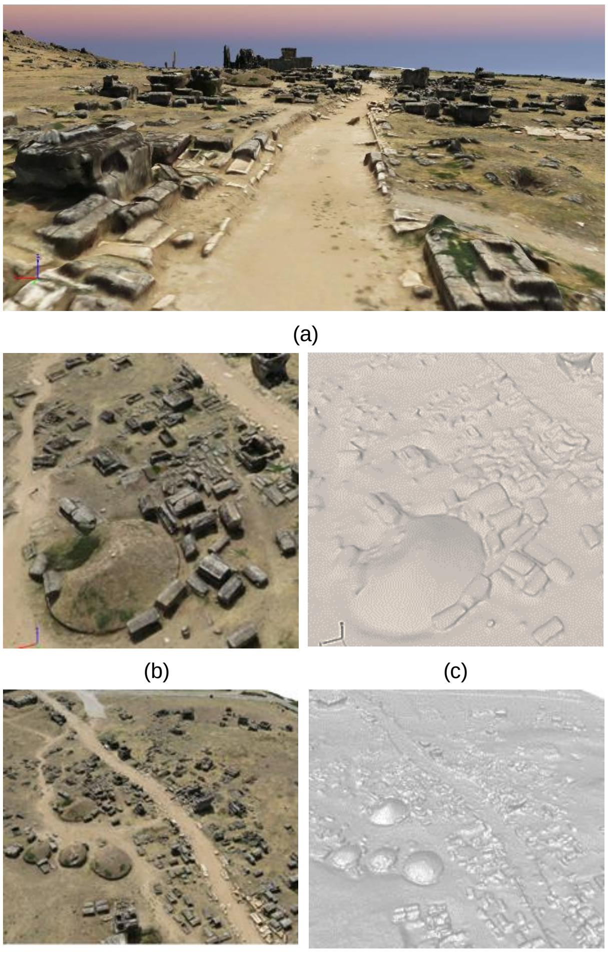


Figure 22: Views reporting the 3D model of Necropolis: a) an aerial view from the central axe. Some other sample views reporting the meshed 3D model of the Necropolis b) and d) compared with textured 3D models c) and e).

According to the eBee system features, the flight range and the flight altitude of about 100 m have enabled the retrieval of a DSM and an orthophoto (Fig. 23) covering the Necropolis area in a high resolution and the area of the recent constructions of tour paths for tourists. From that high-scale DSM (Fig. 23c), it is possible to extratct a detailed mapping of the slope condition in the area. Thanks to this possible approach, together with the performance of a set of focused sections (Figs. 24 and 25) some investigation on hipothetical and recognised alternative pathways and their trend on

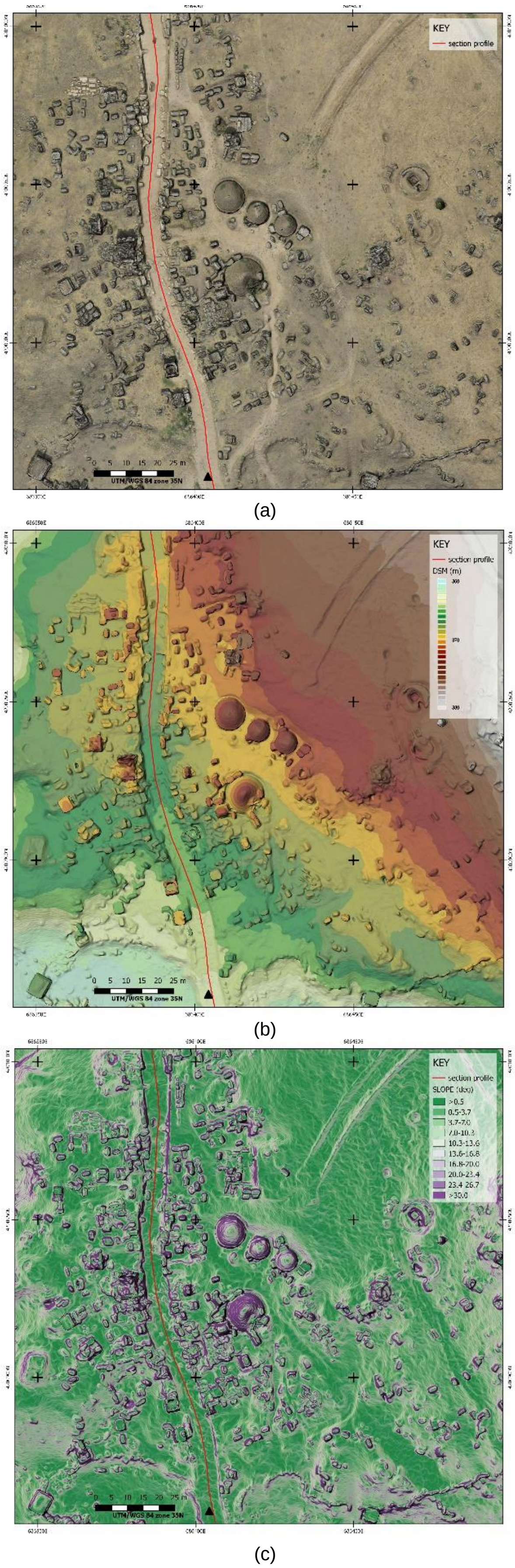
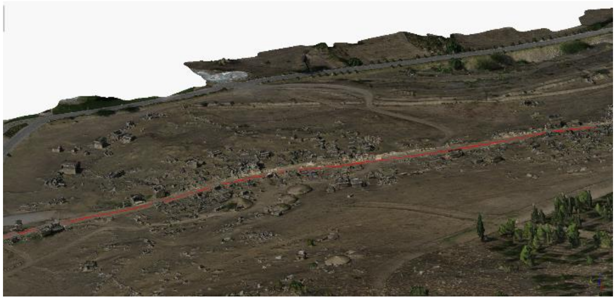


Figure 23: Views reporting the section profile in central axe: a) superimposed on the zoomed RGB orthoimage; b) on shaded DSM model in range color mapping altimetry; c) on slope map in range color.

lateral sides, compared to the principal one, can be carried out. In fact, the dense connection network of paths among many tombs arranged along the main street is a remarkable aspect to be investigated from the archaeological point of view with the support of plano-altimetric morphological information documented by an aerial point of view, in a totally innovative way on this area.



(a)

(b)

Figure 24: Views reporting the 3D model of Necropolis: a) section profile on the central axe; b) a zoomed excerpt.

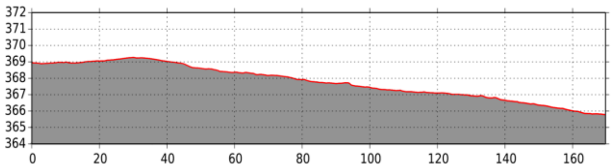


Figure 25: Views reporting the 3D model of Necropolis: section profile on the central axe (a).

5.4. Synthetic overview

Table1 includes some key data related to the processing phase. For example, the timing of the processing machine, the final dimension of point clouds, and the density of the 3D points are listed. The result of the accuracy of the models, which is around 1 cm for the GCP and around 2 cm for the check points (ChP), is very interesting. This precision is really promising, along with the resolution –around 2 cm per pixel for flights of lower altitude and 3 cm per pixel for the flights of higher altitude– it means that the maximum scale of the outcomes is between 1:100 and 1:200.

6. Discussion

These multiple aerial acquisitions and elaborations belong to a 3D survey campaign of the year 2015, in which a fix wing platform was employed, with a nadir camera configuration and a flight altitude of 50<h<100m. Starting from the same device equipment, the aerial data have been analysed and compared according to the context area on which they have been planned. Then, according to the settings based on the type of terrain and

Table 1: Numerical data related to the photogrammetric survey.

		UAV flights data *Sites* (A)	(B)	(C)
		Plutonium/ Apollo Sanctuary	Thermal Bath/ Church	Necropolis
AREA	Covered area	0.11 km^2	0.12 km^2	0.23 km^2
	Type of surface	medium high structures and flat terrain	high structures and flat terrain	small structures and hilled terrain
ACQUISITION	Time of flight	12 min	13 min	15 min
	Altitude flight	57 m	78 m	100 m
	Longitudinal overlap	80%	80%	80%
	Lateral overlap	80%	80%	80%
	Flight Lines	14	12	12
	Acquired images	127	130	147
	GCP	13	16	16
	CP	6	7	8
PROCESSING	Time of processing	05h:46m	3h:21m	07h:38m
	Initial	05m:20s	05m:34s	06m:51s
	Point cloud densification	03h:06m	02h:00m	04h:50m
	3D textured mesh	36m:27s	18m:18s	44m:39s
	DSM generation	01h:46m	43m:08s	01h:38m
	Orthoimage generation	12m:09s	14m:19s	18m:36s
	Tie-points	937,990	724,427	857,220
	3D points	180,977,921	116,707,115	233,631,183
RESULTS	Density of 3D points	4257.29/m^3	3583.82/m^3	1169/m^3
	Medium GCP error (RMS)	0.011m	0.009m	0.014m
	Medium ChP error (RMS)	0.018m	0.019m	0.02m
	Ground sample distance (GSD)	2 cm/pix	2,17 cm/pix	3,3 cm/pix

building features, they have been finally related to the outcomes and their numerical evaluation. This can be useful for the assessment about potentiality in UAV application for different types of contexts, depending on the type of structure and terrain conformation. Due to the scale of the photogrammetric products that are adaptable to the flight altitude, and the downstream of the experiences gained, we can say that the drone surveys are particularly effective for the following purposes that are commonly carried out in archaeological sites. Indeed, starting from 2015 and following the latest research addresses in terms of flight plans, camera configuration and dense image matching algorithms in photogrammetric blocks acquisition and processing, the contribution of oblique acquisition in the 3D models definition is crucial and deepened in more recent research realized by our research group (Aicardi et al., 2016; Chiabrando, Lingua, Maschio, & Teppati Losè, 2017; Chiabrando, Spanò, Sammartano, & Teppati Losè, 2017; Piras, Di Pietra, & Visintini, 2017)

7. Conclusion

After the presentation of these results about the photogrammetric projects, it is possible to evaluate the drone survey as extremely effective in archaeological contexts, thanks to the versatility respect to the archaeological features of the sites and structures and the needs in an excavation process. In perspective, it can be expected that the acquisition phase, the elaboration process, and the results will be more and more strictly linked to information required for the documentation purposes. Data sets with 2 cm resolution and less than 2 cm metric accuracy confirmed us that these products are key elements for the documentation and updating of archaeological contexts.

Another important perspective is the ability to equip flight systems with other sensors that may give significant support to the archaeological investigations, especially with predictive tools, together with the need to put in safety conditions the excavations area.

Below a summary of the most significant considerations concerning the application of UAV methods in archaeological contexts:

- Survey products from aerial point of view can be considered as a quick means of documentation for a low-cost mapping, following the updating of excavation procedures. Meanwhile 3D models would become a suitable database on which it is possible to place/collect/store other reading data in a geospatial perspective, such as information about findings and stratigraphies from digging activities, and set comparative analysis.

- The integration of point clouds from the terrestrial range-based techniques with the aerial contribution of surveys by drone is a very important topic on current researches. High descriptive capabilities of terrestrial laser strategies must be weighed with their complexity in terms of times-costs for acquisition arranging and pointclouds management, registration and processing. New solutions of Mobile Mapping Systems (MMS) for rapid acquisition of point clouds are available and under experimentation in complex scenarios such as the urban and heritage contexts too (Toschi et al., 2017). On the other side, as stated, latest approaches in image densification algoritms and improvements of the sensors quality available on aerial devices equipped with high-resolution cameras allow the production of 3D dense clouds with significant gain in level of geometric definition, which can be rather compared and integrated with the terrestrial ones in terms of accuracy.

- The capacity of the drone survey to document and quantify the surfaces and volumes of structures, from a nadir point of view. Nowadays, thanks to oblique camera contribution, whose applications and optimizations are investigated in current geomatics research, the 3D models are reaching a high descriptive performance in terms of geometric surfaces and radiometry both in the upper parts and in the vertical façades of upstanding walls.

- The chance to both control and compare levels and heights differences in complex, densely built and collapsed areas (as in the Necropolis of Hierapolis) can be extremely effective.

References

Aicardi, I., Chiabrando, F., Grasso, N., Lingua, A. M., Noardo, F., & Spanò, A. (2016). UAV photogrammetry with oblique images: first analysis on data acquisition and processing. *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, *XLI-B1*, 835–842. doi:10.5194/isprsarchives-XLI-B1-835-2016

Aicardi, I., Boccardo, P., Chiabrando, F., Donadio, E., Lingua, A., Maschio, P., Noardo, F. & Spanò, A. (2015). Modelli 3D multisensore per l'acropoli segusina. In: *L'arco di Susa e i monumenti della propaganda imperiale in età augustea*. Segusium (pp. 195–216) - Susa, Italy: Società di Ricerche e Studi Valsusini.

Alçiçek, M. C. (2007). Tectonic development of an orogen-top rift recorded by its terrestrial sedimentation pattern: the Neogene Eşen Basin of southwestern Anatolia, Turkey. *Sedimentary Geology,* 200, 117–140. doi:10.1016/j.sedgeo.2007.04.003

Astori, B., Bonfanti, C., Chiabrando, F., & Spanò, A. (2004). GIS application for knowledge and preservation of Hierapolis of Phryigia site. *International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences*, XXXV (Part B), 354–359.

Bastonero, P., Donadio, E., Chiabrando, F., & Spanò, A. (2014). Fusion of 3D models derived from TLS and image-based techniques for CH enhanced documentation. *ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, II-5, 73–80. doi:10.5194/isprsannals-II-5-73-2014

Chiabrando, F., Lingua, A., Maschio, P., & Teppati Losè, L. (2017). The influence of flight planning and camera orientation in UAVs photogrammetry. A test in the area of Rocca San Silvestro (LI), TUSCANY. *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, *XLII-2/W3*, 163–170. doi:10.5194/isprs-archives-XLII-2-W3-163-2017

Chiabrando, F., Spanò, A. T., Sammartano, G., & Teppati Losè, L. (2017). UAV oblique photogrammetry and lidar data acquisition for 3D documentation of the Hercules Fountain. *Virtual Archaeology Review*, *8*(16), 83–96. doi:10.4995/var.2017.5961

Chiabrando, F., D'Andria, F., Sammartano, G., & Spanò, A. (2016). 3D modelling from UAV data in Hierapolis of Phrigia (TK). In: Proceedings of 8th International Congress on Archaeology, Computer Graphics, Cultural Heritage and Innovation 'ARQUEOLÓGICA 2.0' (pp. 347–349). Valencia, Spain.

Colomina, I., & Molina, P. (2014). Unmanned aerial systems for photogrammetry and remote sensing: A review. *ISPRS Journal of Photogrammetry and Remote Sensing*, *92*, 79–97. doi:10.1016/j.isprsjprs.2014.02.013

D'Andria, F., Scardozzi, G., & Spanò, A. (Eds.) (2008). *Atlante di Hierapolis di Frigia*, Istanbul: Ege Yayinlari.

D'Andria, F. (2013). *Il Ploutonion a Hierapolis di Frigia.* Istanbuler Mitteilungen, 63, 157–217.

D'Andria, F. (2015). Terme Chiesa. In G. Scardozzi (Ed.), *Nuovo atlante di Hierapolis di Frigia, Hierapolis di frigia VII*, Istanbul: Yayinlari.

D'Andria, F. (2016). Le attività della MAIER - Missione Archeologica Italiana a Hierapolis, 2007-2011.In: F . D'Andria, M. P. Caggia & T. Ismaelli (Eds.), *Hierapolis Di Frigia VIII, Le Attività delle Campagne di Scavo Restauro 2007-2011*. Istanbul: Yayinlari.

Fiorillo, F., Jiménez Fernández-Palacios, B., Remondino, F., & Barba, S. (2013). 3D Surveying and modelling of the Archaeological Area of Paestum, Italy. *Virtual Archaeology Review, 4*(8), 55–60. doi:10.4995/var.2013.4306

Invernizzi, S., Spanò, A., & Alfer, C. (2014). Combined laser surveying and finite element modeling for the structural assessment of masonry structures at the Hierapolis Outer Bath complex. In: *9th International Conference on Structural Analysis of Historical Construction SAHC2014*, Mexico City, 15-17 Ottobre 2014.

Krauss, K. (1997). *Photogrammetry, Volume II, Advanced Methods and Applications* (4th ed). Bonn, Germany: Dummler's Verlag.

Kersten, T. P., & Lindstaedt, M. (2012). Potential of automatic 3D object reconstruction from multiple images for applications in architecture, cultural heritage and archaeology. *International Journal of Heritage in the Digital Era*, 399–420. Multi Science Publishing. doi:10.1260/2047-4970.1.3.399

Mcglone, J. C., Mikhail, E. M., & Bethel, J. (2004). *Manual of Photogrammetry*, (5th ed). Bethesda, MD, USA: American Society for Photogrammetry and Remote Sensing.

Moussa, W., Abdel-Wahab, M., & Fritsch, D. (2012). An automatic procedure for combining digital images and laser scanner data. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*; Melbourne, Australia, XXXIX-B5, 229–234. doi:10.5194/isprsarchives-XXXIX-B5-229-2012

Panarelli, P. (2016). Il cosiddetto "Santuario delle Sorgenti" (Ploutonion): le attività di scavo 2008-2011. In F . D'Andria, M. P. Caggia & T. Ismaelli (Eds.), *Hierapolis Di Frigia VIII, Le Attività delle Campagne di Scavo Restauro 2007-2011*. Yayinlari, Istanbul.

Piras, M., Di Pietra, V., & Visintini, D. (2017). 3D modeling of industrial heritage building using COTs system : test, limits and performances. *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, XLII-2/W6, 281–288. doi:10.5194/isprs-archives-XLII-2-W6-281-2017

Rinaudo, F. Chiabrando, F. Lingua, A., & Spanò A. T. (2012). Archaeological site monitoring: UAV photogrammetry can be an answer. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, XXXIX-B5, 583–588

Remondino, F., Barazzetti, L., Nex, F., Scaioni, M., & Sarazzi, D. (2011). UAV photogrammetry for mapping and 3D modeling–current status and future perspectives. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences,* 38-1/C22, 25–31.

Ritti, T. (1985). *Fonti letterarie ed epigrafiche* (Hierapolis – Scavi e ricerche, I). Roma, Italy: Giorgio Bretschneider Editore.

Ronchetta, D. (2015). Necropoli Nord. In: Scardozzi (Ed), *Nuovo atlante di Hierapolis di Frigia, Hierapolis di Frigia VII*. Istanbul: Yayinlari.

Ruiz Sabina, J., Gallego Valle, D., Peña Ruiz, C., Molero García, J., & Gómez Laguna, A. (2015). Aerial photogrammetry by drone in archaeological sites with large structures. Methodological approach and practical application in the medieval castles of Campo de Montiel. *Virtual Archaeology Review, 6*(13), 5–19. doi:10.4995/var.2015.4366

Sauerbier, M., & Eisenbeiss, H. (2010). UAVs for the documentation of archaeological excavations*. International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences*, 38-5, 526–531.

Semeraro, G. (2016), Ricerche nel Santuario di Apollo (2007-2011). In F. D'Andria, M. P. Caggia & T. Ismaelli (Eds.), *Hierapolis Di Frigia VIII, Le Attività delle Campagne di Scavo Restauro 2007-2011*. Istanbul: Yayinlari.

Semeraro, G. (2012), Ricerche nel santuario di Apollo. In F. D'Andria, M. P. Caggia & T. Ismaelli (Eds), *Hierapolis di Frigia, Le attività delle campagne di scavo e restauro 2004-2006*. Istanbul: Yayinlari.

Scardozzi G., & Ahrens S. (2015). Le necropoli: inquadramento topografico generale e sviluppo storico. In G. Scardozzi (Ed.), *Nuovo atlante di Hierapolis di Frigia, Hierapolis di Frigia VII*. Istanbul: Yayinlari.

Strecha, C. (2014). The rayCloud–a vision beyond the point cloud. Fédération Internationale des Géomètres Congress 2014, *Engaging the Challenges - Enhancing the Relevance*. Kuala Lumpur, Malaysia 16 – 21 June 2014

Themistocleous, K., Ioannides, M., Agapiou, A., & Hadjimitsis, D. G. (2015). The methodology of documenting cultural heritage sites using photogrammetry, UAV, and 3D printing techniques: the case study of Asinou Church in Cyprus. In *Third International Conference on Remote Sensing and Geoinformation of the Environment*, International Society for Optics and Photonics, 953510. doi:10.1117/12.2195626

Toschi, I., Ramos, M. M., Nocerino, E., Menna, F., Remondino, F., Moe, K., … Fassi, F. (2017). Oblique photogrammetry supporting 3D urban reconstruction of complex scenarios. *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, *XLII-1/W1*, 519–526. doi:10.5194/isprs-archives-XLII-1-W1-519-2017