The Use of UAVs for Cultural Heritage and Archaeology

Kyriacos Themistocleous

Abstract This chapter focuses on the uses of unmanned aerial vehicles (UAVs) for documenting and monitoring cultural heritage and archaeological sites. High-resolution aerial imagery from UAVs also allows the rapid generation of 3D digital surface models for documentation and model reconstruction in a variety of applications. This chapter provides various examples of cultural heritage and archaeological sites in Cyprus that have been documented with high-resolution cameras aboard UAVs. Photogrammetry is also used to create 3D models of the site, which can also be printed using a digital printer.

Keywords UAVs · Cultural heritage · Archaeology · Photogrammetry

Introduction

The documentation of architectural cultural heritage sites has traditionally been expensive and labor-intensive. Innovative technologies, such as unmanned aerial vehicles (UAVs), provide an affordable, reliable, and straightforward method of capturing cultural heritage sites, thereby providing a more efficient and sustainable approach to documentation of cultural heritage structures. UAVs have proven to be invaluable in the fields of archaeology and cultural heritage, as they provide a non-invasive, time- and cost-efficient way to document cultural heritage sites. Most importantly, they are able to include the cultural landscape in which ancient vestiges are located in the documentation process. UAVs are a low-cost, nonintrusive, non-contact, cost- and time-efficient alternative to traditional methods of archaeological documentation and monitoring as they are able to acquire high spatial resolution data with high temporal frequencies over large areas. Aerial imagery from UAVs also allows the rapid generation of 3D digital surface models for documentation and model reconstruction in a variety of applications.

K. Themistocleous (✉)
Department of Civil Engineering and Geomatics, Faculty of Engineering and Technology, Cyprus University of Technology, Limassol, Cyprus
e-mail: k.themistocleous@cut.ac.cy

D. G. Hadjimitsis et al. (eds.), *Remote Sensing for Archaeology and Cultural Landscapes*, Springer Remote Sensing/Photogrammetry,
https://doi.org/10.1007/978-3-030-10979-0_14

This chapter presents an overview of case studies conducted using UAVs to document and monitor archaeological and cultural heritage sites in Cyprus with high resolution. The case studies include the use of UAVs for the purposes of aerial photography and photogrammetry, which produces ortho-images and generates 3D models of the site.

UAVs

Although airborne and satellite sensors are the most widely used methods in remote sensing to date, UAVs are becoming an alternative remote sensing method, as they are easier to use and are accessible to a wider audience. Currently, unmanned aerial vehicles (UAVs) such as gliders and copters provide a low-cost, high-quality image comparable to airborne sensors. The use of UAVs for monitoring purposes provides a low-cost, non-invasive technique to acquire high spatial resolution data with high temporal frequencies, especially in areas that have limited coverage and are inaccessible to humans. Research indicates that aerial remote sensing and imaging can be conducted using large-scale low-altitude imaging and geospatial information (Colomina and Molina 2014; Cho et al. 2013; Mayr 2013; Petrie 2013). Recent developments in photogrammetry technology provide a simple and cost-effective method of generating relatively accurate 3D models from 2D images (Ioannides et al. 2013; Themistocleous et al. 2014b, 2015a, b, c). These techniques provide a set of new tools to capture, store, process, share, visualize, and annotate 3D models in the field (Themistocleous et al. 2014a, 2015b).

The use of cost-effective unmanned aerial vehicles (UAVs) are becoming common tools for researchers for numerous applications. According to Burkart (Burkhart et al. 2014), the emerging development of small versatile UAVs for use in remote sensing offers simple and affordable observation from the air. Since UAVs vary in size and payload capacity, various sensors can be installed onto the UAV platform (Fig. 1). The sensors that can be added to the UAV platform include visible spectrum cameras and multispectral, infrared, and thermal cameras (Themistocleous et al. 2014a), thereby creating an unmanned aerial system appropriate for remote sensing applications. Due to the decreasing size of the sensors, receivers, and antennas, it is now possible to create an integration of various sensors, as their low weight

Fig. 1 Left—Sony NEX 7visible spectrum camera. Center—Tetracam multispectral camera. Right—FLIR thermal camera

and small size render them ideal for use on UAVs (Colomina and Molina 2014; Kostrzewa et al. 2003; Ruffino and Moccia 2005; Scholtz et al. 2011).

UAVs can be divided into two types: fixed-wing copter and glider. Each type of UAV has its own advantages and limitations, which are discussed in the sections below.

Fixed-Wing Copter

A copter system is a very powerful aerial platform with enhanced stability and maneuverability and powerful enough to lift a payload of several kilograms. For autonomous flight and improved maneuverability, the copter can be equipped with an internal GPS, gyros, compass, altitude control, telemetry, acceleration, and barometric sensors for altitude control. Copters are available with 4, 6, or 8 motorized propellers and can carry a payload of up to 2.5 kg on the mechanized viewing platform (Fig. 2). The main advantage of this configuration is that the copter can remain steady in the air and respond smoothly to flight commands from the operator, due to the five separate sensors and three gyroscopes that work together to maintain stable and controlled flight. The ground station transmitters allow the operator to easily control the copter system and the viewing angle of the camera. Using a video system, the live video of the camera is transmitted to a ground station. Flight times range from 8 to 25 minutes, depending on the payload and battery. To maximize flight time, two batteries can be connected in series to provide a flight time up to 40 minutes. The copter can be programmed to fly planned waypoint routes by using the GPS onboard navigation system and photographs can be triggered automatically. During the flight, the current position of the copter can be shown using a portable computer or a tablet.

Due to the internal GPS of the copter, the operator is able to take measurements of the same target at different heights by using the wireless PDA. The copter has a mech-

Fig. 2 Selected fixed-wing copters used in the case studies

anized camera mount that could be controlled remotely. The cameras and video recorders are attached to the camera mount and aerial photographs can be taken using the manual trigger through the ground control systems. The system can also be preprogrammed to take photographs at certain points and angles on a planned waypoint route. The camera mount is balanced horizontally and vertically by servomotors, which allows the camera to be vertical to the ground at all times. The copter had the capability to be raised up to 3 km in the air, thus providing data acquisition at higher elevations that the helium balloon platform. However, at high elevations, it was difficult for the operator to keep the copter within his line of sight and control the unit.

One of the main limitations of the fixed-wing copter is the battery capacity. Flight times are approximately 10 min when the payload was at maximum capacity and 20 min with normal payload, thereby minimizing the utilization of the copter for data collection. As well, the copter required calibration every time it was switched on in order to calibrate the internal GPS. The copter required that the operator have considerable experience in lift-off and landing copters to operate the copter and avoid damage to the instrument. The operator needs to be aware of the time limitations of the battery to avoid any crashes and possible damage to the copter. Special care is necessary in urban areas to avoid any collisions with electrical cables, buildings, etc. An additional problem of the copter is that it is quite large and bulky, which makes transport difficult.

Recently, there has been an influx of smaller copters with integrated cameras, such as the DJI Phantom series. These UAVs have an integrated 20 megapixel camera, which is extremely light and easy to manage. The unit has a built-in high-precision three-axis camera stabilization system that allows for smooth aerial photography. The integrated GPS autopilot system includes position holding, altitude lock, and stable hovering, thereby providing constant stability in flight. The UAV has a Wi-Fi wireless connection up to a distance of 300 meters, as well as real-time telemetry data and flight parameters. However, a main drawback of the copter is that the battery flight time is only 25 min. The unit has an intelligent operator control that displays the current position of the UAV in relation to the pilot as well as ground station support, thereby enabling extensive flight planning for automated flights.

Gliders

One of the benefits of the glider is that it has a flight duration of up to 90 min, which is four times the flight duration of other UAVs. The QuestUAV Q-POD is a glider UAV that can be used with different payload bays (Fig. 3). Q-Pods are designed to

Fig. 3 QuestUAV glider

be easily interchangeable. The modular design consists of one airframe and multiple sensor pods (Q-Pods). The A-frame carries the permanent equipment including the wings, motor, avionics, and autopilot. The Q-Pods slip easily into the A-frame and carry single or multiple sensors and the battery pack. The unit contains aircraft system status indicators, including current mode, critical sensor condition, GPS, onboard voltage monitoring, and communication link quality. As well, there is a real-time, auto-scaling moving map automatically linked with the planned waypoints and flight path. The UAV has a 100 km range and has an operational ceiling of 10,000 ft.

One of the biggest drawbacks of the Quest UAV system is that it required two to three people to operate it. As the glider is in constant motion, there are limitations on the types of sensors that can be used while the unit is in motion. The price point is more expensive than the previous systems examined. Also, extensive training and practice are required in order to operate the glider, due to safety requirements and flight regulations.

UAV Applications for Cultural Heritage

UAVs are being used for surveying cultural heritage sites due to their affordability, reliability, ease of use, and the quality of the processed measurements (Colomina and Molina 2014; Themistocleous et al. 2015a; Lo Brutto et al. 2014; Rinaudo et al. 2012). Research indicates that aerial remote sensing and imaging can be conducted using large-scale low-altitude imaging and geospatial information (Colomina and Molina 2014; Cho et al. 2013; Mayr 2013; Petrie 2013). Research indicates that UAV data provide more detailed surveys of the archaeological site (Hassani 2015; Remondino and Rizzi 2009; El-Hakim et al. 2004; Gruen et al. 2005; Rönnholm et al. 2007; Guidi et al. 2009), which are used to document the site. UAVs are also useful to survey inaccessible and/or dangerous areas which cannot be accessed directly using other systems or piloted aerial systems (Everaerts 2008; Eisenbeiss 2009). Several cultural heritage researchers have used UAVs for archaeological sites in the Mediterranean (Rinaudo et al. 2012; Brumana et al. 2013; Remondino et al. 2011) as well as in Germany, Cambodia, and Hungary (Seitz and Altenbach 2011; Meszaros 2011). Also, researchers have used the combination of aerial imagery for 3D reconstruction of the cultural heritage site (Eisenbeiss 2009; Fiorillo et al. 2012).

Remote sensing technologies on a UAV platform are extremely useful for the detection and monitoring of cultural heritage features (Themistocleous et al. 2014a, b, c; Agapiou et al. 2013). UAVs can be an efficient, non-invasive, and low-cost resource to document cultural heritage sites (Themistocleous et al. 2014a, b, c; Agapiou et al. 2013) and can be fitted with sensors which are able to produce an unprecedented volume of high-resolution, geo-tagged image sets of cultural heritage sites from above (Themistocleous et al. 2014a, b; Kostrzewa et al. 2003; Ruffino and Moccia 2005; Scholtz et al. 2011). Researchers have used the combination of aerial imagery for 3D reconstruction of the cultural heritage site (Eisenbeiss 2009; Fiorillo et al. 2012) through the use of photogrammetry.

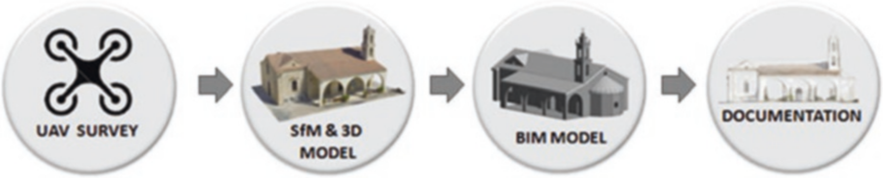

Fig. 4 Methodology

The methodology followed for the case studies presented in this chapter begins with a UAV survey where high-resolution aerial images are acquired. These images are then processed using Structure from Motion software, which creates a 3D digital model. The 3D model can then be exported into a BIM model, where the structure can be documented in terms of floor plans, elevations, and sections (Fig. 4).

Photogrammetry

Photogrammetry is a three-dimensional coordinate technique that uses computer analysis of photographic images for measurement. The fundamental principle of photogrammetry is aerial triangulation, where images from at least two different locations can be developed from each camera to point on the object and processed to produce the three-dimensional coordinates of the point of interest. Photogrammetry is used to conduct the image processing of the images acquired with the UAV, where the digital images are interpolated in order to create high-resolution, scaled, and geo-referenced 3D models from them. Photogrammetry generates the creation of 3D models by reconstructing a dense point cloud and generating polygonal mesh model based on the dense cloud data. In addition, the software has an automatic tool of texture projection, which makes automatic projection from the color directly on the surfaces possible (Meszaros 2011).

The first step in the program's procedure is called Structure from Motion (SFM) (Scopigno et al. 2015; Ingwer et al. 2015; Giuliano 2014). Structure from Motion is a photogrammetric method for creating three-dimensional models of a feature or topography from overlapping two-dimensional photographs taken from many locations and orientations to reconstruct the photographed scene. SfM analyses the dataset, detecting geometrical patterns in order to reconstruct the virtual positions of the cameras that were used in order to align the images, including building a sparse point cloud (tie points).

The second step involves the creation of a complete geometry of the scene using a multi-viewpoint stereo algorithms to build a dense point cloud. At this stage the dataset of images are employed to produce a high-resolution geometry of the surface. This step successfully creates a 3D model, also known as a digital surface model (DSM). The processing began with the orthomosaic production from these multiple images, which was used for digital terrain modeling (DTM) production from which a contour map can be generated. All images derived from the UAV can be included in processing or it is possible to select a sub-set of images on key sites with the study area for more detailed analysis ensuring sufficient overlap and ground control points (GCPs) allow for this. Photogrammetry software allows generation of high-resolution geo-referenced orthomosaics, exceptionally detailed DTMs and textured polygonal models through the use of the image overlay (Eisenbeiss 2009).

Following, surfacing algorithms employ the dense cloud's 3D point positions and the look angles from the photos to the matched points to build the geometrical mesh. The coordinates from the GCPs are then applied in order to scale the model to the correct dimensions. The software automatically aligns images based on pairing of features and creates a "sparse cloud" of elevations based on these points. The completed alignment is then used to develop a dense point cloud which is used to create a surface which allows draping of the imagery over the model by creating and building a texture from the original images and overlays the imagery onto the model mesh (Themistocleous et al. 2014c). The photogrammetry software then builds a polygon mesh and calculates a texture for the mesh. The software generates the building of 3D models by reconstructing a dense point cloud and generating polygonal mesh model based on the dense cloud data. In addition, photogrammetry has an automatic tool of texture projection, which makes automatic projection from the color directly on the surfaces possible (Meszaros 2011).

Image Processing

When cameras used in acquiring images have a wide-angle lens, lens distortion removal is required by calibrating the camera and removing the distortion by estimating the camera calibration parameters of center principal point, square pixels, and distortion models using the Brown distortion model (Brown 1966). Camera calibration data can also be calculated by the Agisoft Lens software (and exported if needed) or imported from an external source.

In the examples presented in this chapter, Agisoft PhotoScan Pro photogrammetry software was used to conduct the image processing. Agisoft PhotoScan is capable of interpolating digital images in order to create high-resolution, scaled, and geo-referenced 3D models from them. All clear images with sufficient overlap were included in the processing in order to generate a dense point cloud of the church. Ground control points (GCP) were applied to correct the scale and geo-reference the model. To complete the geo-referencing task, the program requires either Global Positioning System (GPS) coordinates associated with cameras, provided in an EXIF/plain text file, or GCP coordinates that can be used to achieve higher accuracy (up to 1 cm). Based on the latest multi-view 3D reconstruction technology, the software operates with arbitrary images and is efficient in both controlled and uncontrolled conditions (Remondino et al. 2011). Photos can be taken from any position, providing that the object to be reconstructed is visible on at least two photos with sufficient overlay. Both image alignment and 3D model reconstruction are fully automated.

Building Information Modeling

After the 3D model generation, the point cloud model is converted to the .rcp indexed format and imported into Autodesk Revit software to generate a Building Information Model (BIM). BIM is an intelligent 3D model-based process that involves the generation and management of digital representations of physical and functional characteristics of places. It can also be defined as a BIM virtual information model. BIM design tools allow extraction of different views from a building model for drawing production and other uses. After the BIM model is constructed, drawings of the plans, elevations, and sections of the church can be generated directly from the BIM model for documentation purposes. Also, information such as material, color, height, thickness, etc. can be added to each component in the BIM database.

Case Studies

The below case studies feature a variety of examples of how UAVs were used in order to acquire aerial images and document different types of cultural heritage and archaeological sites. Different UAVs were utilized based on the survey area. Gliders were used for surveying an extensive area, whereas drones were used for smaller areas and structures. As previously mentioned, the methodology used was the same in all case studies. First, GCPs were established at each site and the high-resolution aerial images were acquired using UAVs with different sensors. Second, once the aerial imagery was obtained using the UAV, the images were processed using SfM software to create a 3D model and then produce an ortho-image and digital elevation model. In some of the structures, the 3D model was imported into BIM in order to produce drawings, floor plans, and elevations.

Curium Case Study

The study took place in the southwest of Cyprus, in the archaeological site of Curium, which is situated outside the modern city of Limassol, Cyprus. Curium is considered one of the most significant archaeological sites on the island. Although the Kingdom of Curium was established in the Cypro-Geometric period (1050–750 BC), the majority of the archaeological remains within the Curium archaeological area date to the Roman and Late Roman/Early Byzantine periods. The area is particularly noted for its magnificent Greco-Roman theater, which was initially constructed in the late second century BC, until being abandoned in the later fourth century AD, most likely following successive earthquakes in the area.

In the Curium study, the QuestUAV Q-Pod Surveyor was used (Themistocleous et al. 2014a) in order to cover the entire site with a 20MP high-resolution camera.

Quest UAV Q-Pods are small unmanned airborne vehicle (UAV) capable of carrying a payload in flight and flying a pre-programmed route that is created in its flight planning software. All the necessary flight permissions were acquired from the Cyprus Aviation Authority (CAA) and the Sovereign Bases Area Administration (SBAA). The selected UAV was flown at a low altitude of 125 meters to provide high-resolution data for survey. Single images were taken automatically with a 60% overlap in an x and y direction in order to build a large detailed ortho-image and create a 3D model for accurate survey work (Themistocleous et al. 2015b). A 20 minute flight was needed to survey a 1 square km area with a 3 cm resolution. The UAV included a GPS unit that geo-tagged all the aerial images with the latitude and longitude within the metadata file of every image (Themistocleous et al. 2014a). Fixed ground control points distributed throughout the site were used in order to geo-reference the image with an accuracy up to 2 cm. The result was a high-resolution ortho-rectified image of the Curium site, which included the ancient hill, amphitheater, and all the monuments (Figs. 5 and 6).

The aerial images were processed in Agisoft Photoscan in order to create a 3D textured model of the amphitheater, as well as a digital terrain model (DTM) (Themistocleous et al. 2014a) (Figs. 7 and 8). The survey of the Curium site was conducted in order to document the entire site and examine the capabilities of the SfM technique in large archaeological sites, such as the Curium site area.

The process used in this case study is very useful in documenting large archaeo-landscapes as satellite imagery cannot provide the resolution that is available with UAV images. Ortho-images that are produced by UAV using photogrammetric methods are more accurate when used with GCPs and can provide more information since the resolution is very high, especially with cameras exceeding 20MP resolution. The capabilities of the state-of-the-art drones, UAVs, and multi-copters provide stable

Fig. 5 Ortho-image of the ancient Curium archaeological site

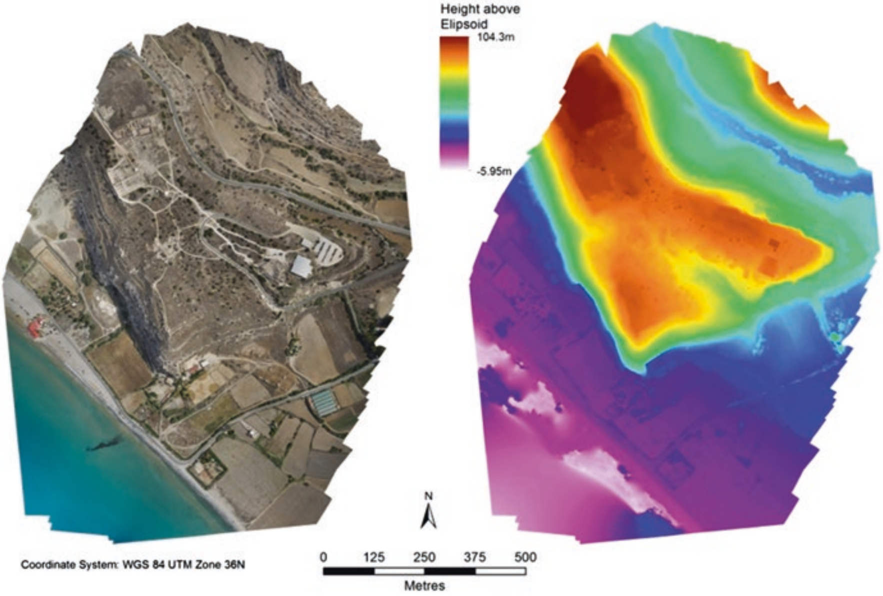

Fig. 6 Orthomosaic and reconstructed DTM of the ancient Curium archaeological site

Fig. 7 3D textured model of Curium in Agisoft PhotoScan Professional

aerial images using mechanisms to stabilize the camera, which are known as gimbles, thereby providing sharp and clear images that are geo-referenced due to the internal GPS of the UAV. This assists in the photogrammetry and modeling process, since the images are providing enough geo-referenced information in order to create an accurate and geometrically correct geo-referenced model.

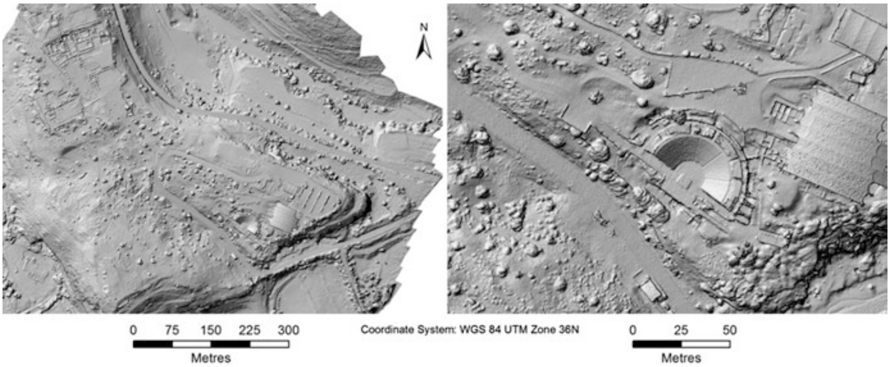

Fig. 8 DTM from Agisoft PhotoScan Professional

Fig. 9 3D model and 3D printed model of Curium amphitheater

The DTM of the amphitheater of the Curium archaeological site was used to print a 3D model (Fig. 9). The model was printed by “CUTing Edge” of Cyprus University of Technology, and it is now exhibited in the local museum of Curium. The model serves both for educational reasons as well as for visually impaired people (Themistocleous et al. 2016a).

Nea Paphos Mosaics and Archaeological Park Case Study

Nea Paphos was established at the end of the fourth century BC and was the capital city of Cyprus during the Roman period. The Nea Paphos archaeological park is a vast archaeological area, with remains of villas, palaces, theaters, fortresses, and tombs and is also a UNESCO World Heritage Site. Among the most significant remains discovered to date are four large and elaborate Roman villas (the House of Dionysos, the House of Aion, the House of Theseus, and the House of Orpheus), all with superb preserved mosaic floors. These mosaics constitute an illuminated album of ancient Greek mythology, with representations of Greek gods, goddesses, and heroes, as well as activities of everyday life. The mosaics of Nea Paphos are extremely rare and are considered among the finest specimens in the world; they cover the Hellenistic period to the Byzantine period (UNESCO 2017).

Due to the size of the site, different UAVs were used to document archaeological sites in Nea Paphos, Cyprus (Themistocleous et al. 2014c, 2015a, b). Aerial images were taken with different UAV systems, including gliders and multi-rotors in order to survey the site. Archaeologists estimate that only 10% of Nea Paphos has been excavated. Therefore, researchers have been unable to reconstruct what Nea Paphos must have looked like at the time of its creation. Therefore, UAV surveys are important in assisting archaeologists and cultural heritage experts to manage the site and monitor environmental changes from erosion and pollution, since the site is located next to the sea and the modern city of Paphos.

In order to survey the entire site, 350 images were taken, and 56 GCPs were distributed over the site, generating a 3 cm per pixel resolution ortho-image and 13 cm per pixel DEM (Fig. 10). Contour lines were created to determine the topography of the area. Due to the high-resolution images derived from the UAVs, compared with satellite images, many crop marks are visible, which suggests possible underground archaeological features.

In order to document the famous mosaics in the archaeological park, multi-copters with a 20 MP high-resolution camera were flown at a low altitude of 50 meters and 80% overlap in both directions (forward and side overlap). This provided the ability to capture a higher-resolution model of 1 cm per pixel and create a more accurate 3D model of the site (Fig. 11).

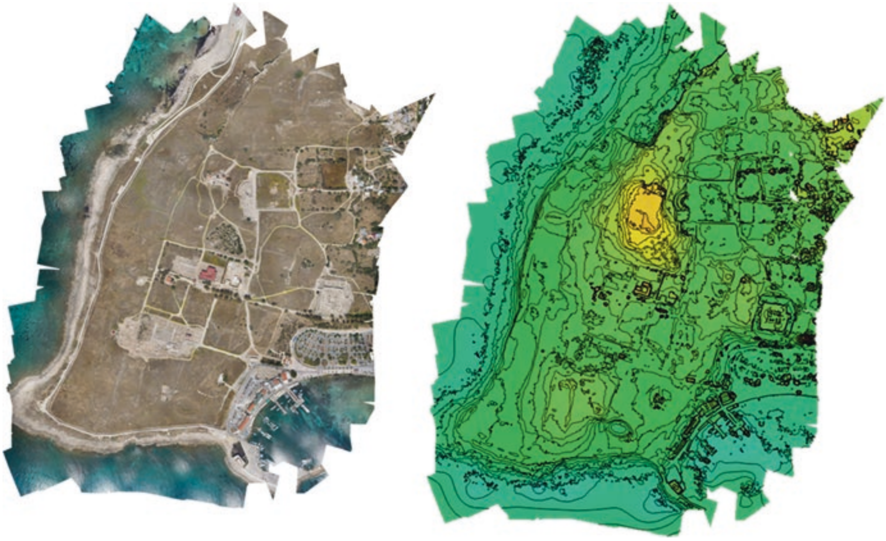

Fig. 10 Left: Ortho-image of Nea Paphos using a glider. Right: DEM with contour lines created from the 3D model

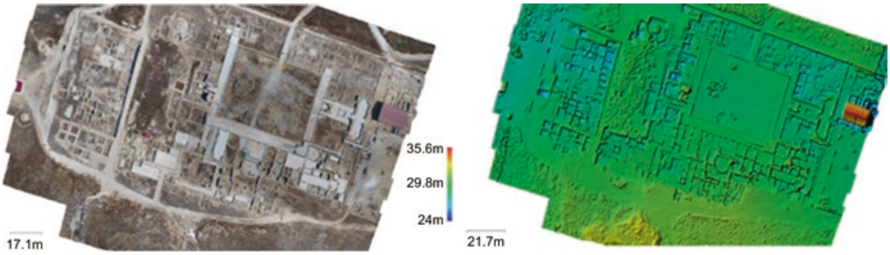

Fig. 11 Left: Ortho-image of the House of Aion, the House of Theseus, and the House of Orpheus. Right: DEM of the House of Aion, the House of Theseus, and the House of Orpheus created from the 3D model

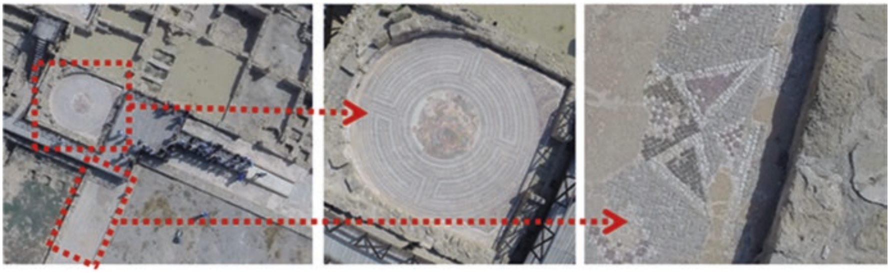

Fig. 12 Left—Aerial photograph of the archaeological park in Paphos, Cyprus. Center—Aerial photograph of the mosaic floor. Right—Aerial photograph of the mosaic corridor

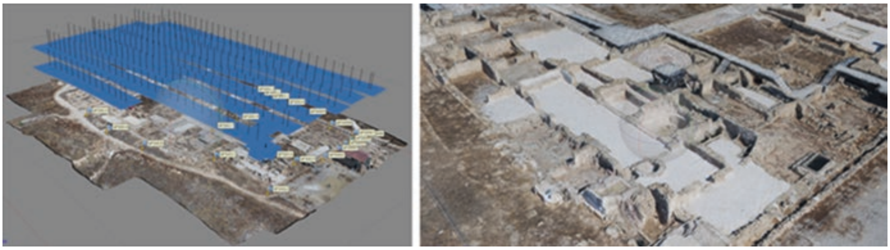

Fig. 13 3D model of archaeological park in Paphos using SfM

As a result, the images and the model generated from the high resolution images are extremely detailed to the point where the individual mosaics can be seen, as shown in Fig. 12.

Using all the images and GCPs acquired from the UAVs, a geo-referenced model and ortho-image were produced using the methodology described in this chapter and as shown in Fig. 13.

The geo-referenced ortho-images generated in this site will be compared with other images of the same study area at different times in order to identify any environmental changes in order for the relevant authorities to take the necessary actions to protect the site from further damage.

Fabrica Hill Case Study

Fabrica Hill is situated near Saint Paul's Pillar and the Ancient Theater Ruins in the city of Paphos. The Fabrica Hill most likely dates back to Hellenistic times and was used during Byzantine times as a quarry and storage area. The hill was named Fabrica because a textile mill existed at the site during the Middle Ages. The site includes some minor ancient mosaics that have been partially restores, as well as several ancient quarry caves from the Hellenistic period. The numerous underground caves are of sizeable proportions, and their coated walls may have been painted. The presence of these features makes Fabrica a very complex system and a challenging case study for accurate documentation (Themistocleous et al. 2014b). During the preparation for the "Paphos 2017- European Capital of Culture," the Municipality of Paphos requested that the site be documented in order to redesign the site and make it more accessible to tourists.

An aerial surveying of Fabrica Hill was conducted using a quadcopter equipped with a GoPro Hero 3 Camera (Themistocleous et al. 2014b, 2015b). In addition, the Leica laser scanner was used to support the UAV survey by providing an internal 3D model of the area. All images acquired by the copter were processed through the use of Agisoft Photoscan Profession software, while the point cloud data were processed in the Cyclone environment. Over 300 high-resolution images were taken above the Fabrica Hill and were post-processed using Agisoft Photoscan Professional software. The immediate outcome of the post-processing was the orthomosaic production deriving from the merging and layering of these multiple images (Fig. 14). The ortho-image was further exploited in order to produce the digital terrain model (DTM) of the area in order to generate a contour map. Further to the orthomosaic of the area, relative 3D models have been also retrieved. The most impressive models were those of the ancient amphitheater (Fig. 15).

All the 3D models and ortho-images were provided to the municipality and the architects in order to prepare a proposed plan for renovation of the area.

Asinou Church Case Study

The study area is the church of Panagia Phorbiotissa, better known as Asinou Church, which is located in the north foothills of the Troodos Mountains of Cyprus, which is a UNESCO World Heritage Site (Themistocleous et al. 2015c). A quadcopter with an added gimble, telemetry, and GoPro HERO3+ camera was used to acquire the aerial images of the church in order to create a 3D model. The small quadcopter was used due to its maneuverability, which was needed to take images above and around the church (Fig. 16).

The copter was flown in manual mode to ensure that all the images necessary for image processing are taken and to avoid any obstacles around the church, especially trees. During the flight, two operators were required for the aerial survey; one operator controlled the flight path of the UAV, while the other operator

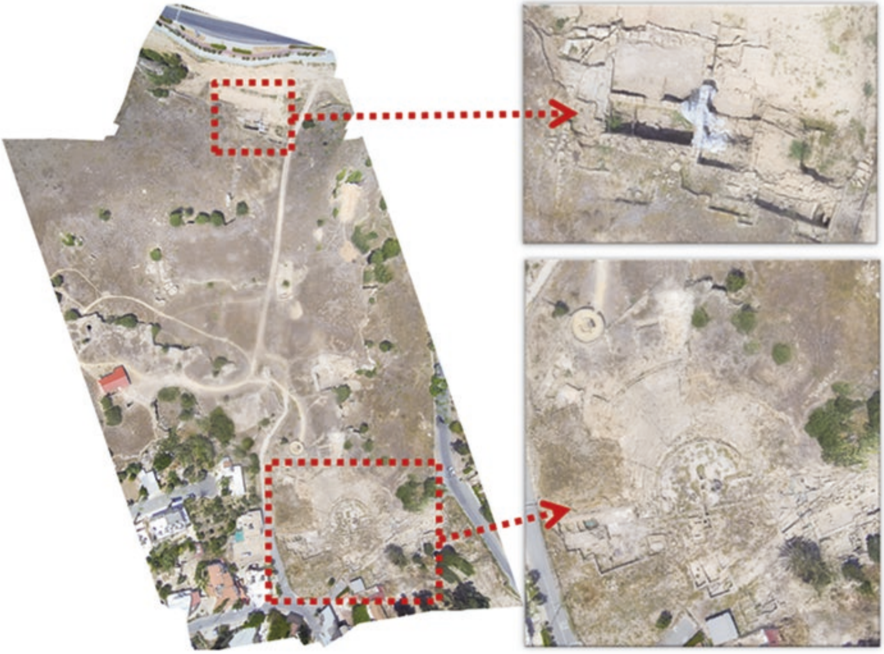

Fig. 14 Ortho-image of Fabrica Hills

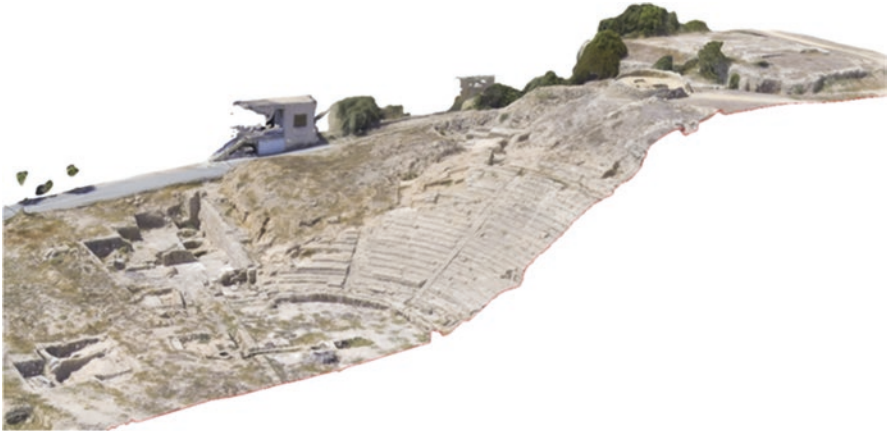

Fig. 15 3D section of the amphitheater located at Fabrica Hill

monitored the UAV telemetry data. The telemetry information was transmitted to the operator on a monitor in order to verify the position, distance, height, and battery life of the quadcopter. This was necessary to guarantee the overlap and correct position of each image.

Fig. 16 Quadcopter with GoPro HERO3+ camera during flight

Fig. 17 Left, photographic image church; center, 3D model; right, 3D printed model

Over 1000 images were taken at Asinou Church, which were post-processed by removing the lens distortion and then processed using the Agisoft Photoscan Professional software. Since the GoPro HERO3+ camera used a wide-angle lens, lens distortion removal was required by calibrating the camera and removing the distortion using the appropriate distortion filter (Themistocleous et al. 2015c). Agisoft PhotoScan was used to conduct the image processing, thereby generating high-resolution geo-referenced orthomosaic, detailed DTMs, and textured polygonal models through the use of image overlay. Due to the manual flight parameters and low speed of the copter around the structure, the rolling shutter issue usually associated with the GoPro cameras were not an issue.

The processing began with the orthomosaic production from these multiple images, which was used for the 3D model (Fig. 17). Following the orthomosaic production, a high-resolution 3D mesh model of the church was generated and exported to a surface model (Themistocleous et al. 2015c). The surface model was imported into Autodesk 3DS Max in order to clean up, fix, and optimize the mesh. Any unnecessary noise or busy surroundings were cleaned up, and large mesh issues, such as particles, holes, spikes and tunnels, were fixed. The mesh was then prepared for printing by exporting the corrected model into a .stl file, where a 3D printer was used to generate a 3D model. The model was printed using a Makerbot Replicator 3D printer with PLA filament and layer resolution of 100 microns, which provided an accurate representation of the church.

Foinikaria Church Case Study

The study focused on the Church of Panagia Chryseleousa in Foinikaria village, which is located in the Limassol District of Cyprus. The survey was done in cooperation with the Holy Bishopric of Lemesos in an effort to document the church in a short amount of time. In the study, the hexacopter with attached GoPro HERO+ 12MP camera was used to take aerial images of the church (Themistocleous et al. 2016b) (Fig. 18). The hexacopter was used due to its maneuverability to take images above and around the church. A gimble was added to the camera to provide high-precision three-axis camera stabilization system that allows for smooth aerial photography. The integrated GPS included position holding, altitude lock, and stable hovering to provide constant stability in flight. The flying altitude was relatively low at 10 meters in order to produce higher-resolution images. The copter was flown in manual mode to ensure that all the images necessary for image processing are taken and to avoid any obstacles around the church, especially trees. During the flight, two operators were required for the aerial survey; one operator controlled the flight path of the UAV, while the other operator monitored the UAV telemetry data. The telemetry information was transmitted to the operator on a monitor in order to verify the position, distance, height, and battery life of the hexacopter.

Fig. 18 Foinikaria church, with UAV flyover and ground control point (GCP)

Over 1000 images were taken at the Foinikaria Church, which were post-processed by removing the lens distortion and then processed using the Agisoft Photoscan Professional software. The processing began with the orthomosaic production from these multiple images, which was used for the 3D model. Following the orthomosaic production, the model was exported from Agisoft into SketchFab for visualization purposes. The study found that particular areas were not well documented on the 3D model, due to an insufficient number of images in specific locations, such as the bell tower. This is evident below, where the bell tower is not clearly modeled.

Autodesk Revit software was used to generate a BIM 3D model of the church, including the bell tower (Fig. 19). The BIM model was overlaid with the point cloud (Themistocleous et al. 2016b).

The point cloud provided enough information so the structure of the building can be accurately modeled without the need of any in situ measurements. The point cloud information was especially necessary to model the roof, bell tower, arches, and openings. This provided a fast and accurate method for documenting the church. As well, the point cloud was able to capture the rough surface texture resulting of weathering (Fig. 20).

Sections of the 3D model overlaid with the point cloud. This provides detailed information regarding the exterior walls of the church and the structure of the narthex (Fig. 21).

Using the Revit software, drawings including floor plans, elevations, and sections of the church were generated (Fig. 22). A database was created to include information regarding the structure, including wall height, thickness, material, etc. This provided a valuable source of documentation of the church, for future restoration and maintenance works. Also, the documentation of the site was important to study possible expansion projects.

The elevations are also overlaid with the point cloud to provide additional information on the building, such as surface texture, color, and materials (Fig. 23).

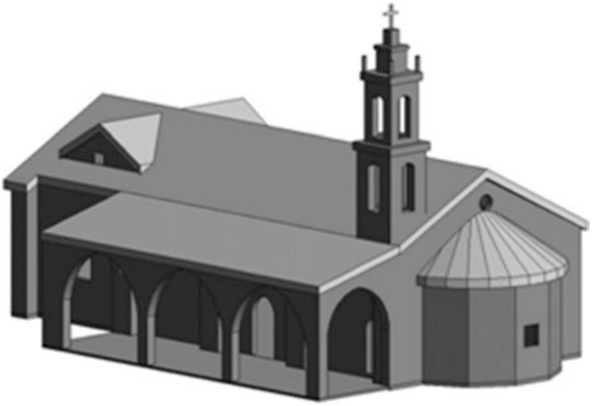

Fig. 19 BIM model of the church

Fig. 20 Left, 3D model of church; right, 3D point cloud model integrated with BIM model

Fig. 21 Point cloud section with BIM model

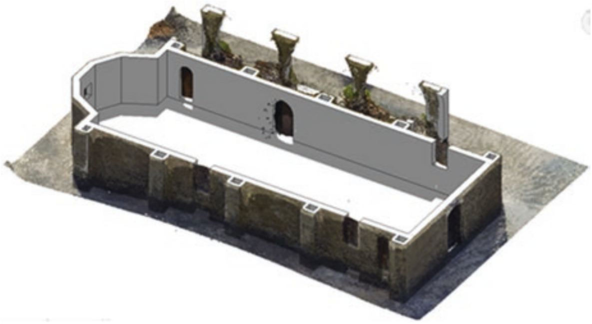

Fig. 22 Drawings of the Foinikaria church generated from BIM

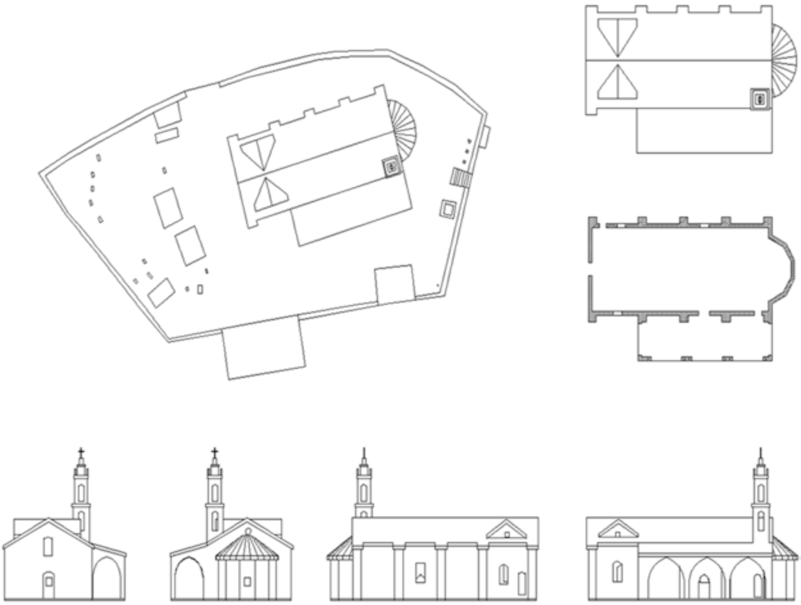

Fig. 23 Drawings of plans and elevations extracted from the BIM model

Choirokoitia Case Study

The Neolithic settlement of Choirokoitia is one of the most important prehistoric sites in the Eastern Mediterranean (UNESCO 2016). Included in the UNESCO World Cultural Heritage list since 1988, Choirokoitia is one of the best preserved Neolithic settlements in Cyprus and the Eastern Mediterranean. Occupied from the seventh to the fifth millennium BC, the site was officially abandoned in the fourth millennium BC for unknown reasons (UNESCO). Under the PROTHEGO project, which monitors and documents UNESCO cultural heritage sites vulnerable to geo-hazards, several UAV surveys have been done of the archaeological site of Choirokoitia, near Limassol Cyprus. Choirokoitia is a UNESCO World Heritage site that is vulnerable to ground deformations; therefore, UAVs were used to document the site (Themistocleous et al. 2016c). Surveying techniques, such as total station, leveling, and Global Navigation Satellite Systems (GNSS), were used to measure the positional changes of any point on the surface at millimeter level accuracy. In order to document the Choirokoitia sites, UAV images were used to create ortho-photos, dense clouds, 3D model, and digital elevation models (Themistocleous et al. 2017). Different multi-copter UAVs with a high-resolution 20MP camera were used to acquire images over the site with fixed ground control points for geo-referencing in order to produce a photogrammetric ortho-image

Fig. 24 Inspire 2 UAV with 20mp Zenmuse X5S camera and sensors

Fig. 25 Ortho-image of Choirokoitia site 29 October 2016

and point cloud 3D model of the demonstration site and also for comparison over temporal intervals (Fig. 24).

Aerial images were taken using UAVs on 29 October 2016 and 2 February 2017. Over 450 images were taken of the Choirokoitia site on 29 October 2016, and over 460 images were taken on 2 February 2017. Ground control points (GCP) were applied to correct the scale and geo-reference the model. The images were then pre-processed by removing the lens distortion and then processed using the Agisoft Photoscan Professional software (Fig. 25). The aerial imagery obtained from the UAVs was imported into SfM software to create rapid and automated generation of a point cloud model and 3D mesh model in order to document and monitor the Choirokoitia site for geo-hazards (Themistocleous et al. 2017).

All clear images with sufficient overlap were included in the processing in order to generate a dense point cloud of the Choirokoitia site. The images taken on 2 February 2017 were able to cover more of the mountain; therefore, the Choirokoitia site is outlined for clarification. In Fig. 26 and 27, the image on the left is from the

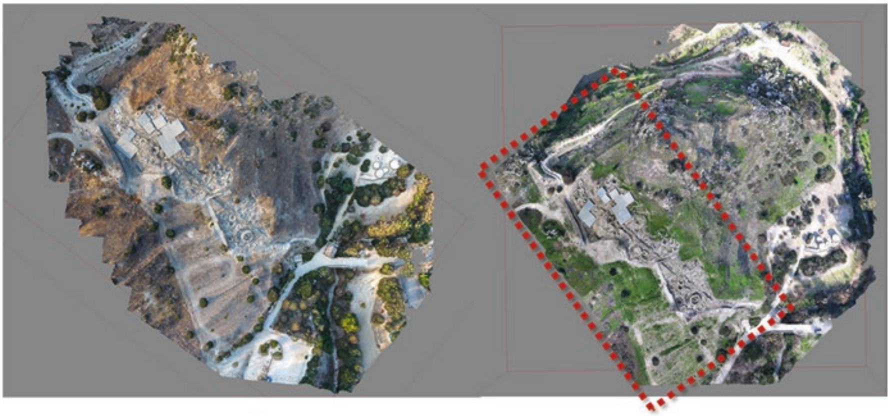

Fig. 26 Point cloud generation of Choirokoitia site

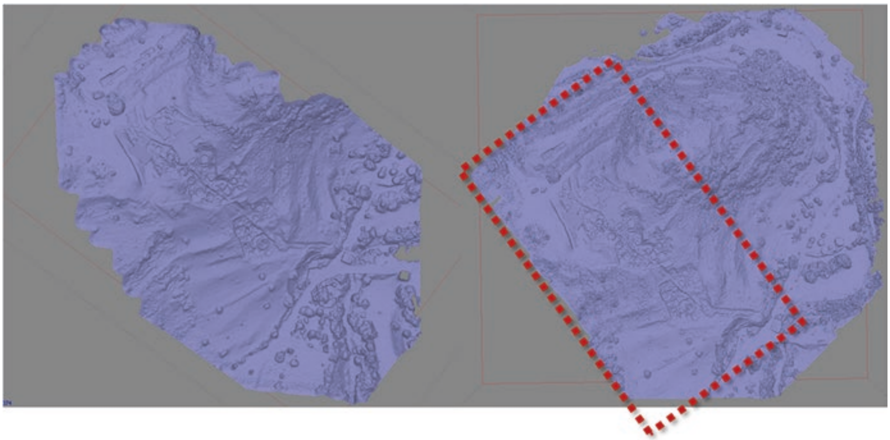

Fig. 27 3D surface model of Choirokoitia site

survey conducted on 29 October 2016, where the image on the right outlined in red is from the survey conducted on 2 February 2017.

As is evident, there was a dramatic difference in the level of vegetation present at the site on the dates that the images were acquired. The October 2016 images show sparse vegetation, while the images acquired in February 2017 show significantly more vegetation present at the site. As it was easier to identify vegetation in the images acquired in the winter campaign due to the color and morphology of the vegetation, masking was done in order to subtract the vegetation from the model in order to generate the DEM of the ground surface (Fig. 28). This was done by using interpolation of the areas where the vegetation was previously present. A contour

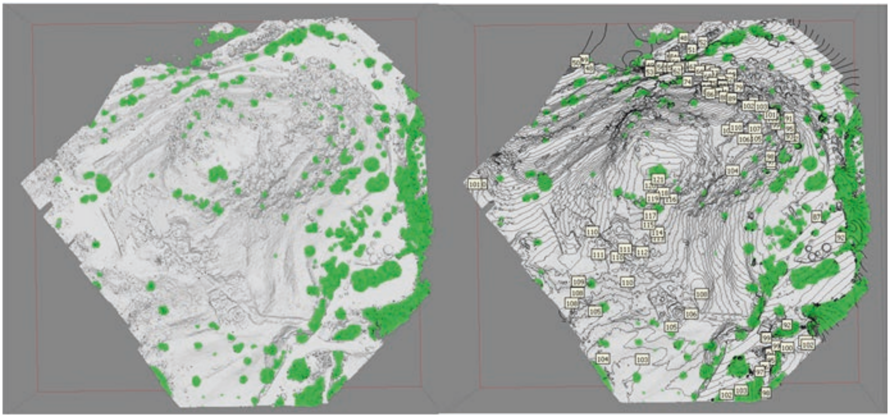

Fig. 28 Vegetation subtraction and contour generation

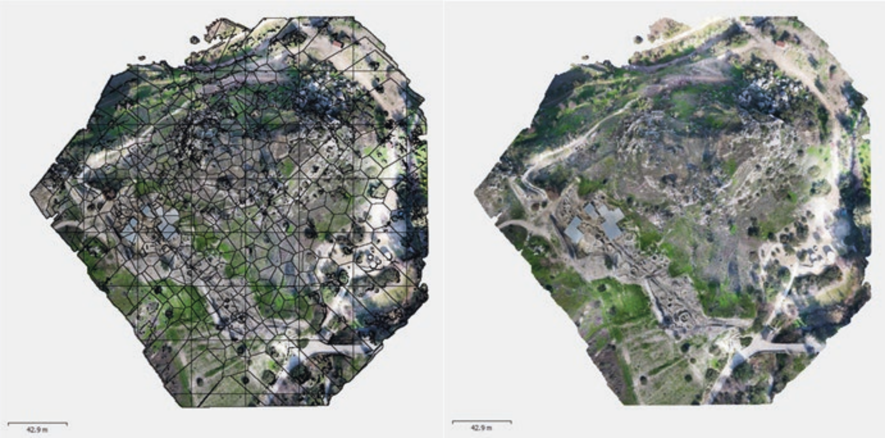

Fig. 29 Stitch imaging and ortho-generation

map of the area was then generated using stitch imaging using the DEM model without vegetation (Fig. 29).

The generated DEM model can assist in creating a simulation model to determine the rockfall patterns in the area (Fig. 30). In these types of simulations, it is important that vegetation be removed from the model in order to be more accurate using only the geological features of the landscape.

The ground-based geotechnical monitoring was also compared and validated with InSAR data to evaluate cultural heritage sites deformation trends and to understand its behavior over the last two decades.

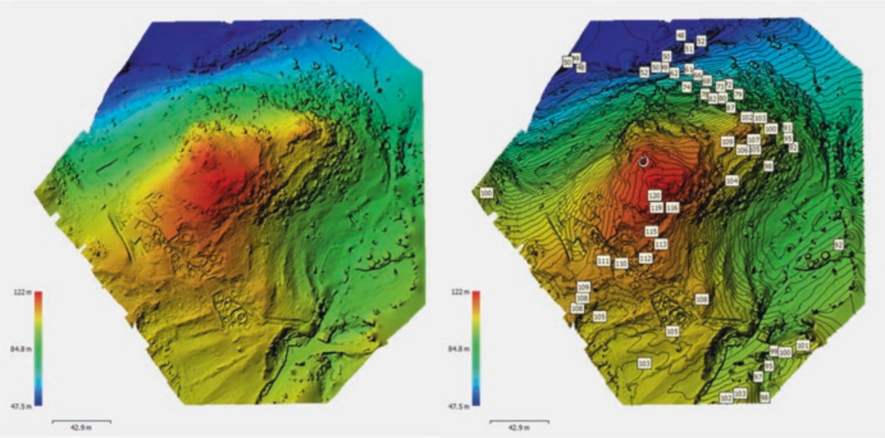

Fig. 30 Digital elevation model of Choirokoitia site

Amathus Necropolis Case Study

The ancient town of Amathus is situated on the south coast of Cyprus, about 7 km east of the town of Lemesos and dates to the Neolithic period. East and west of Amathus are two important necropolis with carved tombs which date from the Geometric to the Roman period. During the excavations of the tombs, rich archaeological material came to light, part of which is now exhibited in the Lemesos District Museum. The Department of Antiquities also focuses on the management, preservation and promotion of the archaeological site of Amathus, through the application of concrete strategies focused on securing its sustainability and development.

In cooperation with the Department of Antiquities, high-resolution digital cameras with VNIR sensors were used to document burial mounds in the Amathus archaeological site at varying elevations. The UAV survey was conducted as construction was scheduled to begin in the area; therefore, quick documentation of the archaeological site was necessary while the site was being excavated (Fig. 31). Since there was ongoing development in the area, the site was backfilled at the end of the archaeological excavation as a method of preservation and conservation. This example shows how UAVs can be important in documenting archaeological sites when documentation needs to be done in a limited time for a large area.

The aerial images in Fig. 32 were taken within a 1 month period, showing the excavations that took place on the site. Below, the image on the left shows the area at the beginning of the excavation, where the image on the right shows the area a month later, where different tombs were excavated.

At the site, there were various archaeological findings that were documented using the UAV while the site was being excavated. For example, the below image shows the documentation of a tomb that was located on the site. The UAV was able to enter into the burial chamber and document the entire structure. A 3D model was

Fig. 31 Ortho-image of the overall excavation site in Amathus, including detail of burial site

Fig. 32 Top, beginning of excavation; bottom, 1 month after the beginning of the excavation

Fig. 33 3D model of burial chamber at Amathus necropolis

created to show the capability of the UAV to provide detailed documentation of an archaeological dig, as shown in Fig. 33.

UAVs can be a valuable tool to document archaeological sites, especially when time is limited and high-resolution documentation is needed.

Conclusion

UAVs have become an extremely important tool for cultural heritage experts for the documentation and analysis of cultural heritage sites as they provide a cost-effective and efficient manner to acquire high spatial resolution data with high temporal frequencies, especially in areas that have limited coverage and are inaccessible to humans. The case studies presented in this chapter highlighted the ability of UAVs to provide high-resolution data of a cultural heritage site using a non-invasive technology and high accuracy with the use of ground control points.

The case studies examined various cultural heritage sites in Cyprus, where the high-resolution aerial imagery obtained from the UAVs was imported into Structure from Motion photogrammetry to create rapid and automated generation of a point cloud model and 3D mesh model. The high accuracy of the ortho-image and 3D model can be used to document and monitor changes of the cultural heritage sites over time. A printed 3D model can also be made of the structure. Also, the point cloud generated can be exported into BIM, in order to produce a BIM model and drawings of the structure. The high-accuracy documentation generated from the BIM model can be used for future renovation or expansion of the site.

Acknowledgment We would like to thank the ERATOSTHENES Research Centre and its staff for their invaluable assistance. Special thanks to the Department of Antiquities of Cyprus, the Cyprus Remote Sensing Society, the Cyprus Research Promotion Foundation, the Holy Bishopric of Lemesos, QuestUAV, and the Southwestern Baptist Theological Seminary. Also, the author wishes to acknowledge the Cyprus Aviation Authority (CAA) and the Sovereign Bases Area Administration (SBAA) for their assistance in providing flight permission. Finally, additional thanks to the “ATHENA” project H2020-TWINN2015 of the European Commission, No. 691936, the “PROTection of European Cultural HEritage from GeO - hazards (PROTHEGO)” project JPICH HERITAGE PLUS/0314/36 and the Cultural Landscape risk Identification, Management and Assessment (CLIMA) project, JPICH HERITAGE PLUS/0314/07.

References

Agapiou A, Cuca B, Themistocleous K, Alexakis DD, Hadjimitsis DG (2013) Integrated method for tracking changes in archeo-landscapes using remote and close-range technologies. Proceedings of the International Congress of Digital Heritage, 28 October–01 November, 2013, Marseille, France, 2013. Doi: https://doi.org/10.1109/DigitalHeritage.2013.6743740

Brown DC (1966) Decentering distortion of lenses. Photometr Eng 32(3):444–462

Brumana R, Oreni D, Van Hecke L, Barazzetti L, Previtali M, Roncoroni F, Valente R (2013) Combined geometric and thermal analysis from UAV platforms for archaeological heritage documentation. ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences, Volume II-5/W1, XXIV Int. CIPA Symposium, Sept. 2–6, Strasbourg, France, pp. 49–54

Burkhart A, Cogliati S, Schickling A, Rascher U (2014) A novel UAV-based ultra-light weight spectrometer for field spectroscopy. Sensors J IEEE 14(1):62–67

Cho G, Hildebrand A, Claussen J, Cosyn P, Morris S (2013) Pilotless aerial vehicle systems: size, scale and functions. Coordinates 9:8–16

Colomina I, Molina P (2014) Unmanned aerial systems for photogrammetry and remote sensing: a review. ISPRS J Photogramm Remote Sens 92:79–97

Eisenbeiss H (2009) UAV Photogrammetry, Ph.D. Thesis. Institute fur Geodesie und Photogrammetrie, ETH-Zurch. Zurich, Switzerland

El-Hakim SF, Beraldin JA, Picard M, Godin G (2004) Detailed 3D reconstruction of large-scale heritage sites with integrated techniques. IEEE Comput Graph Appl 24(3):21–29

Everaerts J (2008) The use of Unmanned Aerial Vehicles (UAVS) for remote sensing and mapping. IAPRS SIS 37:B11187–B11192

Fiorillo F, Jimenez B, Remondino F, Barba S (2012) 3D surveying and modeling of the archaeological area of Paestum, Italy. Virtual Archaeol Rev 4:55–60

Giuliano MG (2014) Cultural Heritage: an example of graphical documentation with automated photogrammetric systems. International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences XL.5: 251–255. Gottingen: Copernicus GmbH. 2014

Gruen A, Remondino F, Zhang L (2005) The Bamiyan project: multi-resolution image-based modeling. In: Baltsavias E, Gruen A, Van Gool L, Pateraki M (eds) Recording, modeling and visualization of cultural heritage. Taylor and Francis, Balkema. ISBN 0 415 39208 X, 45–54

Guidi G, Remondino F, Russo M, Menna F, Rizzi A, Ercoli S (2009) A multi-resolution methodology for the 3D modeling of large and complex archaeological areas. Int J Archit Comput 7(1):40–55

Hassani F (2015) Documentation of cultural heritage techniques, potentials and constraints. International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, Volume XL-5/W7, 25th Intl CIPA Symp. 2015, 31 August – 04 September 2015, Taipei, Taiwan

Ingwer P, Gassen F, Püst S, Duhn M, Schälicke M, Müller K, Ruhm H, Rettig J, Hasche E, Fischer A, Creutzburg R (2015) Practical usefulness of structure from motion (SfM) point clouds obtained from different consumer cameras. Proceedings of SPIE 9411, Mobile Devices and Multimedia: Enabling Technologies, Algorithms, and Applications 2015, 941102

Ioannides M, Hadjiprocopis A, Doulamis N, Doulamis A, Protopapadakis E, Makantasis K, Santos P, Fellner D, Stork A, Balet O, Julien M, Weinlinger G, Johnson PS, Klein M, Fritsch D (2013) Online 4D reconstruction using multi-images available under open access. ISPRS Annals of Photogrammetry, Remote Sensing and Spatial Information Sciences II-5/W1(2013):169–174

Kostrzewa J, Meyer W, Laband S, Tere W, Petrovich P, Swanson K, Sundra C, Sener W, Wilmott J (2003) Infrared microsensory pay-load for miniature unmanned aerial vehicles. Proceedings of the SPIE 5090, Unattended Ground Sensor Technologies and Applications, v265

Lo Brutto M, Garraffa A, Meli P (2014) UAV platforms for cultural heritage survey: first results. ISPRS Annals Photogramm Remote Sens Spat Inf Sci II-5(2014):227–234

Mayr W (2013) Unmanned aerial systems -for the rest of us. Proceedings of the 53rd Pho togrammetric Week. Institute fur Photo-grammetrie, Universitat Stuttgart, 125–134

Meszaros J (2011) Aerial surveying UAV based on open-source hardware and software. Proceedings of the International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, XXXVIII-1/C22

Petrie G (2013) Commercial operation of lightweight UAVs for aerial imaging and mapping. GEOInformatics 16:28–39

Remondino F, Rizzi A (2009) Reality-based 3D documentation of world heritage sites: methodologies, problems and examples. Proceedings of the 22nd CIPA symposium, October 11–15, 2009, Kyoto, Japan

Remondino F, Barazzetti L, Nex F, Caioni M, Sarazi D (2011) UAV photogrammetry for mapping and 3D modelling-current status and future perspectives. Proceedings of the International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, 25–31

Rinaudo F, Chiabrando F, Lingua A, Span A (2012) Archaeological site monitoring: UAV photogrammetry can be an answer. Proceedings of the International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences Volume XXXIX-B5, 2012XXII ISPRS Congress, 25 August–01 September 2012, Melbourne, Australia,. 583–588

Rönnholm P, Honkavaara E, Litkey P, Hyyppä H, Hyyppä J (2007) Integration of laser scanning and photogrammetry. Int Arch Photogramm Remote Sens Spat Inf Sci 36(3/W52):355–362

Ruffino G, Moccia A (2005). Integrated VIS_NIR Hyperspectral/thermal-IR Electro-optical Payload System for a Mini-UAV. American Institute of Aeronautics and Astronautics, 647–664

Scholtz A, Kaschwich C, Kruger A, Kufieta K, Schnetter P, Wilkens C, Kruger T, Vorsmann P (2011) Development of a new multipurpose UAS for scientific application. Proceedings of the International Conference on Unmanned Aerial Vehicle in Geomatics (UAV-g), Zurich, Switzerland, September 14–16, 2011,ISSN 1682–1777 Vol XXXVIII-1/C22

Scopigno R, Cignoni P, Pietroni N, Callieri M, Dellepiane M (2015) Digital fabrication Technologies for Cultural Heritage (STAR). EUROGRAPHICS Workshops on Graphics and Cultural Heritage. doi:https://doi.org/10.1117/12.2074892

Seitz C, Altenbach H (2011) Project ArchEye - the quadracopter as the archaeologist's eye. Proceedings of the International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, XXXVIII-1/C22, 297–302

Themistocleous K, Agapiou A, King HM, King N, Hadjimitsis DG (2014a) More than a flight: the extensive contributions of UAV flights to archaeological research - the case study of curium site in Cyprus. Proceedings of the Progress in Cultural Heritage: Documentation, Preservation, and Protection. 5th International Conference, EuroMed 2014, Limassol, Cyprus. Springer LNCS 8740, EuroMed2014 Conference, 396–409

Themistocleous K, Agapiou A, Cuca B, Hadjimitsis DG (2014b) 3D Documentation Of Cultural Heritage Sites. Proceedings of the Progress in Cultural Heritage: Documentation, Preservation, and Protection. 5th International Conference, EuroMed 2014, Limassol, Cyprus, Springer LNCS 8740, EuroMed2014 Conference

Themistocleous K, Agapiou A, Alexakis D, Cuca B, Hadjimitsis DG (2014c) Lessons learnt from using UAVs in Cyprus: landscapes applications. Proceedings of the Archland UAV Conference 2014, 23–25 May, Berlin, Germany, 2014

Themistocleous K, Agapiou A, Cuca B, Hadjimitsis DG (2015a) Unmanned aerial systems and spectroscopy for remote sensing applications in archaeology. Proceedings of the 36th

International Symposium on Remote Sensing of Environment (ISRSE-36), 11–15 May, 2015, Berlin Germany

Themistocleous K, Agapiou A, Lysandrou V, Hadjimitsis DG (2015b). The use of UAVs for remote sensing applications: case studies in Cyprus. Proceedings of the SPIE Remote Sensing Conference, 21–24 September, 2015, Toulouse, France

Themistocleous K, Ioannides M, Agapiou A, Hadjimitsis DG (2015c). The methodology of documenting cultural heritage sites using photogrammetry, UAV and 3D printing techniques: the case study of Asinou church in Cyprus. Proceedings of the Third International Conference on Remote Sensing and Geoinformation of Environment, 2015, 16-19 March, 2015

Themistocleous K, Agapiou A, Hadjimitsis DG (2016a) Experiencing cultural heritage sites using 3D modeling for the visually impaired. Proceedings of Euromed 2016: Digital Heritage, Progress in Cultural Heritage: Documentation, Preservation, and Protection, Lecture Notes in Computer Science, Vol. 10059, 171–177, 31 October – 4 November, 2016 Nicosia Cyprus

Themistocleous K, Agapiou A, Hadjimitsis DG (2016b) 3D documentation and BIM modeling of cultural heritage structures using UAVS: the case of the Foinikaria church. Proceedings of the 3D Geoinfo Conference, International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, Volume XLII-2/W2, 2016 11th, 20–21 October 2016, Athens, Greece

Themistocleous K, Agapiou A, Cuca B, Danezis C, Cigna F, Margottini C, Spizzichino D (2016c) Methodology for locale-scale monitoring for the PROTHEGO project: the Choirokoitia case study. Proceedings of SPIE 10005, Earth Resources and Environmental Remote Sensing/GIS Applications VII, 100050M, 26–29 September, 2016, Edinburgh, Scotland. doi:https://doi.org/10.1117/12.2242047

Themistocleous K, Danezis C, Mendonidis E, Lymperopoulou E (2017) Monitoring ground deformation of cultural heritage sites using UAVs and geodetic techniques: the case study of Choirokoitia, JPI PROTHEGO project. SPIE Remote Sensing Conference, 11–14 September, 2017. Warsaw, Poland

UNESCO World Heritage List “Choirokoitia”. http://whc.unesco.org/en/list/848. (1 March, 2016)

UNESCO World Heritage List “Paphos”. http://whc.unesco.org/en/list/79. (20 August, 2017)