CHALLENGING ARCHITECTURES: AN INTEGRATED AND MULTIPURPOSE SURVEY FOR THE COMPLETE MAPPING OF THE EMIR PALACE IN KOGON (UZBEKISTAN)

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KEY WORDS: Cultural Heritage, Integrated Survey, Laser Scanning, Orthoimage, Photogrammetry.

ABSTRACT:

The documentation of Cultural Heritage, and in particular architecture, is nowadays conducted with a combination of several geomatic techniques. Most of them relies on the exploitation of 3D point cloud, which is the state of art data to produce almost every output. The starting point of each recovery intervention is the survey, which enable a multidisciplinary approach for the knowledge of a building and, consequently, to preserve it for future generation. When it comes with complex architectures, however, the surveying approach is more compelling and challenging at the same time. The definition of the final accuracy requires a tidy design process that should be done a priori, and a set of strict rules need to be respected. With the advent of new automatic procedures, the number of data collected increases, but this doesn't mean that well established method, like topography, can be neglected. This work is the demonstration of how old and new method must coexist. The present work describes the work carried out to the complete 3D reconstruction of a complex building, namely the Emir's Palace place in Kogon, Uzbekistan. Given its dimension and decorative apparatus, maintaining a high standard of definition without losing metrological accuracy was the main challenge. The work was carried out with a combination of both Terrestrial Laser Scanner and Aerial Photogrammetry for the 3D reconstruction, and on a very accurate topographic network for the combination of produced point clouds. The result of this first phase of the work was a polygonal network with a millimetric accuracy. Besides, another important contribution of the paper lies on the exploitation of the panoramic images coming from the TLS within a photogrammetric software. Indeed, by exploiting the depth map, it was possible to produce very detailed orthophotos for the production of 1:10 scale drawings. The work, performed in a joint venture between Academia and SMEs, is an excellent example (useful to be shared within the research community dealing with 3D representation and optimization) of innovative methodologies developed to produce reliable drawings and 3D representation for different purposes, being the starting point for each kind of project.

1. INTRODUCTION

The Government of the Republic of Uzbekistan (GoU) recognizes the pressing need for a comprehensive approach to medium-sized cities in the country. To this end, the GoU has solicited the World Bank's assistance in developing a National Medium-Size Cities Program. This program will address key challenges in improving the quality of life, urban management, and service delivery using internationally recognized best practices. The Medium-Size Cities Integrated Urban Development Project (MSCIUDP) aims to support the GoU in enhancing the quality of life of targeted medium-sized cities in Uzbekistan. The project will achieve this through selected demonstration investments to improve urban infrastructure, public spaces, and access to services. To this end, several cultural heritage sites have been identified for restoration and adaptive reuse, with construction supervision services provided for several selected cultural heritage assets in the city of Kogon. This paper will describe the entire project, with a focus on the specific role of academia in preparing, assessing, and validating the complex geomatic data derived from the integrated survey. In particular, the paper will detail the work conducted on the Palace of the Emir of Bukhara, which represents a compelling study case given its dimension, complexity and articulated decorative apparatus. This research will contribute significantly to the growing body of knowledge on heritage site restoration and adaptive reuse, providing valuable insights for practitioners and policymakers alike. More in deep, this research adds new experiences about the full integration of geomatic techniques, pushing efforts on the accuracy definition given by a very precise topographic network. It will be shown that, albeit new acquisition techniques are able to automatize both acquisition and processing, the realization of a very strong metrological baseline give a solid backbone to subsequent phases of intervention. Another important contribution of this manuscript lies on the integration of both photogrammetric and laser scanner pipelines, to achieve the highest resolution even in richly decorated environments.

2. STATE-OF-THE-ART

Uzbek architecture represents the pages of its people's history, but climate change and natural disasters, as well as human activities, pose a huge threat to the survival of this cultural heritage. The study of complex historical architectures necessarily starts with a detailed and geometrically accurate graphic representation, which allows for a complete analysis and understanding of their planimetric and volumetric development, their structural, material and construction characteristics and their state of preservation (Carraro et al., 2019; Monego et al., 2019; Tucci et al., 2019).

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https://doi.org/10.5194/isprs-archives-XLVIII-M-2-2023-1225-2023

The integration of various geomatics techniques is always necessary for conducting metric surveys of this type of architectural structures. These surveys are not conducted merely for the sake of measurement, but rather to support precise analyses and planning of conservation and restoration interventions, as well as management interventions. Each of these actions necessitates a distinct type of metric survey, with varying descriptive content and metrics. The choice of what, where and when use different technologies depends heavily on the end requirements for the final 3D model (Rinaudo & Scolamiero, 2021). In some cases, different parts of the same building may require distinct types of surveys, and therefore, employing multiple metric survey techniques is a cost-effective and practical approach (Fassi, 2007; Owda et al., 2018; Previato et al., 2022). The current trend towards integrating different measurement techniques is further supported by the fact that each technique (such as aerial and terrestrial photogrammetry, laser scanning, SLAM, etc.) has its own limitations in terms of achievable accuracy and degree of detail. So, an integrated approach between the use of TLS - Terrestrial Laser Scanner and aerial photogrammetry or UAV - Unmanned Aerial Vehicle allows to exploit the potential of both techniques, to achieving the best completeness and quality of the resulting representations (Barba et al., 2019; Hassan et al., 2019).

In general, a TLS usually provides information on building facades, while aerial photogrammetry can provide the perspective for building roofs. In this study, a UAV system and a TLS were used in an integrated project to acquire 3D point clouds to facilitate the acquisition of comprehensive information on an object of cultural heritage interest. (Xu et al., 2014). So, UAVs with image processing technology were used to obtain point cloud data to overcome and compensate for the limitations of the laser scanner, although its use has been limited by its lack of precision (Moon et al., 2019). This kind of documentation will be very important not only for the ongoing project, but also as a documentation of the situation before and after the restoration works. The integrated approach opens up new opportunities for accurate and detailed representation and visualisation of high-resolution point clouds and orthoimages (Quattrini et al., 2015).

3. METHODOLOGY

3.1 Case Study

The Emir's Palace is located 12 km from east side of historical part of Bukhara city, World Heritage Property. In the beginning, name of this side was called “New Bukhara” but now this area is known as Kogon. The background to the construction of the Palace of the Emir of Bukhara was the expansion of the Russian Empire into Central Asia in the second half of the 19th century. The Palace was built in 1895 by the Emir of Bukhara, Seid Abdulahad Khan, the last ruling dynasty of the Emirate of Bukhara, which at the time was a part of the Russian Empire.

The Palace’s architecture was conceived by famous Russian architect Leonty Nikolaevich Benoaga and designed by Mauritanian, Arabic and combining Baroque architectural styles and it is built with the support of Bukhara and Russian masters. Main function of the Palace was the welcoming of guests; therefore, building was designed with all the amenities needed to welcome guests: guest rooms, restaurants, lounges, bedrooms, bathrooms and luxurious waiting rooms. Few images of the Palace are depicted in Figure 1.

Figure 1. Photos of outdoor and indoor of Emir Palace.

The building has a complex structure and composition based on the principle of equal visual perception from all sides. The composition is based on a combination of smaller and larger volumes of very different shapes and configurations in the plan.

The layout is based on large ceremonial halls along the longitudinal axis, among which a hall of great importance stands out. The building has three entrance doors in total, three of which are located on three sides of the building.

The main entrance is on the asymmetrical southern façade, but the main façade is still the strictly symmetrical eastern one. The main entrance leads through a single-storey open archway, behind which is the second-storey volume and a lightly vaulted pavilion, crowning the whole composition with a distinctive decorative dome and flag. Inside, there are many carved decorations that cover the pillars, beams and even the trunks of the columns. Innumerable columns, large domes and minarets make the palace look grander and more majestic and the rooms of the palace were heated with the help of stoves built in the Dutch style (Figure 2).

Figure 2. Site Plan: Emir Palace and its surroundings.

The general condition of the building is critical. The building is slightly deformed under the influence of earthquakes back to 130 years, and there are vertical cracks in the walls. The roof of the second floor should be replaced. Building materials in the roof, mostly brought from Russia in 1887, some building materials are obsolete and should be replaced too. In present day, the building is a state historical monument, owned by the government of Uzbekistan, and is known as the Railway Workers' Palace of Culture (Pochekaev, 2018).

3.2 Geomatic survey

Considering the specific requirements of the project, the surveying methodology adopted is aimed at promoting the integrated use of different sensors in order to obtain compete 3D model of the building. The pursuit of a "best practice" methodology, has been a focal point both during the inception and the operational phases of the activities carried out.
An accurate topographical and architectural survey has been carried out using the latest equipment such as laser scanner with integrated digital camera, UAV, GNSS receiver and Total Station. In particular, the requested survey will be used as a basis for a clear mapping of the different construction techniques and for the identification of different types of deterioration, without considering that the documentation produced will be very important for keeping track of the situation before and after the restoration work.
The definition of the representation scale entails the design of the acquisition campaign, considering both parameters and acquisition times. The geomatic acquisition systems chosen for this survey where the following:

- Drone (Photogrammetry): DJI Phantom 4 RTK
- Laser Scanner: Faro Focus^{M}70 CAM2

a. b.

Figure 3. Tools used for 3D survey: a. DJI Phantom 4 RTK for close-range aerial photogrammetry; b. Faro Focus^{M}70 CAM2.

Each survey technique requires different data collection procedures, and each technique is characterised by different accuracy and resolution. Therefore, as explained below, a TLS survey was carried out in all accessible exterior and interior spaces where 1:20/1:50 scale accuracy was required.
Meanwhile, automatic digital photogrammetry using UAV images was considered to survey some inaccessible areas of the complex where lower accuracy and 1:100 scale could be accepted, such as the roofs and some high parts of the main building facades. Details about the collected data are reported in Table 1 and described in details here following.

SYSTEMS	SENSOR	DATASET
UAV	DJI Phantom 4 RTK	1468 images
TLS	Faro Focus^{M}70 CAM2	146 single scans

Table 1. General overview of sensor employed and data acquired.

3.2.1 Data collection phase

The surveying operations were carried out by employing the Faro Focus^{M}70 laser scanner (Table 2). It is a high-precision laser scanner with an integrated HDR camera that captures high-resolution colour images during the scanning process. The camera can also capture panoramic images, which in this case were essential for further processing. Numerous high contrast markers were placed on most vertical surfaces (walls of rooms, courtyards where applicable and façades), with the provision of having at least two markers visible from each scan position. In parallel, all markers were surveyed through a total station (Leica TS-02) following the establishment of a polygonal network placed within a local reference system (Figure 4).

Faro Focus^{M}70 CAM2 - *Datasheet*	
Laser scanner	
Laser class	Class 1
Range	up to 70 meters
Measurement accuracy	±1mm
Measurement rate	up to 976,000 points per second
Field of view	360° x 305°
Camera	
Integrated HDR camera resolution	165 megapixels
Integrated HDR camera range	up to 135 meters

Table 2. Faro Focus^{M}70 CAM2 Datasheet: key features.

Faro Focus^{M}70 terrestrial laser scanner was used to create 3D point cloud of Emir Palace. All rooms in the first and second floors are scanned with checkboard targets. Exterior facades are also scanned from outside. In total the palace was scanned from 146 positions (Figure 4). The number of TLS stations and their concrete location depend on the topography, the ratio of building height to street width, the presence of vehicles and people, etc. Target based registration method was used to register of all point clouds. In order to measure the coordinates of each target, control points were established outside and inside of the palace, first and second floor. In total, 34 control points were counted within the control network. The network was also joined with the second floor of the building, while here in this paper only the recordings of the first one are reported. Least square methods were used to adjust these control points using STARNET software. Standard deviation of error propagation was estimated maximum 1 sm (Table 3). Then from these control points, the coordinates of each target points were estimated using Leica TS-02 total station.

Figure 4. Upper view of the TLS scans positions (146).

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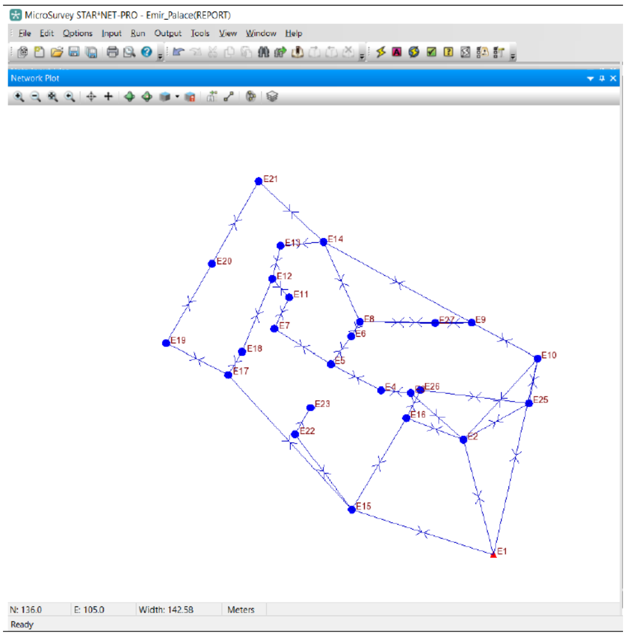


Figure 5. Closed polygonal with the Total Station and network of the control points. Example from the first floor.

Station	X	Y	Z
E1	0.000000	0.000000	0.000000
E2	0.000555	0.002114	0.002222
E10	0.001734	0.002796	0.002428
E15	0.002568	0.001851	0.002596
E3	0.002853	0.003180	0.002617
E16	0.002292	0.002129	0.002410
E25	0.001481	0.002588	0.002435
E4	0.003994	0.003207	0.002652
E9	0.003604	0.003113	0.002714
E5	0.003411	0.003335	0.002709
E6	0.003833	0.004024	0.002730
E7	0.004224	0.004132	0.002924
E8	0.003684	0.003360	0.002732
E14	0.004371	0.003684	0.002948
E27	0.004652	0.003110	0.002781
E11	0.004432	0.004616	0.002938
E12	0.004204	0.004318	0.002935
E13	0.004517	0.004012	0.002958
E18	0.003844	0.004747	0.003177
E21	0.005493	0.004588	0.003437
E17	0.003453	0.004112	0.003185
E22	0.003810	0.004321	0.003455
E26	0.002745	0.002575	0.002486
E20	0.004934	0.005216	0.003609
E19	0.004441	0.005013	0.003444
E23	0.005003	0.006830	0.003679
		Standard deviation	<1sm

Table 3. Station Coordinate Standard Deviations (meters).

Phantom 4 RTK - *Datasheet*	
Aircraft	
Take-off weight	1391 g
Maximum altitude above sea level	6000 meters
Flight autonomy	About 30 minutes
Camera	
Sensor	1" CMOS; Effective Pixels: 20M
Optics	Field of view (FOV) 84°; 8.8mm/24mm (35mm format equivalent) f/2.8 - f/11 autofocus 1m - ∞
ISO range	100 - 3200 (automatic) 100- 12800 (manual)
Maximum image size	4864×3648 (4:3) 5472×3648 (3:2)

Table 4. DJI Phantom 4 RTK *Datasheet:* key features.

UAV image acquisition was performed using a DJI Phantom 4 RTK drone. In order to achieve a more appropriate acquisition, three flights were made to collect data from the outdoor area in manual mode and to avoid the lack of GNSS connection due to the urban complexity around the complex. The datasets were acquired with a nadir and oblique camera configuration and then integrated into a single photogrammetric project to obtain a complete aerial model of the area (Figure 6).

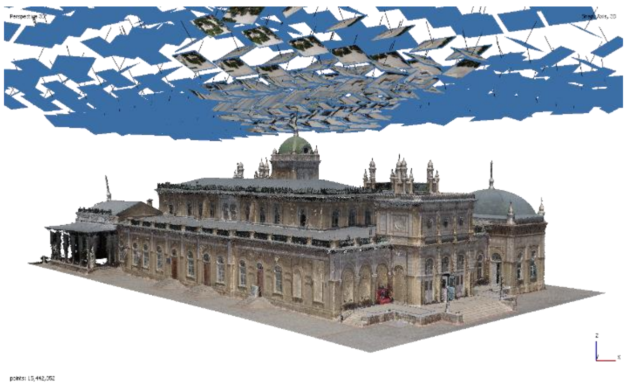


Figure 6. Photogrammetric point cloud UAV.

3.2.2 Data processing

To generate the 3D model, the point clouds obtained by laser and panoramic data image were processed using Metashape Agisoft® software, which recorded all datasets using a common reference system (local coordinates), with origin at the point where each station was located.

But first the following steps had to be taken (also shown in Figure 7):

- Image processing to convert the two-dimensional image acquired by the UAV into 3D point cloud data;
- Export the panoramic images and depth maps acquired by the laser scanner (Figure 8);
- Scale and coordinate transformation of the photogrammetric data for fusion with the laser scanning data;
- Data optimisation to facilitate interoperability and data management.

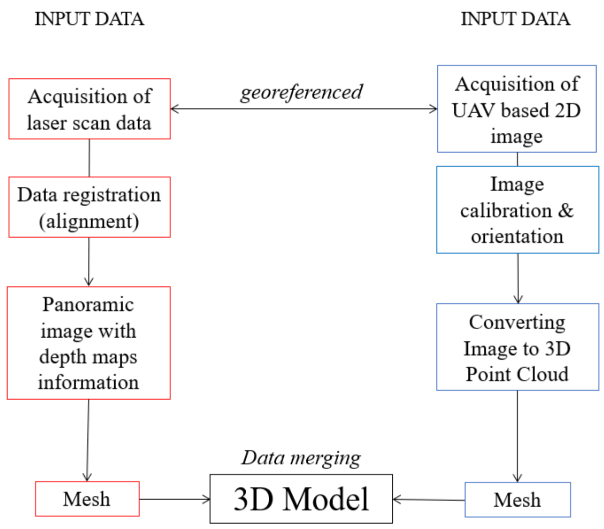
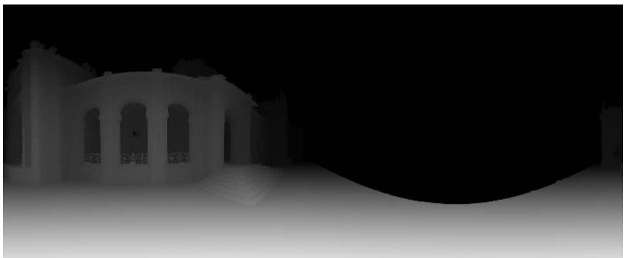
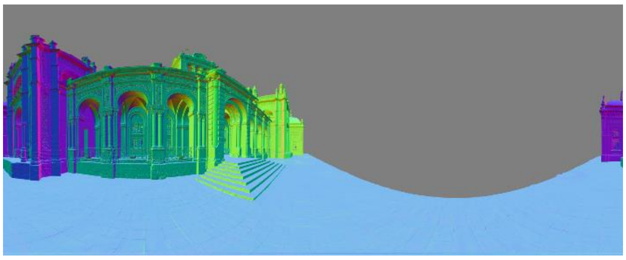


Figure 7. Methodology Workflow.

a.



b.



c.

Figure 8. Example of panoramic images by laser scanner: a. diffuse; b. depth maps; c. normal.

In order to obtain a clear mapping of the different construction techniques and to identify the different types of degradation present, no direct work was done on the point clouds, although they were very dense. But the SfM - Structure from Motion workflow relied on the panoramic photos acquired by TLS to generate a surface model.

DATA COLLECTION		DATA PROCESSING	
SENSORS	IMAGES	PRODUCTS AND OPERATION	SOFTWARE
Close-range terrestrial photogrammetry	Spherical	Point Cloud SfM approach	Agisoft ® Metashape
Close-range aerial photogrammetry	Frame		

Table 5. Data collection and processing

After loading all the images and laser scan data into the Metashape project, it was not possible to follow the traditional model building workflow, but to use a special overlay script[1]. Alignment is then carried out using corresponding points between the scans, which are used to triangulate the camera positions in the same space during the survey.
At the end of the alignment, the mesh is generated based on depth maps, which correctly utilise the depth data from the laser scan and incorporate this information into the reconstruction process of the digital image depth maps.
This procedure was carried out for both the elaboration of the interior and exterior parts of the Emir Palace, but separately, as different scales of detail were required.

An individual project was carried out to achieve the required level of detail on a scale of 1:20 for each interior space surveyed (31 elements).

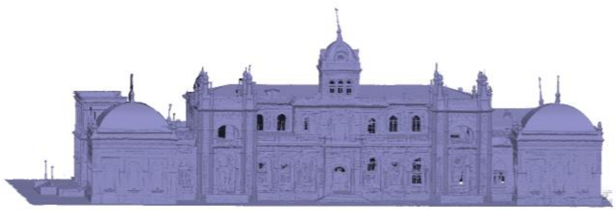


Figure 9. Merging Mesh.

To obtain a complete mesh of the exterior of the building, it was necessary to supplement the mesh obtained from the reconstructed point cloud with UAV images.
If the TLS scans are essential to improve the details of the mesh, the UAV scans provide general information about the geometry of the scene. The limited accuracy of the latter at image level is considered sufficient to reveal the shape and structure of the surface. The integration of the two surfaces improves the completeness of the coverage, allowing the modelling of details and complex heritage objects. The global mesh of the Emirate Palace appears to have a slightly lower level of detail due to the difference in resolution between the spherical and photogrammetric images, while maintaining a level of detail at a scale of 1:50.
The colour information obtained from the scanner's camera was then used to generate the various orthophotos required for the restoration project.

[1] Script Metashape (https://github.com/agisoft-llc/metashape-scripts/blob/master/src/quick_layout.py)

Figure 10. High resolution ortho-image for 1:50 representation scale. Example of the Main Façade.

In fact, Mesh-generated orthophotos are obtained by processing a 3D model based on a mesh, resulting in an orthogonal projection of the photographed object (Xu et al., 2014). The use of mesh-generated orthophotos is important as they provide a precise and detailed image of the architecture in question, enabling the precise identification of details of the structure and the planning of targeted restoration work. In particular, this type of imagery can be used to detect lesions, cracks and other structural issues that may be difficult to detect with other techniques (Cera et al., 2017; Okada et al., 2016).

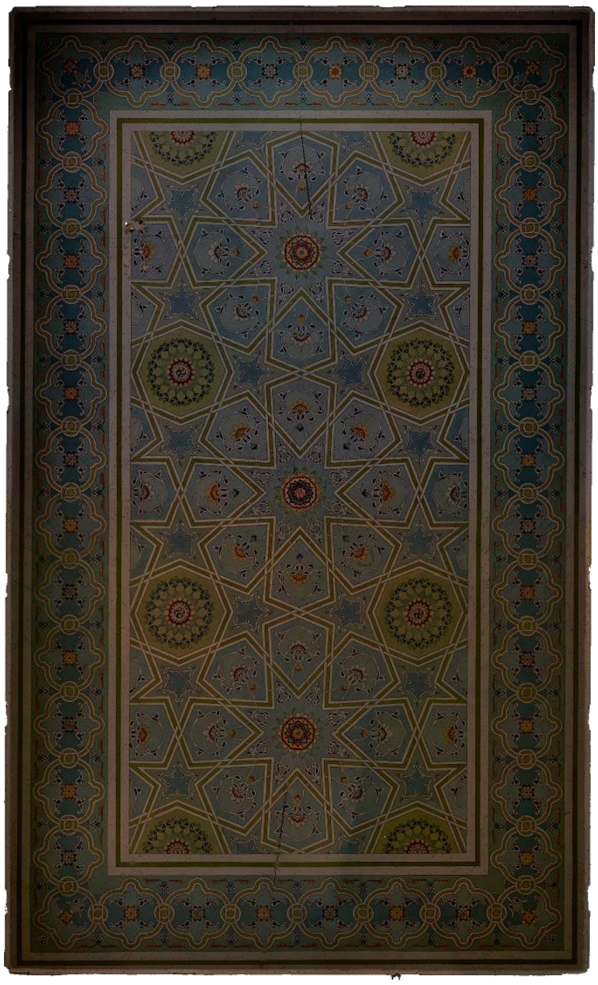


Figure 11. High resolution ortho-image for 1:20 representation scale. Detail: hypography.

Figure 12. High resolution ortho-image for 1:20 representation scale. Example of Room D. Detail: mesh and orto-image.

a. b.

Figure 13. Project drawings: a. Mapping Material; b. Mapping Decay.

The same procedure was also used to obtain orthophotos of the exterior elevations, longitudinal sections, floor plans of the Emir Palace and its rooms, including floors and hypography (es. Figure 11-12).

4. RESULTS

Based on the field survey, 3D point cloud models of the building under investigation and the parts of the building to be analysed and restored were produced. Orthophotos of plans, sections and elevations and the corresponding metric survey drawings were produced. This type of documentation will be very important not only for the current project, but also for documenting the situation before and after the restoration work.
At the same time, data collection and historical research was carried out to gain a deeper understanding of the development of the buildings and their surroundings, as well as other information relevant to the project, such as similar types of buildings, applicable laws and regulations, or the ownership and location of utility services.
Thanks to the work describe before, different actors and experts were able to proceed with several kinds of analysis. Indeed, one of the first outcomes of the developed work was a thorough documentation that could be adaptable for different purposes. Indeed, the developed 3D model could be managed and queried, allowing to decompose the whole building according to the specific need.
In particular, several degradation maps and material maps were produced as elaborates, as they are important tools in a historic building restoration project.
A decay map with the graphic representation of the current condition of the building, highlighting areas where decay or deterioration present in the structures, surfaces, and decorative elements was done. It has been an essential tool for identifying restoration priorities and defining necessary interventions to restore the building to its original condition. The decay map also contributed in identifying factors that were responsible to the deterioration of the building, such as atmospheric pollution, acid rain, humidity, and other external agents. An example of this kind of output is depicted in Figure 13b.

On the other hand, a materials map with the graphic representation of the various types of materials used in the construction of the historic building, such as stone, brick, wood, iron, glass, and other materials was produced. This map has been useful for identifying the original materials used in the construction of the building and for defining the most appropriate restoration interventions for each type of material. For example, the materials map can indicate the use of specific stones that may be difficult to obtain and require particular attention and care during restoration (Figure 13a).
Both the decay map and materials map are essential for the success of a restoration project. They help identify the most appropriate interventions for the preservation and conservation of the historic building and ensure that the restoration is carried out in a scientifically sound manner.
Several scientific articles have discussed the importance of these tools in cultural heritage restoration projects. For example, a study by Franco et al. (2017) highlighted the importance of decay mapping in the restoration of historic buildings, demonstrating how this tool can help identify the causes of decay and guide the selection of appropriate restoration interventions. Similarly, a study by Ferreira et al. (2020) emphasized the significance of materials mapping in cultural heritage restoration, discussing the importance of identifying and characterizing the original materials used in historic buildings to ensure their proper conservation and preservation.
The contribution of the proposed work moves in this direction, by developing a strategy that enable different experts to cooperate within the same accurate model, with a high degree of precision. Indeed, once the 3D point cloud was registered in Recap, the advantage of importing it in a photogrammetric software and to manage it completely within it lies in the possibility to extract data with the required level of detail, decomposing the building in sub-elements and elaborating the different data "on-demand".

5. CONCLUSION

In this paper, a combination of geomatic techniques to document a complex building was proposed. The work, beside adopting well-established procedures, confirms the importance of exploiting the topographical network for the registration of the TLS point clouds, with a millimetric accuracy for the whole building. The Polygonal network was essential even for merging the Photogrammetric data, and to validate the subsequent "by-products" of the processing. In conclusion, the use of photogrammetry and laser scanner technologies provides different approaches to survey a cultural heritage object, each with its own strengths and weaknesses. The photogrammetric approach is cost-effective, but its software for close range applications is still limited in generating dense surface models automatically.

The laser scanner approach, on the other hand, is expensive but is indispensable for accurate modeling in complicated cases. Both methodologies require a topographic survey for quality testing and precise georeferencing procedures, and modeling aspect becomes more and more important. However, the integration of these two systems has shown to ensure fast and efficient 3D surveying for complex historic architectures. It is worth noting that, in cases like this where there are not commercial software available to process TLS data, the integration of the depth map from the TLS panoramic images can be a valuable alternative to achieve the maximum result possible in terms of both accuracy and quality of the images; indeed, orthophotos could be printed with a scale of representation lower than 1:10. The research conducted shows how the integration procedure between the two systems ensures fast and efficient 3D surveying for complex historic architectures, such as the Emir's Palace. The work, performed in a joint venture between Academia and SMEs, is an excellent example (useful to be shared within the research community dealing with 3D representation and optimization) of innovative methodologies developed to produce reliable drawings and 3D representation for different purposes, being the starting point for each kind of project.

ACKNOWLEDGEMENTS

This work was partially founded within the Project "Consulting services for the preparation of detailed design, bidding documents, and construction supervision for restoration and adaptive reuse of the emir palace and selected cultural heritage assets in Kagan" by the ministry of investments and foreign trade of the republic of Uzbekistan. The authors would like to thank Alessandra Toccacieli for her dedication, Prof. Fulvio Rinaudo, vice Rector of Taschkent University for his suggestions, and a special thank goes to the students that, despite a temperature of over 50C°, continued to work hardly.

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