Unmanned Aerial Vehicle Photography: Exploring the Medieval City of Merv, on the Silk Roads of Central Asia

Tim Williams*

The Ancient Merv Project is a collaboration between the Turkmenistan Ministry of Culture, the Ancient Merv State Park and the UCL Institute of Archaeology. It aims to research, protect and conserve the remains of one of the great historic cities of the Silk Roads. This paper explores a new survey of the Islamic city using an Unmanned Aerial Vehicle to take comprehensive and systematic vertical photographs to assist in the analysis of the medieval cityscape. The background to the research and the application of the technology are presented, together with our initial conclusions.

The first city at Merv was constructed in the 6th century BCE, probably as part of the expansion into the region of the Persian Achaemenid Empire. Lying on one of the main branches of the ancient Silk Roads, which connected Europe and Africa to the Far East, a succession of cities flourished. By the early medieval period these encompassed over 1,000ha (**Fig. 1**). The great Islamic city of Sultan Kala, capital of the eastern Islamic world, was perhaps the third largest city in the world in the mid-12th century CE (Chase-Dunn and Willard, 1993; Chandler, 1987). Sacked by the Mongols in 1221 CE, it never recovered, by-passed by the changing patterns of world trade; while later cities developed nearby, the medieval city had little subsequent disturbance.

What this has left us is one of the greatest urban archaeological sites of the world. With between 4–17m of complex archaeological stratigraphy, uninterrupted over the 1,000ha,

there are upwards of 50 million cubic metres of archaeological deposits. These start almost immediately below the surface, with stunning preservation, particularly of the 10th- to 13th-century phase of the city (**Fig. 2**). Today, however, little is visible on the surface, but there is a legible medieval urban landscape – not from the ground, but from the air (see below).

One of the aims of the Ancient Merv project is to produce an *Atlas of Islamic Merv*, an interpretation of the city of Sultan Kala and its suburbs from about the 8th-13th centuries CE (Williams, 2007a). Characterising and understanding the spatial organisation of early Islamic cities represents a major challenge for archaeologists and historians, especially as many of the medieval cities of the Islamic world are buried by later urban communities, leaving us to extrapolate from much later urban forms. Merv offers a rare opportunity to explore the nature of an early Islamic city, especially its flourishing under the Seljuks (cf. the scale and clarity of the material from Samarra, over a much shorter period: Northedge, 2005; forthcoming). This part of the project

* UCL Institute of Archaeology,
London WC1H 0PY, United Kingdom
tim.d.williams@ucl.ac.uk
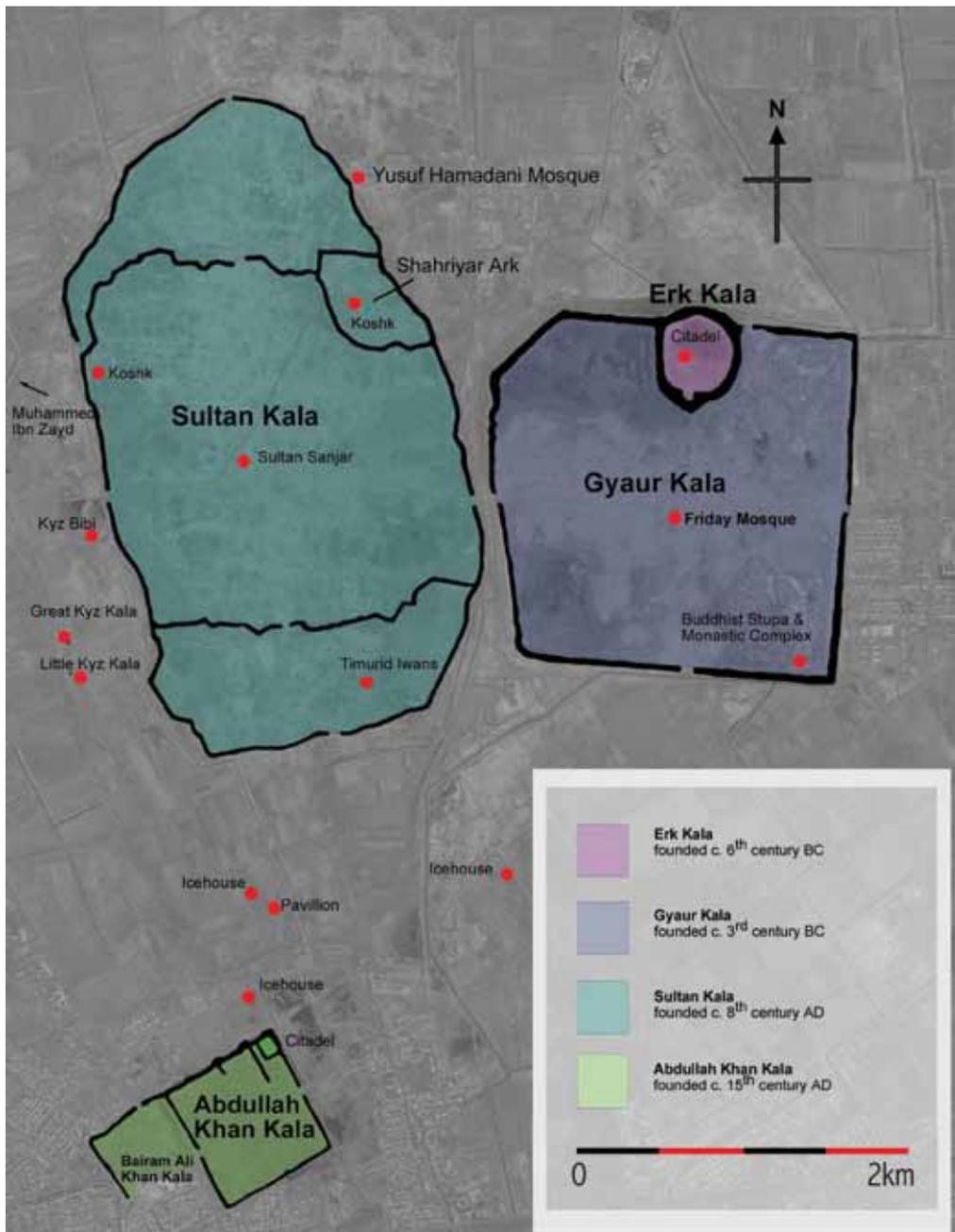
Fig. 1: The cities of Merv. The earliest, Erk Kala, was founded in the 6th century BCE; in the 3rd century BCE it became the citadel for the larger Hellenistic city of *Antiochia Marginana* (today known as Gyaur Kala). Around the 8th century CE the new city of Sultan Kala was built to the west, with Gyaur Kala becoming an industrial suburb. In the 15th century the Timurid city of Abdullah Khan Kala was constructed to the south, with the walled extension Bairam Ali Khan Kala added in the 18th century.

Fig. 2: Excavation of one of the central markets of the Islamic city in 2010. The walls of the buildings (in the background), destroyed in the Mongol sack of the city, still stand c.2.5m high, to just below the contemporary ground surface, with the floors and herringbone brick courtyard preserved under the destruction debris and erosion material.

(Williams, 2008) aims to explore the broad structure and organisation of the urban space, including:

a.   public/communal versus private/domestic space – to enable an understanding of neighbourhoods, and social organisation/structuring of the urban space;

b.   public/communal building functions – to enable an understanding of the structure of neighbourhoods, and the provision of services and facilities, and the central or diffused structure of the facilities; and

c.   unbuilt space outside private and public/communal building complexes – to enable an understanding of the nature of the built environment, the quantity of garden and other space, access, etc.

The UCL Institute of Archaeology has developed a long collaboration with the Ministry of Culture in Turkmenistan to research, conserve and present the archaeology of Merv.[1]

Previous air-borne survey

The only vertical aerial photographs (APs) we have been able to discover for the area were taken by the Soviets in the 1970s. Unfortunately, no negatives could be located and the surviving prints, which are damaged, do not provide a complete coverage and have a number of exposure and focus issues. Nevertheless, the images clearly demonstrated the potential of such an approach, with excellent definition of buildings, streets, canals, etc. (**Fig. 3**).

A lack of accurate base maps of the region[2] complicated the geo-referencing of these images. Thus it was decided to acquire a high-resolution satellite image – to provide a frame of reference against which to attempt

Fig. 3: Soviet (1970s) vertical air photograph covering the north central part of Sultan Kala, with the citadel (Shahriyar Ark) visible upper right and the Madjān Canal winding its way northward (top).

the rectification of these APs, to act as a base map for future survey work, and to provide new comprehensive imagery – and in April 2001 the Merv project commissioned an IKONOS satellite image (**Fig. 4**). In advance, Prof. Peter Dare (Dept of Geodesy and Geomatics Engineering, University of New Brunswick) established a control network, using a Global Positioning System (GPS), linked to the International Terrestrial Reference Frame (ITRF) (Ziebart *et al.*, 2002; **Fig. 5**). This enabled us to reference the satellite image accurately and to use this as a base for working on the existing AP data. We have started to map

out the Islamic cityscape (Williams, 2008).

However, the patchy quality of the 1970s photographs, and the resolution of the satellite imagery, was sometimes frustrating. It was clear that a new campaign of aerial photography could yield important additional information. In particular, repeated flights, documenting the site at different times of the year (to explore the impact of changing moisture and vegetation) and at different times of the day (to explore the ability of changing light strengths and angles to highlight features and surface compaction), could potentially add significantly to our ability to

Fig. 4: Part of the IKONOS satellite image taken in April 2001, showing the north central part of Sultan Kala (broadly the same area as **Fig. 3**). Its 1m resolution does not provide the same level of detail as an AP, but the excellent quality – and the ability to geo-rectify it – provides the basis for AP analysis.

map the cityscape.

But there were significant problems in collecting new material, not least the availability of appropriate planes and the sensitivity of the area (not far from the military airfield at Mary). Over a number of years repeated attempts to arrange new surveys failed. Then the advent of Unmanned Aerial Vehicles (UAVs) began to offer an alternative method of data collection.

Using a UAV

Early commercially available UAVs were often quite difficult to fly (at least in terms of straight and level flying, necessary for good survey images), and often only flew at relatively low altitudes (c.50–150m). The latter meant that the images taken covered a relatively small area: so the practicalities of surveying some 10km^2 of a city and its suburbs were daunting. In addition, early UAVs had issues of stability – both camera wobble (leading to non-vertical pictures) and camera shake (resulting in blurred images) – as also in the ability to control flight paths, with the difficulty of ensuring overlapping images. Even when acquired, the 'stitching' of such a large number of images into a photo-mosaic, and their geo-rectification, would be a time-consuming and complex endeavour.

The quality of UAVs has improved massively during the last few years and, with this, there has been a considerable widen-

Fig. 5: The Lecia Global Positioning System (GPS) set up to establish a control point, on one of the road bridges near Ancient Merv, to geo-reference the IKONOS satellite image.

Fig. 6: The *swinglet* CAM UAV (© senseFly LLC).

ing of their application and use (Anderson, 2012). The breakthrough for our work has come with the advent of more sophisticated flight-control software, enabling the user to prepare flight plans more accurately and systematically, thus ensuring consistent coverage, and with the development of semi-automatic systems to create geo-rectified photo-mosaics from the data captured.[3]

The equipment

The project purchased a *swinglet* CAM,[4] a ready-to-deploy light-weight mini UAV, weighing just 500g, with a wing span of 80cm (**Fig. 6**). It has an on-board system comprising a compact 12-megapixel digital camera,

Fig. 7: The rugged carrying case for the UAV (mounted in the lid) and its supporting equipment, making it easy to transport.

a GPS and a radio receiver, and is controlled by a ground-based computer, a semi-rugged tablet, via a 2.4GHz radio modem for data transfer. The UAV, all its accessories and the ground-based computer can be stored in a single carrying case (**Fig. 7**).

Flight programming

The crucial development for our application of this system for archaeological survey was the quality of flight programming. This enabled us to develop a comprehensive survey strategy, at a variety of resolutions, across pre-defined flight patterns. The autopilot software, *e-mo-tion* (Electronic MOnitoring staTION) (**Fig. 8**), allows the user to establish:

1. the area to be photographed (either by drawing a rectangle over a map or entering specific coordinates);

2. a flight pattern within this, via a series of waypoints (**Fig. 9**), which establishes the orientation and number of runs and the interval of photograph locations along the flight; and

3. the altitude of the flight, which establishes the resolution of the images (see below).

The flight plan is then uploaded to the UAV before take-off. The UAV uses on-board information on wind speed, speed, yaw/pitch/roll, altitude and overall position (via the GPS) to analyse the mission and continuously adjust the UAV to maintain the flight plan; all of which is monitored by the ground-based computer via the radio link. Photographs are taken automatically, according to the pre-defined plan. However, simple drag-and-drop commands and mouse clicks can be used to update the flight plan, trigger pictures, return the UAV to its starting location, or initiate a landing.

Flight planning is done against a backdrop of a base map or a satellite image, both currently provided by Bing Maps Platform.[5] Unfortunately, Bing's coverage in Turkmenistan is not great, either in terms of mapping roads and features, or in the resolution of the satellite imagery. Flight planning at Merv was difficult as the Bing map for our area only showed a single road, so it was hard to orientate ourselves to the known features of the landscape. The lack of any local internet connection in Turkmenistan also means that any imagery/maps used have to be cached onto the computer before departure. It would be excellent to have the option to choose Google Earth maps/satellite images,[6] or to be able to load our own geo-referenced satellite images or maps as a backdrop.

Image resolution and quality

The scale of resolution of the images is controlled by the flight altitude. The autopilot software selects the UAV altitude based on the user's preferred image resolution: thus a resolution of 2cm per pixel is attained by flying at c.52m, or 4cm/pixel at c.105m, based on the resolution of the camera (see below, **Fig. 11**). The UAV is capable of flying at significantly higher altitudes. Obviously, the area covered in a single flight is dictated by the scale of image overlap selected and the altitude of the flight.

The images are as good as the camera installed on the UAV. However, the system cuts the UAV's motor just before taking a pic-
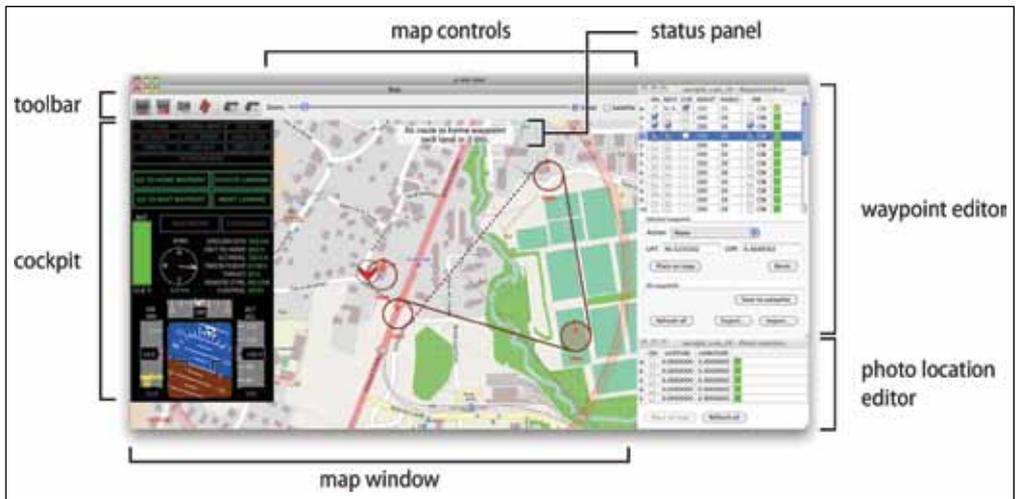
Fig. 8: *e-mo-tion* software panel, showing the map window, the waypoint editor and the photo-graph location editor (© senseFly LLC).

Fig. 9: Tracklog of a single flight in the north-west of Sultan Kala (output as a kml file from the software and displayed on the Google Earth satellite image). The UAV took off north-west from near the centre of the survey area, before starting the systematic north-south runs pre-programmed in the flight plan.

ture to avoid vibrations. It also checks for a level position before triggering the camera shutter. Overall, the stabilisation and wind correction, despite the lightness of the UAV, was excellent. At the 4cm/pixel resolution, few images were blurred or significantly non-vertical; when images were unusable, the scale of overlap ensured that a compos-
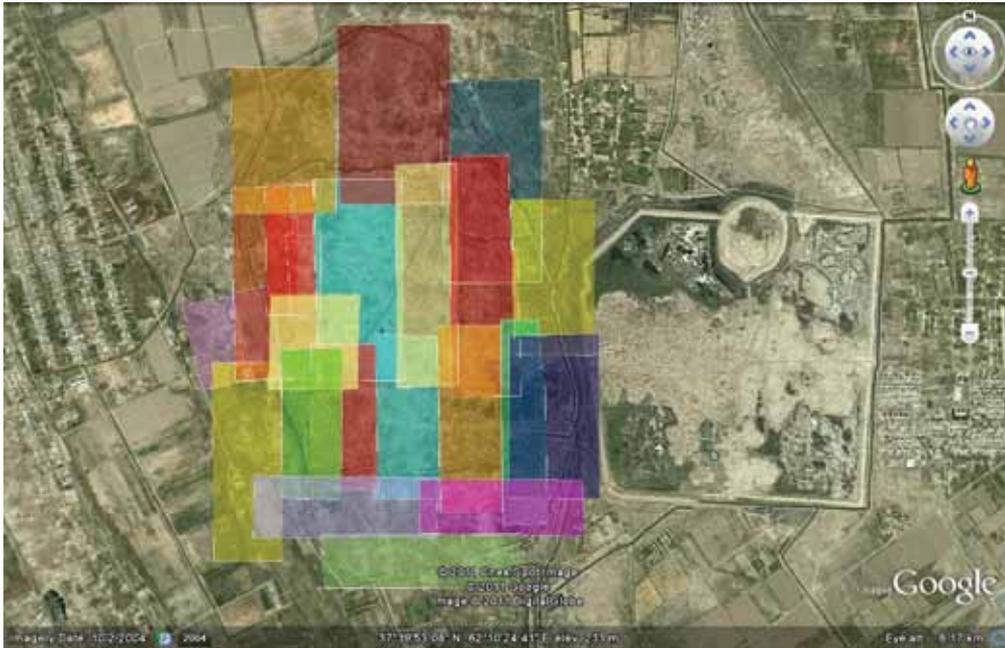
Fig. 10: Coverage of APs over Merv, with each coloured box representing a single flight. Note the larger area covered in the northern part of the survey, when flying at c.105m and capturing 4cm/pixel resolution images, as compared to the smaller survey grids to the south, at the 2cm/pixel resolution.

ite mosaic was still possible. At 2cm/pixel this was more problematic, as the interval between the images was smaller and fluctuating winds did cause some problems, with some gaps developing in the coverage. Indeed, it was generally much harder to control the scale of images generated at this level.

Flight times and wind speeds

The battery pack on the plane is light; on a mostly level flight, with a fully-charged battery, flight time would not exceed 25 minutes (given an average ground speed of 7–10m per second). High winds, or frequent altitude changes, decrease the endurance of the UAV and its lightness means that it cannot operate in wind speeds in excess of 25km/h or 7m/s, although at Merv this was seldom problematic.

Flight data

The UAV's on-board GPS system provides a complete flight log, transmitted to the ground-based computer during the flight. This enables post-flight software on the ground computer to geo-tag each image with information on location, height and plane positioning (latitude, longitude, altitude_amsl, altitude_wgs84, heading, yaw, pitch and roll). It also produces a kml file of the route (a tracklog), which can be directly imported into Google Earth (**Fig. 9**).

Preliminary results of the Merv survey

Coverage

The initial plan was to test general performance of the system, trying different survey patterns and resolutions. But there was also an imperative to capture new data for the *Atlas* project, and it was hoped to cover the entire area of the Islamic city and its suburbs at the maximum 2cm/pixel resolution. However, a short September 2011 field season meant that we only had a 10-day flying window. As a result, the southern area was

Fig. 11: The difference between the 2cm/pixel resolution (**a** & **c**) and the 4cm/pixel resolution (**b** & **d**); images at the top of the mausoleum of Sultan Sanjar, and at the bottom of an excavation trench (MSK027).

captured at 2cm/pixel and the northern area at 4cm/pixel (**Fig. 10**).

It was normally possible to undertake two flights in the morning (between 8.00–9.00am) and one or two flights in the afternoon (between 5.30–6.30pm); most days the electrical power in the Merv region went off between mid-morning and late afternoon, so battery recharging was problematic. The flights were timed to take advantage of reasonably strong light, but at a low angle, to accentuate the largely earthwork nature of the site. It would have been desirable to fly the whole area at the same time each day, but this was impossible given the time constraints. An attempt was made to fly the southern half of the area in the afternoons and the northern section in the mornings, but even this was not always feasible. Over the 10-day period a total of 26 flights were

undertaken, acquiring some 5,800 individual images of which 5,626 were part of consistent survey runs (the rest being test runs, flights over specific rural monuments, etc.):

- 3,553 at 2cm/pixel covering an area of 4.03km^2

- 2,073 at 4cm/pixel covering an area of 5.46km^2

This encompassed most of the Islamic city of Sultan Kala and its associated suburbs, although there was not time to cover all of the suburban areas to the west of the city (**Fig. 11**). The coverage was not perfect, partly due to the time constraints, but also because of the project team needing to get used to the equipment. However, it steadily improved and the 4cm/pixel flight patterns were easier to plan and realise.

Fig. 12: A manually constructed photo-mosaic of an area within the citadel of Shahri-yar Ark.

The image quality was generally excellent and again the 4cm/pixel runs certainly provided good quality imagery for the survey purposes (**Fig. 11,b** & **d**). It was possible in the field to check coverage and to capture imagery of specific monuments and landscapes, and then back at base to undertake some simple manual photo-mosaic creation (**Fig. 12**).

Performance: practical issues

The *swinglet* was easy to deploy. The carry case enabled it to be transported easily and the open nature of the Merv terrain made it simple to launch and observe. The UAV was very quiet: at 100m it could only just be heard when directly overhead – useful because it attracted no attention (including from the local authorities!).

Landing was not the easiest feature; in an unforgiving landscape of camel thorn and broken pottery, it would have been desirable to catch the UAV, but this was not as simple as it might sound. The landing pattern is for the UAV to circle 75m above the take-off point; when landing is initiated, it glides down in a circular pattern. Obviously, with such a light plane, the wind caused it to speed up and slow down as it circled. The engine can be manually kicked in to raise the nose and on good days we guided it down, stalling into the wind at the end, safely into a waiting catcher's arms – but plenty of days we missed! However, since the plane is gliding relatively slowly (the digital camera shuts off before landing and safely retracts), the landings were gentle enough even when we missed, although this resulted in having to pick small bits of grit or camel thorn out of the wings.

Overall, it was easy to learn how to use the software, and the flight programming systems are excellent. Since the mission we have been in close contact with the manufacturer, senseFLY, who have been open to suggestions regarding software development.

Post-processing

The other key feature in the applicability of this survey equipment is the ability to process and use the large number of images generated during the fieldwork. With nearly 6,000 images captured in 10 days – and this is on the low side, given experimentation and power issues – post-flight processing needs to be effective, if we are to generate more than just attractive images of monuments and landscapes.

As stated above, the post-flight software on the field laptop tagged the individual images with basic locational data. The user can then employ a variety of commercial and freeware systems to analyse and process the imagery. However, senseFLY also provides a comprehensive post-flight processing system which

Fig. 13: A low resolution preview of the orthomosaic, as a kml within Google Earth, giving some indication of the coverage of the image, although not of its quality.

enables the creation of geo-referenced ortho-mosaics and digital elevation models (DEM). The software searches for 'matching points' by analysing all uploaded images, matching points and approximate values of the image position and orientation. These are all used in a bundle block adjustment to reconstruct the exact position and orientation of the camera for every acquired image. Based on this reconstruction the matching points are verified and their 3D coordinates calculated. The geo-reference system is WGS84, based on GPS measurements from the autopilot during the flight. Those 3D points are inter-polated to form a triangulated irregular net-work in order to obtain the DEM. This DEM is used to project every image pixel and calcu-late the geo-referenced orthomosaic.[7]

With basic 2D processing one receives a geo-referenced orthomosaic in GeoTIF for-mat, with UTM[8] coordinates (which can be opened with any standard image viewer, Google Earth, and GIS software), and a geo-referenced orthomosaic in KML tile format.

With the pro 3D version one receives also:

· a geo-referenced DEM (in both GeoTIF and ASCII format, using UTM coordi-nates)

· a 3D mesh model in OBJ format,[9] with texture coordinates to wrap the ortho-mosaic on top

· and a collection of coloured cloud of points in PLY format,[10] which are pro-vided in a local coordinate system

· parameters exports (ASCII files contain-ing camera parameters in local metric and geo-referenced coordinates)

· ASCII files containing the 3D points in a compatible format for BINGO/ORIMA/ INPHO, for integration with traditional photogrammetry packages.

All the services come with useful post-flight reports on the data, its accuracy and the processing.

The services at present cost about £6,500 per annum for unlimited use of the 3D system and about £1,600 for the 2D system. Alternatively, it can be paid for by project: for example, the 5.46km² area in the north of Merv, captured at 4cm/pixel resolution, would cost £556 to process through the basic 2D package and £2,266 in the full 3D package.

We have started to run the northern area through the post-flight software as part of a free trial run provided by the manufacturers, while we seek to gather resources for the full project. The orthomosaic generated used 2,007 out of the 2,073 original images, the others being discarded for a variety of reasons. The orthomosaic covers an area of 5.46km² (546.3ha). The mean size of a pixel on the ground of the original images was computed at 4.29441cm. The total number of key-point observations for bundle block adjustment was 14,942,120; with 5,658,181 points for 3D bundle block adjustment. A low resolution preview of the orthomosaic as a kml within Google Earth gives some indication of the coverage of the image (**Fig. 13**).

Conclusions

Overall this has been an excellent opportunity to experiment with this type of aerial survey technology, on a major and complex archaeological landscape. One short season, which included a fair amount time getting used to the equipment, has yielded a significant amount of new imagery, with considerable potential for developing our approaches to mapping the medieval Islamic cityscape.

The UAV was simple to use and deploy, and produced excellent results. The 4cm/pixel coverage was considerably easier to plan and had significantly fewer problems with missing images (caused by vibrations or pitch/roll issues), giving us a good quality orthomosaic coverage. It also demonstrated a strong potential to create an effective DTM of the intricate surface landscape of the cities, with its shallow mounds and depressions. It is hoped that we can raise the funds for the complete 3D project, to support the *Atlas of Islamic Merv*.

In the 2012 season we plan to capture the remaining Islamic landscape at 4cm/pixel resolution, and to experiment with lighting angles (times of day), the scale of overlap of flight runs, and higher level photography. We also plan to return in the Spring of 2013 to explore different weather and soil conditions.

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Notes

1 The Institute of Archaeology's collaboration with the Turkmenistan Ministry of Culture stretches back to 1991, when the former Soviet Central Asian Republic of Turkmenistan gained independence. Ancient Merv, a State Archaeological Park, became a World Heritage Site in 1999. For background, see Herrmann (1999); for an introduction to the current project, see Williams (2004; 2007b).

2 The best were a series of 1:10,000 maps published by the Soviets in 1954, but these are variable in terms of accuracy; although they were explored as a possible base for geo-referencing the vertical APs, the lack of fit, coupled with the quality of the APs themselves, made this problematic.

3 In particular, the work of Prof. Danny Donoghue and Dr Nikolaos Galiatsatos (Dept of Geography, Durham University), and of Prof. Dominic Powlesland (Landscape Research Centre), in archaeological remote sensing; see also the UAV Special Interest Group, established by the Remote Sensing and Photogrammetry Society, at http://rspsoc.org/information-zones/sigs/uav/.

4 Manufactured by senseFly LLC (http://www.sensefly.com) and marketed in the UK by KOREC (http://www.korecgroup.com/).

5 A geospatial mapping platform produced by Microsoft, at http://www.bing.com/maps/.

6 The manufacturer, senseFLY, states that map data caching for offline use is forbidden by Google's license, and that Google Map background will be available in the future, but only with Internet connectivity which will not solve our problems in the field.

7 http://www.sensefly.com/applications/mapping. This service is powered by Pix4D (Pix4UAV version v1.12289).

8 Universal Transverse Mercator coordinate system is a 2-dimensional Cartesian coordinate system.

9 An open geometry definition file format, widely adopted by 3D graphics applications.

10 A widely used polygon file format for storing graphical objects which are described as a collection of polygons.

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