FAST OR EXTENSIVE? COMPARING WORKFLOWS FOR THE GEOMETRICAL ANALYSIS OF THE BUILT HERITAGE

Davide Del Curto[1], Andrea Garzulino[1], Umair Shafqat Malik[1]

[1] Department of Architecture and Urban Studies, Politecnico di Milano, Italy
(davide.delcurto, andrea.garzulino, umairshafqat.malik)@polimi.it

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ABSTRACT:

Three-dimensional digitization has been widely used for the documentation of built heritage. This paper presents two different approaches to the three-dimensional documentation of historic buildings using active 3D Terrestrial Laser Scanning (TLS) devices and data integration from other heterogeneous sources. Both methods aim to produce accurate and complete 3D surveys by integrating data from other sources, such as historical photographs, conservation reports, and traditional drawings, to enable a geometric analysis of the buildings. The first approach aims for completeness and redundancy of geometric information. The second method focuses on rapidness and is suitable for situations where the building is not easily accessible. The two approaches are applied to the case studies of Diotti Palace in Milan and Uzbekistan Hotel in Tashkent, demonstrating the efficiency of the two different datasets for analyzing the built heritage. The paper compares these two approaches and highlights their advantages and drawbacks in terms of the reliability of the resulting data. The study shows how two different methodologies can be adopted in different scenarios to obtain a comprehensive database for reliable and in-depth analysis of historic buildings.

1. INTRODUCTION

The use of digital technologies in CH is becoming increasingly important and widespread. These technologies provide new possibilities for Cultural Heritage (CH) preservation, archiving, restoration, data collection, recording, monitoring, structuring, analysis, interrogation, interpretation, communication, exploitation, research, and discovery, enabling researchers to study and understand CH objects and sites in more detail. The use of accurate and comprehensive 3D surveys, in particular, can be fundamental for the analysis and interpretation of historic buildings and monuments (Grilli and Remondino, 2019).

Several approaches can be used for digitally surveying buildings. These approaches can be divided into two classes based on their operating principles. Active 3D devices project a coded light on the surface of the objects to be measured, which is then detected by a sensing device such as a camera or a photodetector. Passive 3D surveying methods, on the other hand, use ambient light to detect the features of the object being surveyed (El-Hakim et al., 1995).

Digital photogrammetry is a commonly used passive method for CH surveying. This technique employs 2D images taken from different viewpoints to detect 3D features on the surface of an object. Terrestrial photogrammetry is generally used for small to medium-sized objects to obtain detailed geometric and texture information, while aerial photogrammetry is preferred for larger, more complex, and inaccessible structures.

Digital photogrammetry is a commonly used passive method for surveying historical buildings. This method detects 3D features on the surface of an object by aligning 2D photographs taken from different points of view. Terrestrial photogrammetry involves the use of cameras placed on the ground, while aerial photogrammetry utilizes images taken from aircraft or unmanned aerial vehicles (UAVs). Terrestrial photogrammetry is generally used for small to medium-sized objects to obtain detailed geometric and texture information. Aerial photogrammetry is preferred for larger, more complex, and inaccessible structures such as the upper parts of buildings, archaeological landscapes, aqueducts, and bridges.

During the past few years, UAV-based photogrammetry has emerged as a cost-effective and reliable alternative to classical manned aerial photogrammetry for the documentation of CH sites, as well as providing valuable information for excavation and restoration projects (Remondino et al., 2012). UAVs equipped with high-resolution cameras can capture images from different angles, providing a rich data source for 3D reconstruction and visualization of CH sites. 3D documentation and mapping of archaeological sites and historical structures are easily achieved with a low-altitude image-based UAV survey (Themistocleous, 2020). UAVs can also be used to survey archaeological sites that are difficult to access or require frequent monitoring. Typical applications of such UAV surveys are the monitoring of different layers of an ongoing excavation of archaeological sites (Rinaudo et al., 2012; Sauerbier and Eisenbeiss, 2010), and 3D reconstruction of the CH sites (Fiorillo et al., 2015).

Active 3D terrestrial laser scanning (TLS) technology that relies on direct distance measurement methods, including Time-of-Flight (ToF) and Phase-Shift (PS) laser scanners, has also become increasingly widespread in the digitization of cultural heritage (CH) (Lemmens, 2011). TLS devices emit a laser beam that scans the object's surface, and a sensor records the reflected light, which is then used to create a 3D point cloud. In ToF laser scanners, a short pulse of light is emitted from the laser, and the time taken for the light to travel to the object's surface and back to the scanner is measured. The distance between the scanner and the object is then calculated based on the speed of light. In PS laser scanners, the phase shift of the laser light wave is measured as it reflects off the object's surface. The phase shift is then used to calculate the distance between the scanner and the object. ToF laser scanners are generally faster than PS laser scanners but have lower resolution and accuracy.

TLS devices can capture millions of points in just a few seconds, making it possible to create highly detailed digital models of complex shapes and structures. They can be operated at a distance of a few meters to a few kilometers from the surface of the object being surveyed; therefore, they can be employed to measure large artifacts such as buildings, archaeological sites, or entire territories. The uncertainty of these devices can range from a few millimeters to a few

decimeters, which is usually acceptable for surveying large buildings.
The "Comité International de la Photogrammétrie Architecturale" (CIPA) has defined various criteria for the recording, documentation, and information management for all aspects of CH and to support and encourage the development of specialized tools and techniques in support of these activities (Quintero et al., 2017). The most important criteria emphasize the sensor and data integration (Rinaudo and Scolamiero, 2021), the use of the most suitable technologies to capture different components of built heritage (El-Din Fawzy, 2019), and achieving redundancy in estimating the quality of the obtained 3D measurements (Patias and Hanke, 2008).
Following these criteria, several researchers have proposed 3D digitization and data integration pipelines for the documentation and analysis of historic buildings, CH monuments, and built environments of historical importance. Some examples include the integration of image and range-based techniques for providing complete and multi-scalar information about complex architectures (Russo and Manferdini, 2014), triangulation-based laser scanning merged with the low-resolution models generated by photogrammetry to cover resolutions spanning from 0.25 to 250 mm (Guidi et al., 2009); and sensor integration to solve a typical problem in surveying the top of buildings with terrestrial technologies (Lasaponara et al., 2011; Meyer et al., 2015).
This paper presents two different and contrasting approaches to three-dimensional documentation of the built heritage through active 3D Terrestrial Laser Scanning (TLS) devices. Both have the same goal to create an accurate and complete 3D survey for the description and geometric analysis of the buildings. The aim of this paper is to compare these two approaches and highlight the advantages and drawbacks of the proposed experimental pipelines regarding the reliability of resulted data for the geometric analysis of complex buildings.
The first method investigates the extensive and all-embracing approach in the acquisition phase of the geometries and surfaces of a historic building. The main objectives are redundancy and completeness of the geometric information. The planning of registration activities and the analysis of existing materials have an important role. However, the criticalities of processing large information datasets must be considered and properly organized.
The second method focuses on rapidness and is aimed at situations where the building is not easily or constantly accessible, with the need to reduce the number of days dedicated to site-survey. This method requires tight planning and selection of the parts to be surveyed and a careful analysis of the existing documentation to optimize the records and direct attention to the most critical or missing areas.
The results of this article show how two different methodologies can be adopted in different scenarios to obtain a comprehensive database for a reliable and deeper analysis of historic buildings. The digitization pipelines presented here are an attempt to develop a procedural approach that can meet the most important criteria defined by CIPA for the documentation of CH. These methodologies can specifically be valuable in cases where the purpose is to create a dataset for the geometrical analysis of built heritage. The workflows also focus on the proper integration from other sources such as historical photographs, reports on the state of conservation, direct surveys, and previously available traditional drawings.
The first methodology is illustrated through the case study of the Diotti Palace. This historic neoclassical building has been the location of the office of the Prefect of Milan, Italy, since 1859. The second is instead exemplified by the case study of the Uzbekistan Hotel in Tashkent, one of the most admirable examples of Soviet modernist architecture in the city. The results show the two different geometrical datasets that efficiently represent the morphological and constructive aspects of the case studies with different stratifications and evolutions helpful in analyzing the built heritage.

2. METHODOLOGIES

2.1 The first pipeline

The first pipeline that we propose is to create a 3D database for a historic building that includes not only 3D points cloud from the actual survey but also other inter-disciplinary information on the actual conditions of the structure. It is composed of three phases: data acquisition, processing, and integration.
The data acquisition phase was structured into various blocks to enable concurrent processing and integration of data. This phase involved capturing three-dimensional geometric data utilizing laser scanning technology alongside collecting other relevant information about the building's condition. Each scanning activity was carefully documented using a serial number and manual survey drawings to mark the position, resolution, quality, intensity, color, GPS coordinates, and additional notes. Geometric registrations were arranged into blocks according to the building's location, with one block for external surfaces and several others for the interior spaces based on their levels (ground floor, basement, first floor, second floor, attic). Furthermore, some critical internal details were directly surveyed to facilitate the subsequent processing of the building's point clouds, and on-site verification was conducted using a portable computer. The collected data from each block was integrated simultaneously with other historical and complementary data, such as thermal imaging and endoscopy, which are beneficial for architectural and structural analyses.
The second phase entailed aligning the point clouds obtained during the initial phase, controlling errors generated by operations, applying filters to enhance the data quality, creating the final point cloud, and graphically vectorizing it. The aligned point clouds were utilized to automatically extract 2D plans and section drawings for subsequent vectorization in Computer-aided Design (CAD) software.
Finally, the acquired and processed data were integrated into a complete database, which could be enriched by adding other interdisciplinary data, providing the possibility to extract any geometric or historical details for geometrical analysis of the building.

2.1.1 Case study: The first case study is the Diotti Palace, a neoclassical historic building in Milan, Italy that has served as the office of the Prefect since 1859. The complex on which the Palace was built dates back to the first half of the 17th century. While the building is in good condition overall, many cracks have been observed on its internal and external surfaces. These degradation phenomena are suspected to be linked to the construction of the M4 underground metro line in Milan, which recently began in the vicinity of the palace. This hypothesis is based on a comparison of images taken before and after the construction of the M4 line.
To evaluate the ongoing degradation of the building and understand whether the M4 line construction site has caused temporary vibrations or if the degradation is still in progress, targeted structural investigations were necessary. A comprehensive approach was employed, including a three-dimensional survey using laser scanning methodology, historical-archival analysis, and targeted diagnostic investigations. This approach provided a database of information useful for the group of engineers tasked with evaluating the building's structural stability.

While previous studies and research have been conducted on the Diotti Palace's state of conservation and geometry, they are outdated and lack the level of detail required for current investigations. The only reliable data used for the three-dimensional survey were the building's plans, which were used to plan the survey and subdivide the rooms. Therefore, this study provides new insights into the structural stability of the Diotti Palace, which can inform future preservation efforts.

Apart from a few specific publications on the history and development of the Diotti Palace (Bologna, 1981; Lanza and Somarè, 1993; Raponi and Scotti, 2005), the building has also been studied over the years concerning its state of preservation, as well as its geometric and morphological characteristics. Nevertheless, these investigations are currently outdated and lack the level of detail required for the current analysis. The only source of information used for planning the three-dimensional survey was the building plans, which were used for designing the three-dimensional survey as they were reliable to locate and subdivide the rooms with respect to the physical spaces.

2.1.2 Surveying instruments: Different instruments were used for the data acquisition phase in this case study. The first step was to examine the building's material and state of conservation by inspecting its internal and external surfaces. This was done by photographic shots of the walls or portions that had cracks using a full-frame mirrorless camera (Sony α1) equipped with a wide-angle zoom lens (Sony FE 16-35mm F2.8 GM), which allowed for high-resolution photographic shots (50.1 MP) to be taken. These shots provided information on the walls' surface situation and improved the building's geometric knowledge level.

The building was analyzed morphologically by utilizing two 3D Terrestrial Laser Scanning (TLS) devices based on Phase-Shift (PS) measurements. The first was the FARO Focus 3D 120 Uni and the second was the FARO Focus 3D S350. The use of laser scanners based on PS measurements allowed for faster and more precise data acquisition than ToF scanners, which has helped overcome the initial hurdle of the maximum achievable range of up to 350 meters (Previtali et al., 2014; Rüther et al., 2009; Suchocki, 2020). Moreover, these PS devices are compact in size, making them perfect for complex and intricate situations where ease of handling and low weight are critical factors in conducting long and extensive acquisitions. Despite the approximately ten years difference between the release dates of the two devices, their data accuracy has remained quite similar.

Furthermore, two additional surveying methodologies were used to define the building's construction technologies. The first analysis involved examining the thermal characteristics of the surfaces using a non-destructive device, the FLIR T1020 thermal imaging camera. The second investigation methodology, which was destructive, involved a video endoscope to identify material changes inside the walls, particularly in the underground portions of the building. Combining these two types of analysis helped to improve the knowledge gained from the historical-archivist analysis regarding the materials and construction techniques used in the entire complex. The thermal imaging camera was particularly useful as it could identify temperature differences down to <20mK (thermal sensitivity/NETD at 30°C) for clear and low-noise results.

2.1.3 Data acquisition: Before beginning the data acquisition process, meticulous planning and design were undertaken for the registration points. Given the complex's large size, which encompasses approximately 19,000 gross square meters of flooring and around 4,500 square meters of outdoor spaces, this phase was crucial to ensure a proper balance in the number and arrangement of scans required. The first phase of the recordings commenced by capturing all external fronts visible from the entrance floor, which resulted in approximately 250 complete scans. For the indoor spaces, a rigorous survey campaign was conducted, resulting in the following registrations: 580 scans for the basement, 550 scans for the ground floor, 530 scans for the first floor and mezzanine floors, 500 scans for the second floor, and 400 scans for the attic floor. The internal spaces of the building were thoroughly captured, summing up approximately 2800 complete scans.

The survey aimed to obtain only the geometric description, so acquisitions were made in reflectance mode with grey scales to speed up registration and processing while avoiding excess data. Exceptions were made for interior spaces with complex decorations. A dense acquisition with 3-4 meters between scans was preferred due to obstructions, reduced to 2 meters in smaller or complex rooms. The resolution was determined based on the surveyed area, and a higher resolution was used for exterior scans compared to interior scans (figure 1).

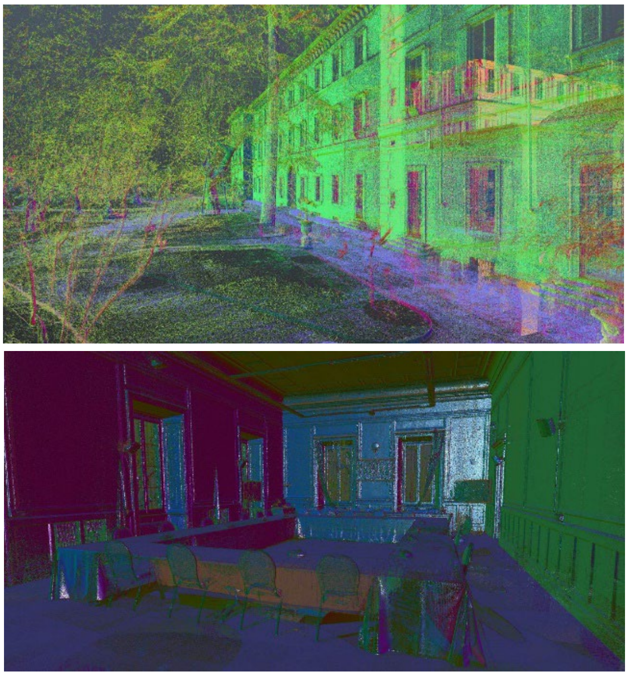

Figure 1. Perspective images of the point cloud from the exterior and internal spaces of the building.

Thermal and endoscopic investigations were focused on specific areas of the building, guided by historical-archival documentation and previous analyses. Thermal images were recorded in difficult-to-access areas, such as painted/decorated vaults and plastered surfaces (Figure 2). A number well above 50% of the detectable spaces and at least one or more rooms per homogeneous area were investigated. The spaces with recently built false ceilings were not detected (many rooms on the second floor and some on the ground and first floors) since the thermography could not provide any results of the vault hidden by a false ceiling.

Thermal shots were recorded in maximum resolution with calibrated emissivity and overlaid with RGB images for precision. Investigations were conducted passively in July and September for maximum heat and natural ventilation. Endoscopic tests were concentrated in the basement, identifying ten points of analysis for material stratigraphy and acquiring video and static images at different depths through endoscopic probes.

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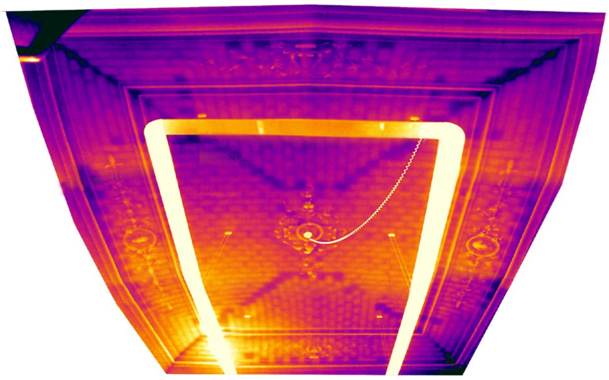

Figure 2. Thermal mosaic of one of the rooms with the vaulted brick ceiling.

2.1.4 Data processing:
Simultaneously with the on-site survey operations, the single-point clouds obtained during the acquisition phase were verified for reliability and subsequently filtered to enhance their quality through portable and desktop workstations. As the instruments could record data up to a distance of approximately 120 or 350 meters, it was necessary to eliminate all unnecessary points, redundant points, and those unrelated to the relevant activities to optimize the results.
Based on the preliminary processing outcomes, macro-blocks were aligned and registered to evaluate the actual coverage of the acquisitions, reliability, the overall density of the clouds, and the correct connection and positioning between the different levels of the building. The points clouds were pre-aligned through the cloud-to-cloud alignment method, along with an automatic top-view analysis. This produced positive results, with an average density of over 25,000 points per square meter and linear/angular errors lower than the restitution scale of 1:100.
The scan registration of the internal spaces produced average linear errors of less than 10mm due to the significant overlap between the scans and the limited room dimensions. This contributed to containing error propagation and enabling excellent accuracy of the LS internal reconstruction, unlike the external portions. The alignment and registration of the external spaces created major issues, mainly in the areas characterized by medium and low vegetation. The maximum error detected was around 25mm in areas partially covered by vegetation, while the average accuracy of the LS external reconstruction was approximately 18mm. The preliminary data analysis confirmed the accuracy of the individual recordings and the acquisition method (figure 3).
Due to the large number of scans and the extended acquisition time, it was not possible to register approximately 2,800 scans in a single group from the beginning. To address this issue, five macro-blocks were created for alignment purposes. These blocks included (1) outdoor spaces, basement level, and ground floor; (2) first-floor, mezzanines, vertical connections with the ground floor, and connections with external spaces; (3) second-floor, mezzanines, and vertical connections with the first floor; (4) attic level of the two lower buildings to the west; and (5) attic level of the main body of the building.
The five blocks shared common areas and surfaces, which allowed for additional checks of geometric coherence and facilitated the creation of a single three-dimensional database containing all the geometric information collected. Similarly, the macro-blocks were aligned using the cloud-to-cloud method along with an automatic analysis from a top view. This method resulted in positive outcomes, densities, and linear and angular errors similar to those achieved before.

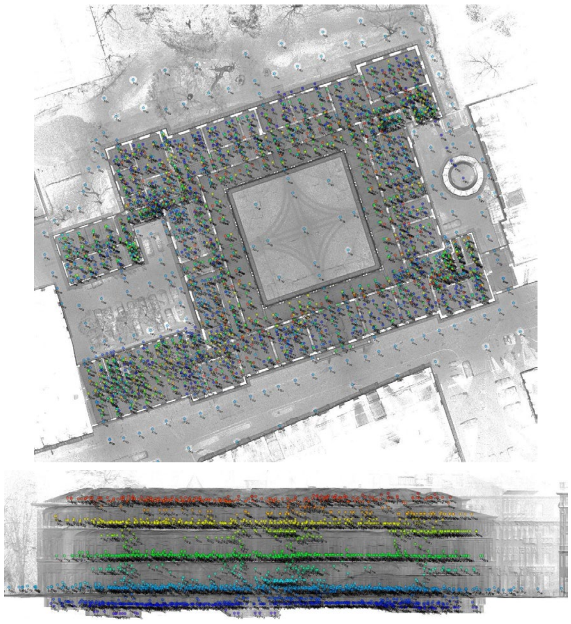

Figure 3. Top and lateral orthographic view of the complete aligned point cloud with individual scan points highlighted.

2.2 The second pipeline

The second proposed process is based on a fast approach for three-dimensional surveying using terrestrial laser scanning devices (TLS) to minimize the timing of the data acquisition phase and thus optimize the entire workflow. In fact, this method provides for the recording and subsequent processing of a selection of internal and external surfaces useful for the geometric description of the building. The proposed process is preferably applicable if the object to be surveyed has repetitive morphological characteristics, a planimetric structure that is not too complex or heterogeneous, and adequate descriptive documentation is available (historical information, drawings, photographs). Examining the building in advance is essential to plan the whole process. The first phase was therefore based on the analysis of the structure from a historical, evolutionary, and morphological point of view, identifying all the distinctive characteristics and the portions to be acquired on a three-dimensional level. This phase gave back a detailed data recording plan together with the selection of the most suitable instrumentation to be used. The second step instead included acquiring 3D geometric data through laser scanning and collecting other information on the actual conditions of the building thanks to direct surveys. As in the previous case, the performed activities were carefully documented. The acquisitions were verified on-site and processed in a subsequent phase to create a final points cloud for the graphical vectorization.

2.2.1 The case study: This methodology is illustrated through the case study of the Uzbekistan Hotel in Tashkent. It is one of the most admirable examples of Soviet modernist architecture in the city due to a well-chosen placement on the urban plot, its elegant curved shape, and, finally, the ornate full-height sun shading screen on the western façade, facing the square (Figure 4). The building was designed between 1931 and 1974, and its construction lasted about five years, from 1969 to 1974 (Gainulin, 1967; Kadyrova, 1977).
The building consists of two main sections: the first with an open "V" plan that is repeated on several levels; the second, on the other hand, is formed by a large room with a trapezoidal-like

shape that houses the reception hall and is made up of two levels (underground and ground floor). The high-rise building contains two underground levels, one mezzanine, and 16 floors above the ground, with a surface area of around 1,700 m2 per single level. The gross floor area is about 34,000m2. It is built entirely in reinforced concrete and steel and is in good condition apart from some localized deterioration patterns, which do not affect its stability.

Figure 4. Main façade of the building.

2.2.2 Surveying instruments: Different instruments and methodologies were used for data acquisition aimed at the qualitative and geometric investigation of the building. In detail, the first activities made it possible to investigate the internal and external surfaces through targeted inspection of all the rooms with the recording of photographic shots. The morphological analysis of the complex was performed using two 3D Terrestrial Laser Scanning (TLS) devices based on Phase-Shift (PS) measurements, the Leica P30 and the Leica RTC360. The former was used to map the external surfaces of the building, while the latter was used to record internal information. Furthermore, the Leica RTC360 device is very small and useful in complex situations, where easy handling and low weight play a fundamental role in articulated acquisitions. Moreover, a Leica Flexline TS09 plus total station was used to acquire the external reference points. Finally, direct measurements were obtained using laser distance meters for all portions of the building not detected using laser scanner instruments. Similarly to the first case study, some diagnostic analyses were carried out to understand the internal thermal behavior of the structure through a thermal imaging camera.

2.2.3 Data acquisition: Considering the overall morphology of the building, its walkable surface, the geometric and morphological repetition of many spaces, and the time available for the acquisitions (four days in total), we proceeded with a targeted typological survey to reduce the registration days to a minimum. In fact, the building has many floors in which the arrangement of the rooms is similar if not the same, thus allowing the information of one floor to be extended to the others after a necessary inspection and verification. For this reason, all the required spaces and surfaces to describe the Hotel geometrically were identified and divided into macro-groups:

- Group A: external elevations from the ground to the top;
- Group B: entrance hall (main spaces, stairwells, and conference room);
- Group C: 8th floor (corridors, stairwells, and some bedrooms);
- Group D: 16th floor (corridors, stairwells, and some bedrooms);
- Group E: 17th floor (main spaces and stairwells);
- Group F: main stairwell from the ground to the top.

The external elevations of the building were acquired through the Leica P30 scanner, given its excellent long-distance recording capabilities. In fact, this instrument can reach 120 meters from the survey location, keeping the points cloud geometrically coherent with a 3D point accuracy of about ±5mm. The Leica RTC360 scanner was used for the low-density external portions and internal spaces for its easy handling, low weight, and a good compromise between distance and precision. This instrument can acquire points at a distance of about 40/50 meters with a 3D point accuracy level of about ±5mm. Considering the only need for a geometric and morphological description of the building, the acquisitions were made in reflectance mode (grey scales, without color) to speed up the recordings and subsequent processing operations and avoid excessive weighting of the three-dimensional database.
Similar to the first case study, the rooms' location, and morphological characteristics did not allow a broad view of the spaces. This forced us to use a dense internal acquisition net with a step of about 5 meters, further reduced to 2 meters for the main stairwell and in most of the minor or complex spaces. Concerning the resolution parameters and the recording quality, it was preferred to use a high-resolution setting for the external acquisition than the subsequent carried out inside. A lower resolution was chosen considering the reduced distance between the instrument and the surfaces to be detected. About 450 scans were acquired, ten externally with the Leica P30 laser scanner, 40 external scans with the Leica RTC360 scanner, and 400 internal scans again with the Leica RTC360 scanner.
Finally, four reference points were materialized (Figure 5) and acquired outside the building through the Leica TS09 theodolite. The references were assigned both the UTM coordinates 42 and the relative orthometric altitude, both local coordinates with an altitude of +/- 0.00m at the entrance to the hall, to facilitate the management and drafting of the documents. The accessible spaces not captured by three-dimensional acquisitions were inspected to evaluate the typological and geometric similarities with the areas directly detected by laser scanners. To integrate the drawings, some planimetric and altimetric measurements were acquired through laser distance meters.

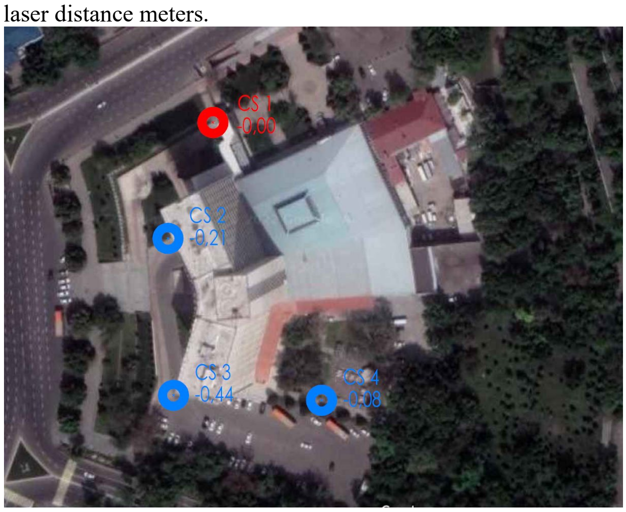

Figure 5. Aerial photo with the positioning of the external references.

2.2.4 Data processing: Similar to the first case study, The point clouds were verified for reliability and filtered to eliminate false or incorrectly acquired points. Redundant and irrelevant points beyond the survey scope were removed to

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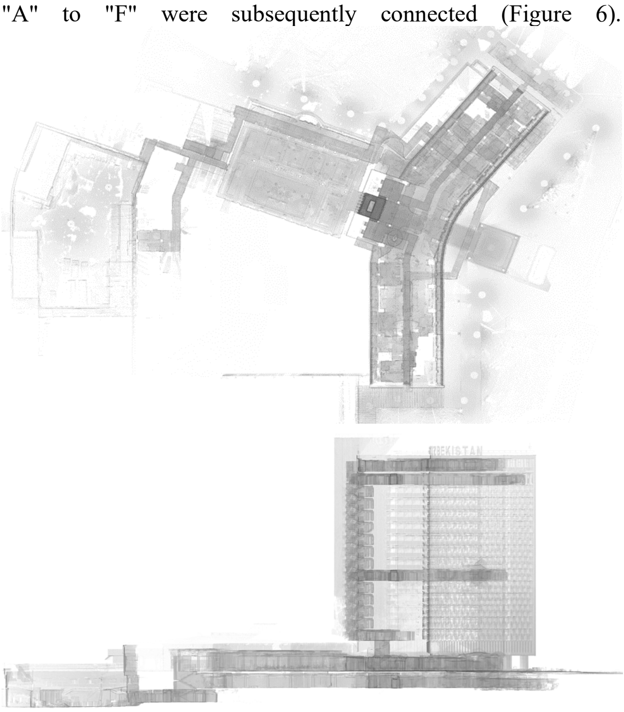
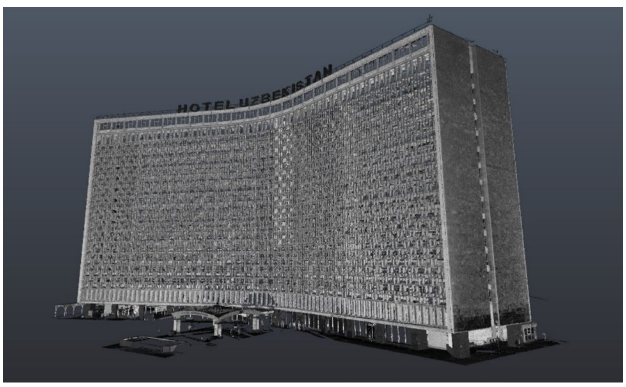
optimize the data. Macro groups of point clouds were aligned and registered to evaluate their density, reliability, and correct positioning between different building levels. The single point clouds acquired with the Leica RTC360 scanner were thus pre-aligned through a cloud-to-cloud method together with an automatic analysis with a top view, giving back positive results and linear and angular errors below the scale of drawing (1: 100). The maximum error detected was about 35mm, found only in the area in front of the spiral staircase, on the third floor. The preliminary data analysis highlighted the individual records' quality and confirmed the acquisition method.
The alignment followed the macro-groups identified at the beginning, creating six different 3D databases (from “A” to “F”).
In addition, the ten external scans acquired with the Leica P30 laser scanner were aligned following another processing method. From each of these scans, it was also possible to acquire the four references positioned outside, which made it possible to calculate the roto-translation factors of single points cloud. Thanks to these parameters, it was possible to create a separate group to which the previously processed groups from "A" to "F" were subsequently connected (Figure 6).



(a)



(b)

Figure 6. **(a)** Top and lateral orthographic view of the complete aligned point cloud; **(b)** perspective image of the point cloud from the exterior of the building.

3. RESULTS

It was possible to project all the points of the complete points clouds on determined horizontal planes to bring out all the morphological characteristics necessary for defining the geometries of the spaces and architectural elements. We opted for two types of projection, the first on the ground and the second towards the ceilings. All the horizontal projections constitute individual metric work environments characterized by unique roto-translations of the geometric components in such a way as to allow a full overlap of the levels that make up the Diotti Palace in the first case and the Hotel in the second. For each floor of the building, the following levels were exported:

- Horizontal profile of the cloud: the portion of points affected by the projection operations did not exceed 5mm in thickness;
- Projections of the points on the ground on the horizontal section plane: different projection levels have been exported based on the altimetric and morphological characteristics of the spaces;
- Projections of the ceiling points on the horizontal section plane: similar to the previous point, different projection levels have been exported based on the altimetric and morphological characteristics of the spaces.

The same export method was also followed for the elevations and sections of the two buildings (Figure 7). For the internal sections, different vertical cutting planes were identified to fully define the morphology of each room on the various levels. For the external facades, we proceeded with the projection of all the points of each elevation of the buildings on vertical planes. The following levels were exported for each vertical section plane:

- Vertical section/profile of the cloud: the portion of points affected by the projection operations did not exceed 5mm in thickness;
- Projections on the vertical section plane: different projection levels were exported based on the morphological characteristics of the rooms and the building.

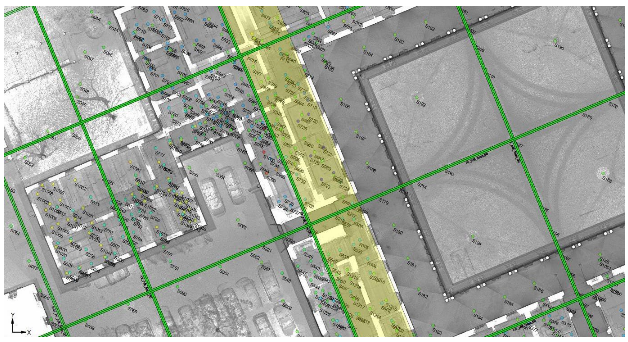
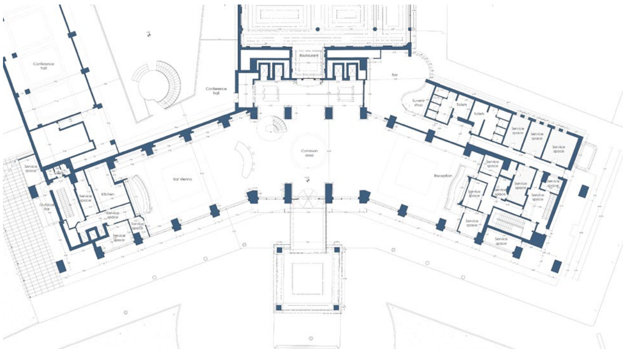


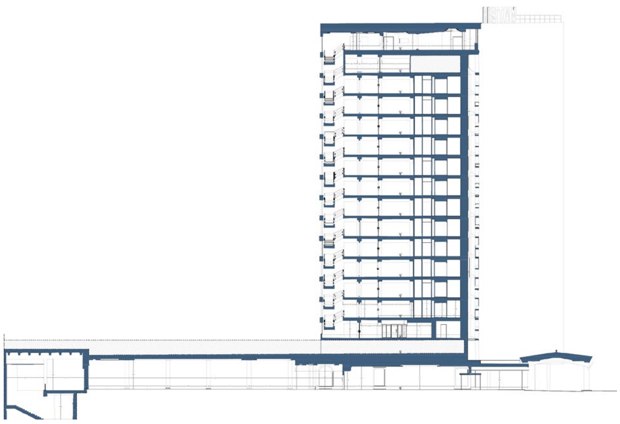
Figure 7. Detail of a portion of the Diotti Palace in zenithal view. The vertical profiles are indicated in green. The area of the projection of the points, including the entire extension surface, is highlighted in yellow.

The processing and extraction carried out in the previous phases allowed the creation of unique two-dimensional databases to ground the subsequent vectorization operation. We initially proceeded with unifying all exports referring to each section plane, horizontal or vertical, systematizing the levels in the vectorial environment. These levels were loaded, maintaining the same point of origin in such a way as to allow certain overlaps between the different horizontal section planes. For the extractions on vertical planes (internal sections and external elevations), we proceeded in the same way, keeping the altimetric position of the point cloud extractions constant and absolute, also in this case, to allow evaluations or checks. For each vector file referring to the drawings, first the section/profile levels were loaded, then the levels in the lower projection, and finally those in the ceiling projection. The different layers and the graphic layout most suitable for defining the geometries concerning the necessary level of detail (1: 100) were identified in these materials. In general, the tools and graphic codes of architectural drawing were used, as summarised below (type of line, color, thickness – Figure 8):

- Masonry section: solid line, black, th. 0.35mm;
- Doors and windows: solid line, black, th. 0.15mm;
- Front projection: solid line, black, th. 0.15mm;
- Ceiling projection: dashed line, black, sp. 0.09mm;
- Details: solid line, black, th. 0.05mm;
- Ceiling details: dashed line, grey, sp. 0.05mm.



(a)



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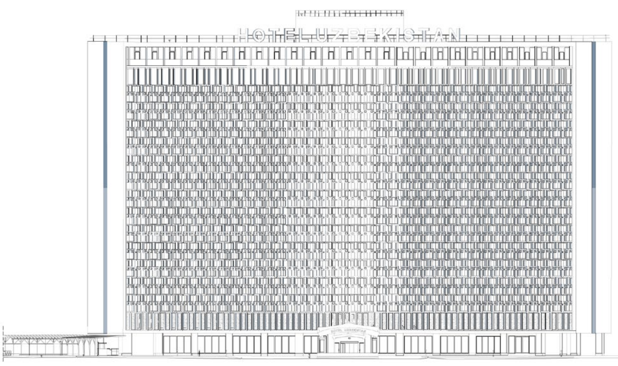

(c)

Figure 8. **(a)** Detail of the ground floor plan of the Uzbekistan Hotel; **(b)** cross-section; **(c)** main external façade.

Concerning the sectioned walls, indicating the area through a solid continuous background was preferred to immediately recognize the wall section affected by the horizontal or vertical section plane. The portions of masonry hidden or not directly detected by the instruments were indicated by a dashed black line with a thickness of 0.35 mm. Therefore, the color and thickness used previously for the sectioned visible structures were maintained by varying only the line type. This system was used only for the completely covered portions of the masonry or for the rooms or spaces to which there was no access. These geometric indications resulted from direct analyses and measurements carried out, thanks to some points of the three-dimensional cloud or, in the absence of information, by analogy with respect to similar and comparable spaces or situations.

The level of simplification of the geometries followed the level of detail of the representation. Therefore, the elements or details smaller than 3.00cm were not represented. In comparison, the characteristics of dimensions between 3.00cm and 7.00cm were simplified to avoid weighing down or making the reading of the graphic elaborations unclear. However, this method did not affect the section's precision, and the survey's level of reliability remained unchanged by the simplification operations. Finally, all the representations were characterized by linear and altimetric dimensioning and textual information.

4. DISCUSSION AND CONCLUSION

The article proposes two pipelines for the documentation of complex historical buildings. The first pipeline, with extensive survey and a prolonged acquisition time, was tested on the case study of Diotti Palace. The results obtained from this process contain three-dimensional metric information to which information from other sources has been anchored. Specifically, the implementation through historical-archival investigations and diagnostic analysis has played a crucial role. The first pipeline is based on typical 3D surveying and data integration techniques. However, the proposed methodology of data acquisition/integration and the validation of the robustness of the resulting data set it apart from other methodologies proposed previously in the literature. The resulting 3D dataset was easily shareable and interpretable after the data acquisition step.

The redundancy of data produced by the first pipeline might pose some drawbacks related to the additional time required for 3D survey planning, data acquisition, and processing. The authors suggest using the proposed pipeline only in cases where: the purpose is to measure the structural vulnerability of a complex building, the sharing of large databases among different professionals is required without additional surveys for specific needs, and the subsequent integration of data from heterogeneous sources might be required.

On the other hand, the second pipeline is characterized by a precise and detailed selection of the spaces to be surveyed to speed up field operations using laser scanner devices. This process has the advantage of greatly simplifying the point cloud acquisitions while still giving back geometric data as reliably as in the first case under examination. It can also be argued that the smaller number of three-dimensional data facilitates data processing. In fact, the reduction in processing times and possible criticalities in the alignment and data recording phase is remarkable.

However, this expeditious methodology has inevitable drawbacks as the acquired and processed portions cannot perfectly define all the spaces of a building. Even in a case like the Uzbekistan Hotel, where the floors are repetitive and tend to be identical, it is difficult to state the exact geometric characteristics of the elements not detected through laser

scanners. This problem can be mitigated by taking some measurements using laser distance meters. However, direct measurements take a long time and, in any case, do not have the same level of detail and accuracy as laser scans. In that case, the authors suggest using the faster approach only in cases where: graphic materials are available and valuable for defining the spaces to survey; repetitiveness of the spaces/levels of the building; short time available for acquisitions and three-dimensional processing; no need for structural analysis or requiring levels of detail for all building elements.
In conclusion, the two proposed data acquisition/integration methodologies proved efficient for the purposes and the level of detail to be achieved. The comparison between them based on specific requirements of extensiveness/speed will provide guidelines for future works in the documentation of built heritage.

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