Unmanned Aerial Vehicles (UAVs) for Documenting and Interpreting Historical Archaeological Sites: Part II—Return of the Drones

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ABSTRACT

Unmanned Aerial Vehicles (UAVs), or "drones" as they have come to be known, are now widely popular in many countries around the world. The newest versions are affordable, easily controlled, and can provide a very useful platform for aerial imagery, videography, and photogrammetry at archaeological sites. They have particularly useful applications at historical sites with standing architecture or surface features, and can help reveal structural layouts and details not visible from the ground. Part I of this discussion covered how to get started with a UAV for archaeology, the legal issues, the nature and costs of the equipment, flight control, and the pitfalls to be avoided. Part II covers the primary applications for archaeology (particularly historical archaeology), some of the important attributes of digital cameras, aerial imaging, postprocessing of such data, and the potential future applications of UAV-based techniques.

Applications for Archaeology

In 2014 a first-of-its-kind conference was sponsored by the Topoi Excellence Cluster at the Frei Universität Berlin, the EU-funded ArchaeoLandscapes Europe Project (Frankfurt), and the Institute for Mediterranean Studies of the Foundation for Research and Technology Hellas (IMS–FORTH) in Rethymno/Crete, Greece. Entitled "The Conference on Applications of Unmanned Aircraft in Archaeology and Historic Preservation," its aims were for experts and users of UAV technology "to exchange experiences, establish contacts and to obtain knowledge and know-how from first hands" (Frei Universität Berlin 2014). The formal sessions took place in Berlin in May 2014, and the presenters shared their experiences of using UAVs (some of them for over nearly a decade)—the successes they have had and the problems they have encountered. The objectives discussed were almost entirely in the area of acquiring low altitude aerial imagery and photogrammetry.

Low Altitude Aerial Imagery

Aerial imagery has long been used in archaeology to get an overhead view of excavation trenches, structures, and to situate sites within the visual, physical, or even astronomical landscape. In the past this has entailed mounting single lens reflex (SLR) cameras on long poles, using cherry pickers or other utility vehicles with extendable platforms, or flying hot-air or helium balloons, kites, or in some well-funded projects, helicopters. Online imagery providers such as Google® Earth, Microsoft® Bing, or Nearmap® have dramatically improved the availability of high and medium altitude aircraft or satellite-gathered photos. But very high resolution, low altitude imagery still often needs to be acquired on a project-specific basis. Today, UAVs mounted with digital SLRs (DSLR) or lightweight fixed-lens digital cameras such as GoPro® have been added to that wide range of techniques.

Each low altitude method has its drawbacks. Pole-mounted photography is a very difficult technique by which to capture any area larger than an excavation trench. When dealing with historical archaeological sites it can be quite impractical to photograph the foundations of large buildings, and standing walls will often screen areas from view. Cherry pickers or extendible-arm utility vehicles can be problematic to move or park on-site, they can be quite expensive to rent, and can very easily damage structural remains. Kites or balloons are perhaps somewhat more practical, but they can only be used in either high- or low-wind situations, respectively, and it may be difficult to acquire oblique views from multiple angles or direct overhead views since they are subject to the prevailing wind direction. Using UAVs on a project may offer somewhat more flexibility across different site types, sizes of area to be covered, and in most weather conditions.

There are several attributes of aerial imagery that archaeologists must familiarize themselves with in order to make the most of it. First, the resolution of the image is of primary importance. Most high altitude aerial imagery generated by satellite is on the order of 1+ m in ground sample distance (GSD). This means that one pixel (i.e., the minimum digital data unit) of the image represents an area of 1 m or more on the ground, regardless of the print size, or number or pixels, of the digital image itself. Many municipal areas or state/federal governments worldwide now provide higher GSD aerial imagery (often for free)—as low as 10 cm or so (i.e., one pixel equals 10 cm on the ground). Each pixel can have only one color in the image, so the purpose of getting lower altitude imagery is to get a finer resolution, where it may be possible to pick out artifacts, features, or structural remains in the image.

With fixed-lens digital and DSLR cameras the image size, shape, and pixel count will be set, so the GSD resolution will change depending on the altitude at which the image is taken. Pixel resolution itself is measured by the number of horizontal and vertical lines in the image. There are a set of standard resolutions most frequently encountered when working with digital imagery, and they may be referred to by names that represent specific configurations or a count of the megapixels (i.e., the horizontal pixel count multiplied by the vertical pixel count and then divided by 1,000,000). For publications, however, the print size of the image and the dots per inch (dpi) are frequently needed, along with the aspect ratio or the ratio of width to height (i.e., the image shape). These are entirely adjustable with photo-editing software but do not change the original resolution, or GSD, at which the image was captured. Figure 1 lists some standard image resolutions, sizes, and shapes.

Lens distortion is a significant component of any imagery and is a function of the focal length (FL) and field of view (FOV). The FL is the distance at which light rays converge and focus is achieved, and is measured in millimeters. The FOV describes the area over which the lens captures light, and is measured in degrees. A longer FL means a narrower FOV. A fisheye lens captures a full 180º in its FOV and will generally have an FL of 4–6 mm. Wide angle lenses typically range between 80–120º FOV, and 12–25 mm FL. Telephoto lenses have a high FL (>85 mm) and a narrow FOV (<30º). The wider the FOV, the greater distortion there is at the edges of the image. The digital camera uses square pixels to capture data in horizontal rows at the resolutions and aspect ratios described in Figure 1, but the FOV causes barrel distortion, which warps the light at the edges of the image, and there are fewer pixels representing a larger area, thus altering the GSD. Most image or video processing software (such as Adobe® Photoshop or Premiere Pro) has built-in tools to correct for lens distortion, but the amount of correction

Pixel Resolution					Image size at 300 dpi:		
Name	**Type**	**Width**	**Height**	**Actual MP**	**cm**	**in**	**Asp. Ratio**
VGA	Photo	640	480	0.31	5.4 × 4.1	2.1 × 1.6	4:3
VHS, DVD	Video	720	480	0.35	6.1 × 4.1	2.4 × 1.6	3:2
XGA	Photo	1152	864	1.00	9.8 × 7.3	3.8 × 2.9	4:3
720p, HD DVD	Video	1280	720	0.92	10.8 × 6.1	4.3 × 2.4	16:9
Blu-ray	Video	1280	720	0.92	10.8 × 6.1	4.3 × 2.4	3:2
960p	Video	1280	960	1.23	10.8 × 8.1	4.3 × 3.2	4:3
2MP	Photo	1600	1200	1.92	13.5 × 10.2	5.3 × 4	4:3
1080p	Video	1920	1080	2.07	16.3 × 9.1	6.4 × 3.6	16:9
1440p (GoPro max)	Video	1920	1440	2.76	16.3 × 12.2	6.4 × 4.8	4:3
3MP	Photo	2048	1536	3.15	17.3 × 13	6.8 × 5.1	4:3
35mm Film	Photo	2300	1525	3.51	19.5 × 12.9	7.7 × 5.1	3:2
4MP	Photo	2400	1600	3.84	20.3 × 13.5	8 × 5.3	3:2
5MP	Photo	2624	1968	5.16	22.2 × 16.7	8.7 × 6.6	4:3
2.7K	Video	2704	1520	4.11	22.9 × 12.9	9 × 5.1	16:9
2.7K 4:3	Video	2704	2028	5.48	22.9 × 17.2	9 × 6.8	4:3
6MP	Photo	3000	2000	6.00	25.4 × 16.9	10 × 6.7	3:2
7MP	Photo	3072	2304	7.08	26 × 19.5	10.2 × 7.7	4:3
8MP, Smartphone (avg)	Photo	3600	2400	8.64	30.5 × 20.3	12 × 8	3:2
10MP	Photo	3680	2760	10.16	31.2 × 23.4	12.3 × 9.2	4:3
4K, UHDTV	Video	3840	2160	8.29	32.5 × 18.3	12.8 × 7.2	16:9
12MP (GoPro max)	Photo	4200	2800	11.76	35.6 × 23.7	14 × 9.3	3:2
8K, UHDTV	Video	7680	4320	33.18	65 × 36.6	25.6 × 14.4	3:2
Smartphone (max)	Photo	7728	5368	41.48	65.4 × 45.4	25.8 × 17.9	4:3
Digital IMAX	Video	10000	7000	70.00	84.7 × 59.3	33.3 × 23.3	4:3
DSLR (max)	Photo	10320	7752	80.00	87.4 × 65.6	34.4 × 25.8	4:3
16K, Digital Cinema	Video	15360	8640	132.71	130 × 73.2	51.2 × 28.8	3:2
Film IMAX	Video	18000	7500	135.00	152.4 × 63.5	60 × 25	2.4:1
Human Eye (approx.)	-	25800	22300	576.00	218.4 × 188.8	86 × 74.3	1.15:1

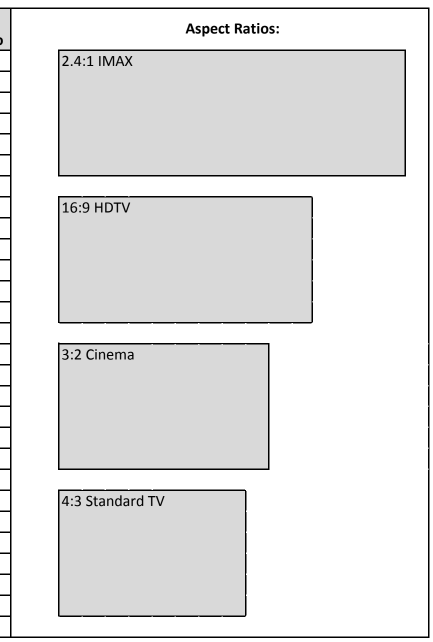

Figure 1. Standard photo/video resolutions, sizes, and shapes. (Graphic by author, 2015.)

needed will depend on the altitude at which the image or video was taken. Figure 2 shows the standard FOVs and relative amounts of distortion for a GoPro Hero 3+ at both 4:3 and 16:9 aspect ratios.

Illustrated in Figure 3 is a UAV-captured overhead aerial image of the abandoned Waddington Roadhouse outside of New Norcia, Western Australia, taken at an elevation of approximately 13 m. Figure 4 shows the same structure in a west-facing oblique angle from closer to 32 m in elevation. Both images were made with a GoPro Hero 3+ Silver mounted on a DJI® F550 hexacopter (the UAV configuration illustrated in Part I of this discussion). Each of these images was extracted from a video taken at 1080p and shot in medium angle exposure. Their pixel resolution is 2.07MP, or 1920 pixels wide by 1080 pixels high. For Figure 3, the GSD resolution is approximately 1 cm near the center of the image but increases to approximately 3 cm toward the edges because of the lens distortion. For Figure 4, the GSD is 4 cm in the foreground and as much as 15 cm in the background due not only to the lens distortion but also the oblique angle of the camera (approximately 40º from vertical). Understanding both the pixel resolution and the GSD is important in order to identify the size and location of features visible in aerial imagery.

Apart from the cost, considering the nature of the site and the desired outcomes is extremely important before choosing a specific method of acquiring aerial imagery. Employing several techniques and generating different kinds of media is often a useful approach. For example, fixed-lens digital cameras now typically provide high resolution video as well as single frame images, or multiframe shutter bursts. With archaeological sites it is often easiest to acquire aerial video or shutter bursts of the site and then search for and extract the best frames for printing or publication. If the resolution is high enough and the lens distortion corrected for, then it is possible to extract a sequence of frames from video for photogrammetry.

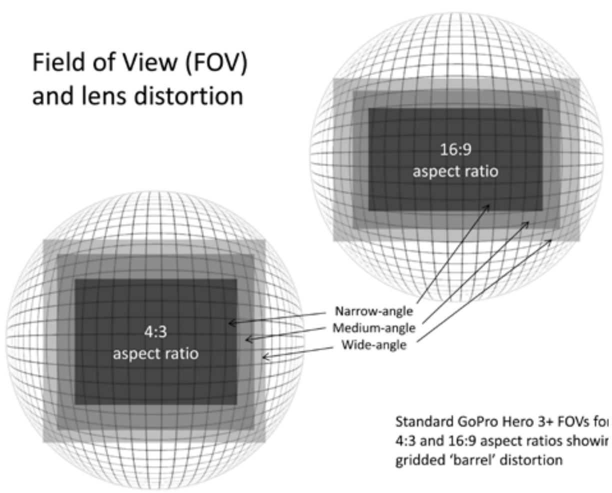

Figure 2. FOV and lens distortion for standard GoPro Hero 3+ lens settings. (Graphic by author, 2015.)

Figure 3. Waddington Roadhouse, Western Australia, from above. (Photo by author, 2015.)

Figure 4. Waddington Roadhouse, oblique angle. (Photo by author, 2015.)

Photogrammetry

Photogrammetry is the practice of calculating elevation (or a Z coordinate) from overlapping photographs. This technique began with analog aerial images as far back as the mid-19th century and was particularly popular during World War II as a method for deriving topographic maps from stereophotographs (paired images taken from dual-mounted cameras). The paired images were situated in their correct X and Y positions and then elevation was calculated by knowing the offset distance between the two camera lenses and using triangulation to common points. By employing lenses, masks, and other analog devices, it was possible to accurately hand draw each elevation contour. Nearly all topographic maps in use today were generated at least partially by stereophoto pair matching in the past. Today, this technique is automated using digital methods.

Specialized photogrammetry software has been developed recently that can automatically rectify and georeference overlapping images and construct a dense point cloud: a digital file consisting of millions of points with X, Y, and Z coordinates. This is a technique known as structure from motion (SFM) and is based on a principle similar to matched stereophotos. Rather than knowing the fixed distance between the lenses, it uses mathematics and digital pattern recognition to calculate the distance/direction of motion between the images and triangulate the surface points. The point cloud generated by SFM can be exported to other software to create a three-dimensional (3-D) mesh, or surface model, by connecting continuous sets of each three neighboring points. A mesh can then be imported into GIS software or 3-D modeling/animation programs for further handling.

In the past photogrammetry required placing visible markers at strategic locations on the ground and manually tagging them in the photographs—a very tedious process. Although large-scale photogrammetry is still best done by fixed-wing UAVs on a preprogrammed flight path, it is now very easy (though processing-intensive) to create 3-D models of standing structures at historical archaeological sites from multirotor UAV imagery, often coupling them with photographs taken on the ground. There is a wide range of SFM software available, and much of it is shareware or a free service (Table 1).

Figure 5 shows a dense point cloud model of the Waddington Roadhouse generated from still images captured from the same overhead video that produced

Table 1. List of Currently Available SFM Software.

Name	Platform	Developer	Cost	Website
123D Catch	Web-based (iOS/Android)	Autodesk	Free	http://www.123dapp.com/catch
3DF Zephyr	Windows	3DFLOW	$3,200	http://www.3dflow.net/3df-zephyr-pro-3d-models-from-photos/
ARC3D	Web-based	KU Leuven	Free	http://www.arc3d.be/
Australis	Windows	Photometrix	$10,100	http://www.photometrix.com.au/?page_id=19
Bundler	Windows/Linux	Noah Snavely	Free	http://www.cs.cornell.edu/~snavely/bundler/
Correlator3D	Windows	SimActive Inc.	price on request	http://www.simactive.com/
DroneMapper	Web-based	DroneMapper	$20 per km2	http://dronemapper.com/
EnsoMOSAIC	Windows	MosaicMill	$900	http://www.mosaicmill.com/
INPHO	Windows	Trimble	price on request	http://www.trimble.com/
iWitness/iWitnessPRO	Windows	Photometrix	$995–$1,995	http://www.photometrix.com.au/
Linearis3D	Windows	Linearis3D	$1,000+	http://www.linearis3d.de/
Mementify	Web-based (iOS)	XLAB	Free	http://mementify.com/
My3DScanner	Web-based	My3DScanner	Free	http://www.my3dscanner.com/
PC-Rect	Windows	DSD	$2,000–$3,000	http://www.dsd.at/
PHOTOMOD 6.0	Windows	Racurs	price on request	http://racurs.ru/
PhotoModeler	Windows	Eos Systems	$1,145	http://www.photomodeler.com/
PhotoScan	Windows/Linux/ OS X	Agisoft	$179–$3,499	http://www.agisoft.ru/
PHOV	Web-based	XLAB	Free	http://phov.eu/
Pix4Dmapper	Windows & Web-based	Pix4D SA	price on request	http://www.pix4d.com/
RealityCapture	Windows	Capturing Reality	price on request	http://www.capturingreality.com/
Smart3DCapture	Windows	ACUTE3D	$3,250+	http://www.acute3d.com/
UASMaster	Windows	Trimble	price on request	http://www.trimble.com/
VI3DIM	Windows	Vi3Dim	$20–$395	http://www.vi3dim.com/
VisualSFM	Windows/Linux/ OS X	Changchang Wu	Free	http://ccwu.me/vsfm/

Figure 3 and displayed in the CloudCompare® interface. This model consists of over 10 million data points and produced a .ply (polygon file format) export file in excess of 263 megabytes. The software used to generate the model was Agisoft® PhotoScan, and the total time to process was approximately 32 hours on a Dell® XPS laptop running 8GB of RAM with an Intel® Core i7 processor and a 2TB external hard drive. The 32 hours included the time necessary to align the photos and generate the ultradense point cloud. It did not include the subsequent mesh that was generated and exported to the GIS.

In this case, approximately 105 seconds of video (1.75 minutes) was cropped from the longer 4.5-minute flight to include just the portion where the UAV passed over the structures at an altitude between 10 m and 30 m above the ground. Those elevations were chosen to keep the GSD between 1 cm and 2 cm. At 30 frames per second, all of the individual frames were extracted from the video as .jpg files, producing 31,500 separate still images using Adobe Premiere Pro CC 2014. Every 10th frame (315 total images) was then selected to build the 3-D model. The final mesh was exported to Meshlab® modeling software for editing and then eventually into ESRI® ArcGIS 10.2.

Photogrammetry models are extremely useful for creating immersive interpretations, for calculating volumetrics or other analyses, and for identifying subtle structural elements or ground surface irregularities. It is becoming more commonly a tool useful to many aspects of historical archaeological research. The models may also be integrated with 3-D graphics software such as Autodesk® 3DS Max or Google Sketchup. In this way one can develop models of what remains from the photogrammetry integrated with interpretations for what the original structures may have looked like in the past. Photogrammetry models can also be integrated with more immersive software such as

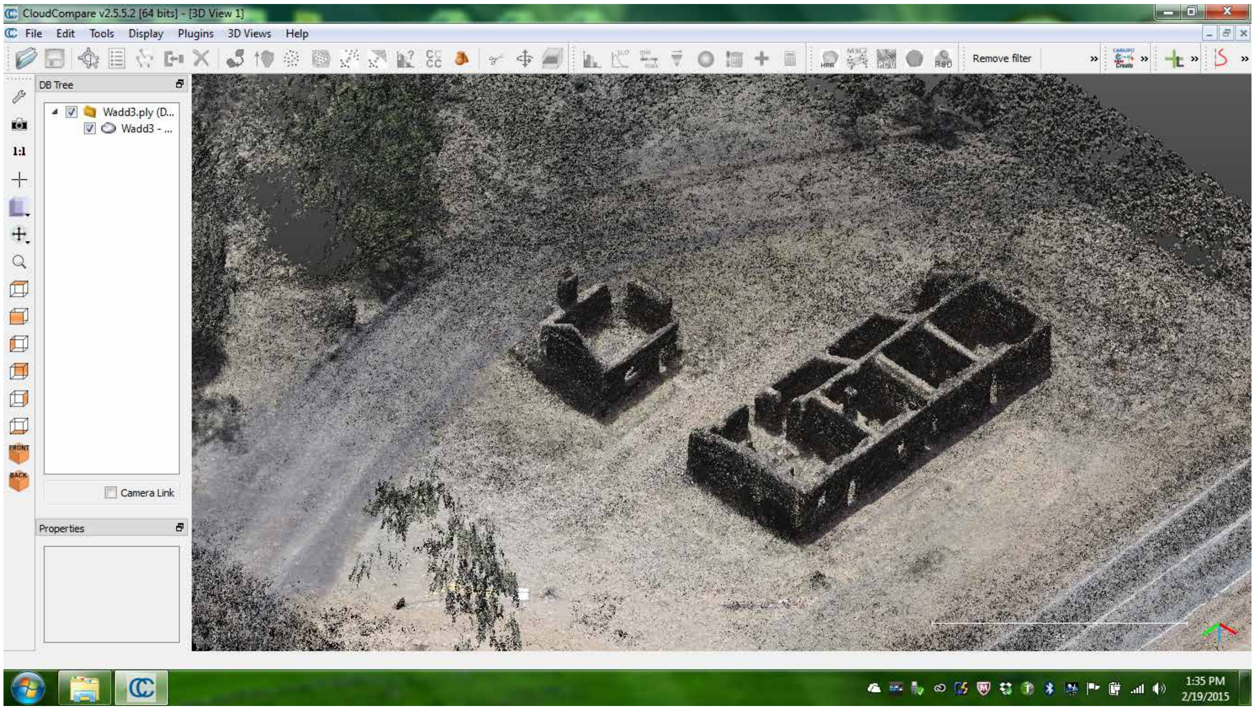

Figure 5. Dense point cloud 3-D model of Waddington Roadhouse. (Graphic by author, 2015.)

Autodesk Maya and Unity3D® to develop animations and interactive environments.

Historical archaeological sites with standing structures are particularly suitable for photogrammetry because they are often very large, have many remains that are difficult to digitize directly with methods such as a total station or handheld differentially corrected GPS (DGPS) device. Again, using UAVs is perhaps the most flexible means of acquiring this large-scale data when lens distortion, camera vibration, and image stabilization can be accomplished. Of particular concern when using aerial imagery for photogrammetry, however, is that overhead and oblique angles will allow excellent data sampling of surfaces parallel to the camera lens (such as the ground or a roof), but much less so when those surfaces are perpendicular to the lens (such as standing walls). As a result, the bases of the walls in the Waddington Roadhouse model illustrated in Figure 5 are much less accurate than the ground surface or the tops of the walls and chimneys. A solution to this is to couple ground-based photographs taken parallel to the standing walls with overhead and oblique aerial imagery when compiling a photogrammetry model.

The Future of UAV Technology

Low altitude data capture from UAVs is not strictly limited to conventional imagery. Currently there are color infrared (CIR), near-infrared (NIR), and forward-looking infrared (FLIR) cameras available for UAVs such as the Flir® Tau 640 (FLIR Systems 2015). There are also ultraviolet (UV) and hyperspectral (HS) cameras such as the Rikola® HS that are also UAV-mountable (Rikola Ltd. 2015). These devices do not necessarily have the highest resolution one might expect from the visible spectrum cameras, but they do allow other ways in which to remotely sense archaeological sites and other locations (Themistocleous 2014).

Light detection and ranging (LiDAR) is another technique for capturing surface topography by conventional aircraft. Recently, lightweight UAV-mountable LiDAR scanners have become available (Riegl Systems 2015). Such applications may give archaeologists the ability to actively control and acquire high resolution digital topographies while in the field. The limitations of airborne LiDAR are a function of platform stability and density of the scans. The more stable the platform and the higher the scan rate, the more accurate the topographic model. The higher the scan rate, however, the higher the price and the devices still suffer from the same parallel/perpendicular data sampling problems as photogrammetry. Identifying the purpose and need for LiDAR data should always precede its use, and it may not be the solution one might always need.

Other digital techniques such as ground-penetrating radar (GPR) and electromagnetic induction (EMI) technologies are now also being carried out using UAVs (Lin et al. 2011; Altdorff et al. 2014). And in the most ironic twist to the future of UAVs, we find the potential for manned multirotor craft to take over the skies (E-volo 2013) using the same RC-controlled electric motor technology as that found in most small UAVs.

There are clearly many more applications of UAV technology awaiting the archaeologists of the future. UAVs with retractable landing gear and rotor arms are becoming easier to transport, yet still maintain a fair rate of stability (e.g., AirDroids Inc. 2015). Waterproof UAVs are also becoming available, making it much less risky to fly them over lakes or the open ocean (e.g., AquaCopters Inc. 2015; QuadH2O Multirotors 2015).

Conclusions

In this day and age we have come to accept rapid technological advances in archaeological methods and techniques. Staying on top of the latest trends can be a daunting task, and one can never be sure of how much practical advantage any given technology is actually providing. Digital recording of sites with handheld GPS units was largely unknown even a scant 15 years ago (especially during the dark times of selective availability), and total station training is now a part of nearly every archaeological field school. Today, archaeologists are acquiring mastery of newer technologies, and we may find that very soon using a UAV at an archaeological site will be as commonplace as using a total station.

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