ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences, Volume VIII-M-1-2021
28th CIPA Symposium “Great Learning & Digital Emotion”, 28 August–1 September 2021, Beijing, China

APPLICATION OF DIGITAL HERITAGE DOCUMENTATION FOR CONDITION ASSESSMENTS AND MONITORING CHANGE IN UZBEKISTAN

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KEY WORDS: Digital Documentation, Cultural Heritage, Condition Assessment, Monitoring, Central Asia, Uzbekistan

ABSTRACT: Cultural heritage is facing irreversible changes due to anthropogenic and natural impacts. Condition assessment is a holistic approach to analyse the historic buildings, structures or sites to record changes and understand their deterioration and causes. Detailed documentation is an essential first step for mapping the condition, analyse, give a diagnosis and propose conservation measures. However, not all the time the appropriate documentation is available or recorded towards this means, making difficult a proper assessment. This paper presents a review of digital documentation tools supporting a systematic assessment of the condition and changes of historic structures. The application aerial and close-range photogrammetry and panoramic photography is illustrated using two case studies within the World Heritage properties in the Central Asia region, Itchan Kala and the Historic Centre of Bukhara in Uzbekistan.

1. INTRODUCTION

1.1 Condition Assessment and Digital Technologies

Cultural heritage in Central Asia is facing irreversible changes due to anthropogenic and natural impacts. Aside from the usual natural exposure and degradation of the fabric, external man-made causes are threatening the sites, among them it can be listed urban expansion and development, agriculture, rural depopulation, and lack of proper conservation or maintenance. The latter two are two direct threats to the fabric that have become increasingly common in the region.

Condition assessment is a common practice to understand the deterioration and causes of historic structures, and changes on their attributes. Accurate recording of the cultural heritage is a prerequisite for the condition mapping and a proper analysis, diagnosis and conservation measures. However, not all the time the appropriate documentation is available or recorded towards this means. Thus, digital documentation offers a number of tools to bridge this gap.

A prerequisite of condition mapping is systematic heritage documentation. As stated by Clark (2001) heritage documentation is the first step in understanding heritage. Thus, for the last decade the government of Uzbekistan has been working on integrating the use of digital technologies for planning conservation works and the monitoring of change within their World Heritage properties (Vileikis et al. 2017). However, it has been only since 2019 that the use of photogrammetry has been introduce in Uzbekistan as a tool for recording the condition of the sites. This task has been supported by the International Institute for Central Asian Studies (IICAS), the UNESCO Tashkent Office and the University College London (UCL).

This paper presents a review of digital documentation tools supporting a systematic assessment of the condition and changes of historic structures. Then, it focuses on how digital documentation, using aerial and close-range photogrammetry, and panoramic photography, serves as a tool for condition assessment. These tools are illustrated with case studies of two World Heritage properties in the Central Asia region along the ancient Silk Roads in Uzbekistan: Itchan Kala and the Historic Centre of Bukhara.

1.2 Tools for Monitoring Condition and Changes of Cultural Heritage

Recently, there has been a large increase of documentation and recording tools in cultural heritage (Saygi and Remondino, 2013). According to Santana et al. (2010) “good decisions in conservation are based on timely, relevant and sufficient information”. Monitoring methods in heritage studies are drawn from standard surveying and recording. Such tools should support the objectives of the monitoring process of data collection, analysis, and management (Walton, 2003). An extensive list can be found in this section.

The development of new technologies is bringing digital technologies to capture heritage data. As discussed by Addison (2007) digital sensors are classified in four groups: visual; locational; dimensional; and environmental. Visual sensors provide impressions of colour, shape and motion of a scene. Dimensional sensors measure the spatial extent: width, height, and length. Locational sensors provide the location of an object based on a geographic coordinate system. Environmental sensors can provide information on factors originating from the environment and affecting the property, as well as information on the age of an object (Santana and Addison, 2007). The latter is closely related to diagnostic sensors.

Two groups of tools exist for surveying and recording cultural heritage, (A) metric and (B) diagnostic (Fidler, 2007). The first group includes mapping and photography based tools and serves to survey and record the baseline information to understand the site in form and space (for digital sensors classification see Addison, 2007). The second group is mainly used to identify a condition when the causes of decay are not evident and there is a need for more detailed assessment. Additionally, their use, nowadays improved with the use of software, aids in monitoring by tracing the damage and

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overlaying new data while keeping history. This paper presents the first group.

1.3 Metric Tools for Recording Cultural Heritage

Metric tools capture information directly or indirectly (Bryan, 2010). The first ones require direct contact with the operator and the data is taken at the point of capture. This means the outcome of the data collected is related to the selection and decisions in the field, requiring often large amount of time at the site. These tools are for example total station, laser distance meter (also disto), levelling (Historic England, 2009), Global Navigation Satellite System (GNSS) receiving information using for example Global Positioning System (GPS) (Historic England, 2005) and hand-drawing (Historic England, 2016). Hand drawn surveys like drawings and field notes, and visual observation for a reconnaissance identification of potential damages are traditional techniques for monitoring, but they require more work when standards have to be upheld (Walton, 2003). Indirect tools require more specialized operators and software, and allow data differentiation (Fidler, 2007; Getty, 2007). The selection of information is carried out during the post capture phase. Thus, these techniques might be faster in the field, but longer time for processing. These tools include photogrammetry and aerial laser scanning (Colomina and Molina, 2014; Federman et al. 2017; Historic England 2017; Remondino, 2011; Rinaudo et al., 2012; Themistocleous et al. 2016), 3D object and terrestrial laser scanning (Historic England, 2011; Remondino, 2011; Tucci et al., 2011; Shrestha et al. 2017), and geophysical survey (Goodman and Piro, 2013; Kvamme, 2003). Digital heritage recording is a technique that is being used to reduce subjectivity inherent in heritage assessment and monitoring by improving accuracy of data collection and analysis. It also allows for more effectively storing, managing, and disseminating the information (Kvamme, 2003).

Metric tools include low cost to high-cost solutions and might require basic to advanced IT and metric survey skills. Thus, each tool to be used should be carefully evaluated (Historic England, 2011; Letellier, 2007; Santana and Van Balen, 2009). Different to direct techniques, indirect techniques, like remote sensing, are more efficient at recording coverage of larger areas such as cities and cultural landscapes. In this study remote sensing refers to the acquisition of information to detect and classify objects on earth without making physical contact with the object using satellite- or aircraft-based sensor technologies (Khosrow-Pour, 2005). To produce accurate site maps, satellite images or aerial photography capture data with high density, and measurements can be systematically repeated, a great advantage for GIS projects. However, the application of those techniques might require costly operations to achieve the desired outcomes (Historic England, 2009; Longley et al., 2011). Table 1 summarizes tools for recording and monitoring the condition of cultural heritage.

Tool	Purpose in Cultural Heritage	Sources
Remote Sensing: Satellite Imagery	Map and monitor cultural landscape, cultural routes and complex archaeological excavations; create Digital Terrain Models; verify boundaries and buffer zones; model impact of site management decisions and policy options; multi-temporal data	Hernandez (2002); Remondino (2011)
Remote Sensing: Digital Aerial Photogrammetry (aircraft – Remotely Piloted Aircraft (RPA)	Understand a historic landscape; monitor and mitigate environmental changes, vegetation type; create 3D models; map and detailed survey of urban areas and archaeological sites; disaster monitoring; monitoring system for planning and archaeological excavation; create orthophotos and thermal-orthophotos	Colomina and Molina (2014); Remondino (2011); Rinaudo et al. (2012); Williams (2012); Federman et al. (2017); Themistocleous et al. (2016)
Remote Sensing: Aerial Laser Scanning	Topographic and landscape mapping; make high-resolution maps; create high-resolution Digital Elevation Models and Digital Terrain Model; obtain information on materials that support intervention or restoration processes; create fluorescence-based maps (raster data)	Historic England (2011); Raimondi et al. (2009)
Geophysical survey (geophysical prospection) e.g. with Ground Penetrating Radar (GPR), Electromagnetics, electrical conductivity	Archaeological imaging or mapping; landscape analysis; create maps of subsurface archaeological features; detect subsurface objects, changes in material properties, structural modifications, voids and cracks	Kvamme (2003); (2013)
3D Scanning	Mid-range: Build models and drawings of complex objects; survey buildings; buildings façades and interiors; surface models; produce detailed maps. Close range: sculpture relief carving; 3D printing; virtual reconstruction; interactive virtual museums; scientific archives	Barber et al. (2006); Historic England (2011); Remondino (2011); Tucci et al. (2011) ; Shrestha et al. (2017)
Global Navigation Satellite System (GNSS), Global Positioning System (GPS); Differential Global Positioning System (DGPS)	Topographic mapping, (archaeological) landscape surveys, inventory mapping linked to cartographic coordinate systems; create a 3D model to do metric and topological analysis on an archaeological excavation unit; establish permanent survey control to aid excavation; monitor sites for conservation purposes, e.g. key elements to ensure that the same photo will be taken with the same view and position	Historic England (2005); Losier et al. (2007)
Panoramic Photography	Identify disturbances; select tests and test areas to determine causes of discoloration; determine cause and cleaning methods e.g. for stone staining; in monitoring to take controlled photopoints	Luhmann (2004); Remondino (2011); Shum and Szeliski (2000); Walton (2003)
High Resolution Panoramic Photos (Gigapan)	Create large and 360° outdoor and indoor panoramas; document architectural buildings; create virtual museums; 3D reconstruction	Fangi (2010); Luhmann (2004)

Tool	Purpose in Cultural Heritage	Sources
Close-range Terrestrial Photogrammetry	Record flat facades and large amount of detail; use of control points; draw architectural façade; create a drawing for a large area containing great detail; identify damage e.g. determine location and quantity of erosion of building materials and surface change; ante-disaster record; monitor direction and magnitude of crack propagation	Historic England (2017); Remondino (2011); Feilden (1987); ICOMOS International Committee on Heritage Documentation (CIPA) 3x3 Rules (Waldhäusl *et al.*, 2013)
Total Station (EDM)	Field survey measures; topographic mapping, building plans and sections; precise control network measurement; monitor structural movement e.g. 3D distortion	Historic England (2009)

Table 1. Digital tools for recording and monitoring the condition of cultural heritage. Source: based on Vileikis (2018).

Historic England (2009, p. 60) states that "recording and monitoring the condition of heritage places is crucially important. Simple procedures can supply long-lasting and valuable information". Studies have shown that the use of photogrammetry is an asset and a cost-effective technique for gathering information. It has a large range of applications. For example, it is used to produce images of frescoes in the interior of a church with difficult accessibility (Percy et al., 2013), to quickly record monuments without previous planning (Almagro, 2013), to carry out good documentation (Fangi et al., 2013), or to monitor archaeological excavations by means of of Unmanned Aerial Vehicles (UAV) (Rinaudo et al., 2012). However, the use of 3D Scanners is well established, and sometimes its combination with photogrammetry, is taking the lead in structural assessments of historic buildings and support the management by producing Historic Building Information Modeling (HBIM) (Shrestha *et al.*, 2017; Themistocleous *et al.*, 2016).

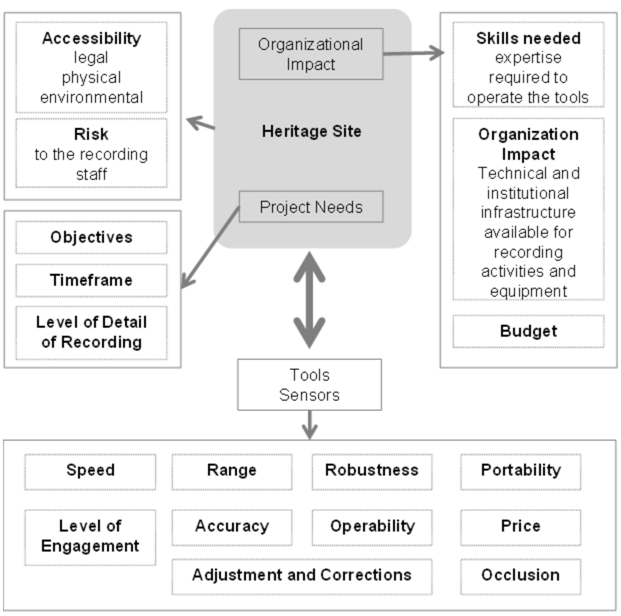

Figure 1. Variables for the selection of tools for heritage recording. Source: based on Santana et al. (2010).

The range of tools and methods selected will vary with the kind of information to be collected, timeframe, and the resources and levels of skills available (Santana and Addison, 2007). Figure 1, shows the four variables identified by Santana et al. (2010) for the selection of tools: heritage place, organization, project and tool. The first one is related to the accessibility to the site in matter of time, legal, physical and environmental factors. The organization refers to the skills available of the team and budget, and the project to the aim and needs for recording. The latter is the relation of the first three variables and the advantages and disadvantages of the tools.

2. CASE STUDIES

The two study areas are located in the heart of Central Asia in the regions of Xorazm and Bukhara in Uzbekistan (see Figure 2 for location). The historic buildings are madrassahs, mosques, minaret and a citadel dating between the 12th and 17th centuries and within the boundaries of the World Heritage properties.

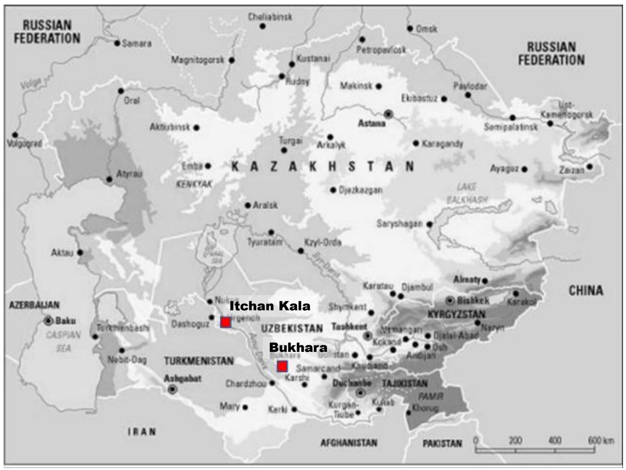

Figure 2 Map of Central Asia showing the location of the case studies, Itchan Kala and Bukhara, in red square.

3. METHODS

Aerial and close-range terrestrial photogrammetry, and panoramic photography, were the methods selected to capture the facades and roofs of the large-scale historic structures based on the projects needs and the tools available as discussed by Santana et al. (2010) (see Figure 1). These techniques were chosen to produce high quality orthophotos as well as architectural plans to map and monitor the condition of the sites. In addition, a total station was used for control points, and terrestrial photogrammetry and 360-degree panoramas were taken in the interiors.

The equipment used in this work was provided by IICAS and the Cultural Heritage Department of the former Ministry of Culture of Uzbekistan in Uzbekistan. A Canon EOS 6D Mark II with a lens 24-105 and a WEIFENG WF-531T tripod was used to take the terrestrial photogrammetry. For the aerial photogrammetry in Itchan Kala a Quadrocopter PHANTOM 4 Pro with Sensor 1 CMOS Effective pixels: 20M and a lens FOV 84° 8.8 mm/24 mm (35 mm format equivalent) f/2.8 – f/11 auto focus at 1 m – ∞ was used. In Bukhara a Mavic 2 Pro and a LEICA Total Station were used. The software used were Pix4Dcapture and DJI GO 4.

A Lenovo Thinkpad X1 Carbon 7 with 16GB RAM was used to process and check the data on site in a medium quality, but too slow for a high quality or production of one 3D model. Later the orthophotos were reprocessed using a workstation with higher configuration RAM 64, CPU i9-9900K 3.60 GHz and GPU GeForce GTX 1060 6GB. Agisoft Metashape Professional software was used for modelling and AutoCAD 2018 to draw the plans and map the damages.

4. WORKFLOWS

4.1 3D Acquisition Workflow

The digital workflow used for the survey was as follows:

- Establish the control points using Total Station.
- Conduct visual inspection to understand the damage and identify the critical issues.
- Use photogrammetry: aerial (drone) was used to capture the sites from above and main facades, exterior and courtyards; and close-range terrestrial photogrammetry was used to record the interior facades.
- Panoramic/360 degrees photography to capture the interiors.

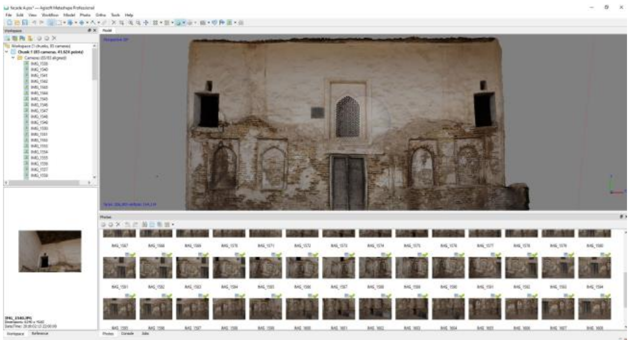

Figure 3. 3D model showing the north interior façade of the Bogbonli Mosque. Source: authors.

4.2 3D Processing Workflow

After the data was recorded, the information was processed with the team using Agisoft Metashape The objective was to use the photogrammetry and to create orthophotos of the facades. The following is the procedure for the processing workflow:

- First, image registration was done and created a point cloud.
- Then, mesh was created and as result a textured mesh. The advantage was that the 3D model will enable to see places you normally cannot reach – such as roofs – and see details you cannot otherwise get to (see Figure 3).
- After the orthophoto was created in Metashape, it was brought into AutoCAD. The image served as a base for drawing the façade and creating an accurate analysis of the damage and deterioration as they were on this day. These images will then be used as base reference points for future monitoring.

5. RESULTS

5.1 Bogbonli Mosque in Khiva

The Bogbonli Mosque is republican listed historic building of the beginning of the 19th century. It is in the southeast of one of the mahallas of the World Heritage property of Itchan Kala. Its heritage significance mainly relies on its rich inscriptions, the domed hall (unlike most of the mosques in Khiva covered by a flat roof on columns), and the ayvan with columns dating from the 14th century with its rich wood ceiling.

The conservation of the historic building was planned to happen between 2019 and 2021 thanks to the EU-UNESCO Silk Roads Heritage Corridors project and implemented by the UNESCO Tashkent Office. However, the Bogbonli Mosque has never been accurately recorded to map the condition of the building. The first documentation of the building dates to 1946, conducted by R. Abdurasulov, and it was not until 1957 that the first architectural measurements were carried out by I. I. Notkin. Thus, the UCL/IICAS team supported the project by carrying out the digital documentation towards its conservation.

Figure 4. Aerial images. Google Earth (left) and CAAL Orthophoto – UAV flight altitude: 35m (right). Source: @Maxar Technologies 2020 Google Earth (left) and CAAL (right).

3D in Google Earth shows some historic buildings in Itchan Kala, but the images are low quality – intended only for visualisation and no high-resolution data for the Bogbonli Mosque was available. Also, the Google Earth image in 2020 was not good enough to clearly see the Mosque and its surroundings. Thus, there was a need to capture high quality data to acquire high levels of detail. Figure 4 shows the advantage of using aerial photogrammetry, to map the site. In this case, the Google Earth satellite image (see Figure 4 left) taken in 2020 has limited resolution in contrast to the orthophoto produced from the drone images captured at 65 m high (Figure 4 right). With the orthophoto the team was able to understand the Mosque in its mahalla -neighbourhood, from the air.

Orthophotos were also created from the drone aerial images taken at 35 m high. The orthophoto together with the 3D model, served to map the condition of the roof and dome and to identify the priorities for the conservation activities as shown in Figure

5. In addition, a 360-degree image was created of the interior of the Mosque (see Figure 6). It served to understand the overall interior condition and identify areas of priority, such as cracks.

Figure 5. Detail of orthophoto of the roof and dome (upper) and detail of the 3D model of the north interior façade (bottom) of Bogbonli Mosque. Source: authors.

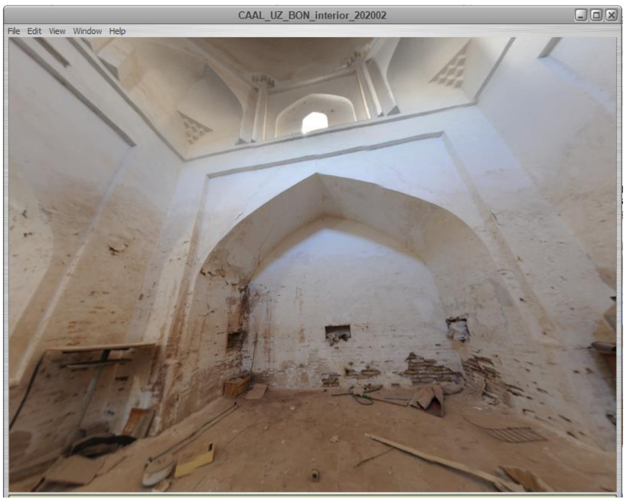

Figure 6. 360 degrees image of the interior of the Bogbonli Mosque. Source: authors.

5.2 Historic Buildings within the Historic Centre of Bukhara

A detailed condition assessment was carried out in February/March 2019 by the team of IICAS to assess the condition of seven main historic buildings within the historic centre of Bukhara, as recommended by the ICOMOS (2018) Advisory mission. The monumental buildings Abdulazizkhan Madrasah, Ulugbek Madrasah, Miri-Arab Madrasah, Kalon Minaret, Kalon Mosque, Amir Alimkhan Madrasah, and four historic structures in Ark were built in between the 12th and the 18th centuries in the core of the ancient city (see Figure 7 for location). The condition assessment formed the basis for recommendations on further conservation activities to protect the heritage values of the historic buildings, as well as the development of a Heritage Impact Assessments (HIA) for its conservation and adaptive reuse (IICAS 2019, Vileikis 2019).

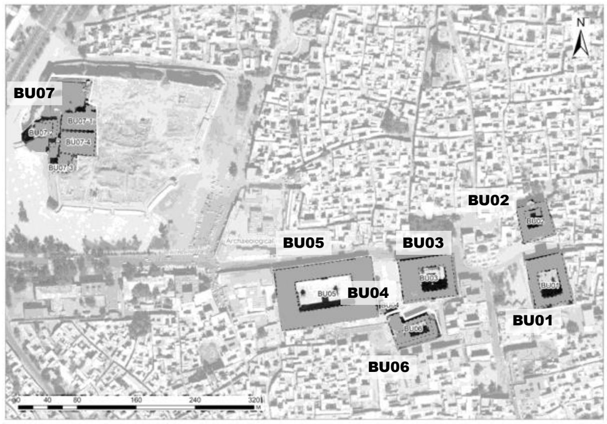

Figure 7. Location of the historic buildings within the historic centre. BU01 Abdulazizkhan Madrasah, BU02 Ulugbek Madrasah, BU03 Miri-Arab Madrasah, BU04 Kalon Minaret, BU05 Kalon Mosque, BU06 Amir Alimkhan Madrasah, and BU07 (1-4) Ark Source: authors.

The implementation of the methodology and workflows in Bukhara is illustrated in the following examples. Each exterior and interior façade and roofs were surveyed at 3 m to 4 m. The flight pattern used was a manual grid.

Figure 8. View of the Kalon Minaret from the courtyard of the Kalon Mosque. Source: authors.

Aerial photogrammetry was an excellent choice to reach high areas of the minaret of 47 meter high. For the first time the minaret Kalon was digitised as a 3D model (see figure 9). Details of the missing parts of the inscriptions and construction details of the bricks can be clearly seen for future research. In the 14 tiers of the horizontal design there is almost no repetition of pattern, including: bows with paired bricks; diamonds; girih; eight-pointed stars; and kufic letters as shown in figure 10.

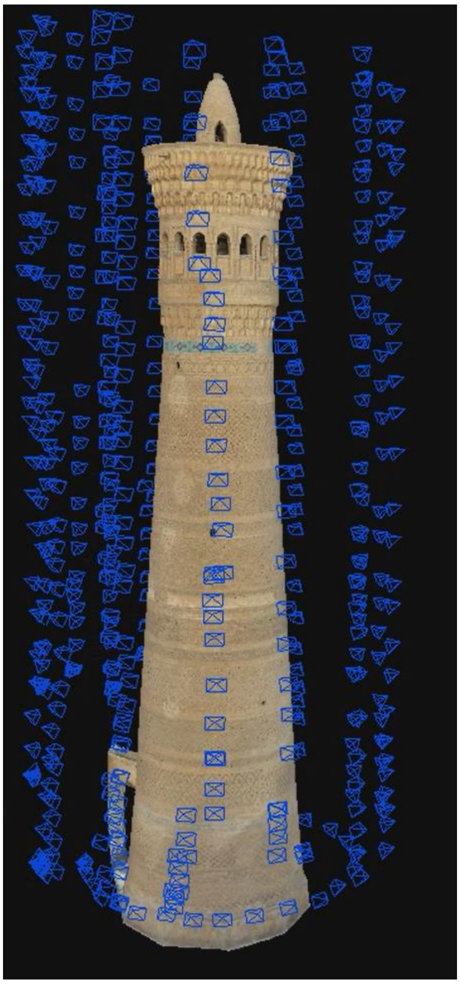

Figure 9. 3D model of Kalon Minaret. 47 m high. Source: authors.

Figure 10. Detail of Kalon Minaret from the 3D model showing missing parts. Source: authors.

As depicted in Figures 11 and 12, using the photogrammetric models, orthophotos of the façades were created to draw architectural drawings and map the condition of the buildings. Details of the majolica revealed missing parts or damaged areas, especially this was useful in higher areas that are difficult to reach such as in the Miri-Arab Madrassah.

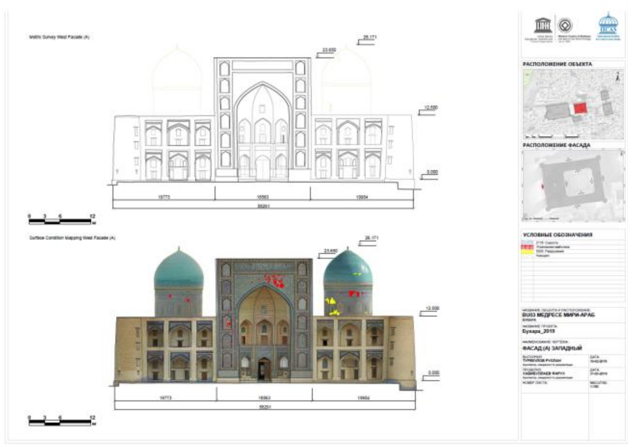

Figure 11. Drawing and orthophoto mapping damages of north Façade of Miri-Arab Madrassah. Source: authors.

Figure 12. Detail of majolica of the of the north façade of Miri-Arab Madrassah with orthophoto as background. Source: authors.

3D models of the buildings also served to understand the complexity of the buildings as seen in the example of the 17th century Abdulazizkhan Madrasah in Figure 13. In the last years, the building was used by craftsmen, renting the spaces for their workshops and shops. They were obliged to provide maintenance and repair to the premises they occupy. The greatest damage to the monument was caused by the work on lowering the cultural layers in the historical center of Bukhara in 2017. The works were carried out using heavy machinery without a scientifically grounded methodology. Consequently, the middle part of the wall of the eastern street façade and several rooms located behind it collapsed. Other parts of the building became as unstable as to be considered in an emergency condition, which, even before the lowering the soil, required reinforcement of the structures.

Figure 13. 3D model of Abdulazizkhan Madrasah. See collapsed wall in the lower centred part. Source: authors.

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The 3D model served as a tool to discuss the damages with the conservation team. It aimed to support the preparation of the HIA for the emergency actions and conservation works by finding appropriate informed solutions.

6. CONCLUSION

The use of digital technologies supported informed decisions for the conservation. The aim of the initiatives was to improve the documentation and condition assessment of the cultural heritage sites by using digital technologies. Documentation is the first step toward a proper management and monitoring strategy. This process could also serve as an example for future work on condition assessment and the use of systematic documentation for the later development of HIA in the region and will remain as a record for future research.

Following the variables for the selection of tools for heritage recording proposed by Santana et al (2010), aerial and terrestrial photogrammetry was a proper tool to produce orthophotos and 3D models. However, flying a drone was not always easy. Although Uzbekistan seems to have a relatively dry atmosphere, in Khiva of the three days of fieldwork, the first day it rained, and it was not possible to fly. The following day witnessed the visit of the Prime Minister of Kazakhstan and his delegation to Itchan Kala, so no flights were allowed. Too much light contrast is one condition for good photogrammetry, so only two mornings and one late afternoon were left for the recording. One of these had to be cancelled because there was no permit to fly that day. Despite these challenges the team was able to capture what was needed. In addition, training was given to the local team, and everyone had a chance to fly the drone.

Figure 14. Team receiving training and hands-on to fly a drone provided by the authors and supported by the CAAL project. Bogbonli Mosque, Itchan Kala. Source: authors.

Now the big challenge is to continue the work at other cultural sites and to transfer this experience towards the preservation of cultural heritage for future generations. The use of 3D scanner seems promising and could be used in further surveys, when available.

ACKNOWLEDGEMENTS

We would like to thank the generous support of the ARCADIA Fund – a charitable fund of Lisbet Rausing and Peter Baldwin for the grant given to the UCL CAAL project for the condition mapping and training of Bogbonli Mosque. In addition, thanks to the UNESCO Tashkent Office for its collaboration.

Also, thanks to the Cultural Heritage Department of the former Ministry of Culture of Uzbekistan for their support with the Bukhara and Khiva projects.

Special acknowledgements are given to the CAAL local partners in Khiva, specially Gavkhar Durdieva, as well as the municipalities and local staff in Bukhara and Khiva for their invaluable contribution to the trainings and discussions.

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