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A MULTI-SENSOR APPROACH TO SURVEY COMPLEX ARCHITECTURES SUPPORTED BY MULTI-CAMERA PHOTOGRAMMETRY

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ABSTRACT:

Point clouds are nowadays a standard format of three-dimensional data. Various survey techniques are available, differing in characteristics, mode of use, and target applications, nevertheless producing point clouds that are similar, comparable, and combinable. According to recent literature, combining data from multiple sensors is an established practice for large surveying projects, particularly in Cultural Heritage, where the geometric complexity of buildings encourages the employment of many sensors. This paper presents a multi-sensor approach to surveying complex architectural spaces. The case study is the Cathedral of Aosta (AO) in Italy, which is interested in a conservation project that requires investigating the two bell towers of the cathedral. The survey aimed to produce a point cloud of 5 mm resolution and 1-2 cm accuracy compatible with the 1:50 scale of representation. The following survey techniques were employed: (i) laser scanning, (ii) terrestrial photogrammetry, (iii) UAV photogrammetry, and (iv) multi-camera fisheye photogrammetry. The distinctive feature of our approach lies in the multi-camera survey, conducted using a prototype composed of five fisheye cameras. The paper describes the data acquisition phase conducted with the different techniques, the mutual verification of the data performed by cross-sections check, the segmentation, and the final assembly of the various portions until a complete point cloud with homogeneous characteristics is obtained. All the data were then collected in a web platform (FlyVast) enriched with data and info made available to the professional to plan future interventions.

1. INTRODUCTION

Geomatics has produced numerous techniques and methods for acquiring 3D information. Recent years have seen an increase in high-density data acquisition methods, which allow the three-dimensional geometry of an object to be characterized with high spatial resolution. Point clouds are now among the most popular survey outputs and a standard three-dimensional data format for most instruments and techniques. The various techniques available, therefore, while differing in characteristics, modes of use, and target applications, produce point clouds that are similar, comparable, and combinable. Consequently, the use of different techniques and their subsequent combination through aggregating their respective results has become an established practice for the geometric description of complex objects. According to recent literature, the combination of data from multiple sensors is now necessary for large survey projects, particularly in Cultural Heritage (CH), where the geometric complexity of buildings encourages the use of many sensors. Many CH digitization projects adopt the strategy of multi-sensor surveying by fusing together range-based with image-based approaches. This is the case with the fusion of the two most widely used surveying methodologies at the architectural scale: surveying with TLS (Terrestrial Laser Scanner) and with close-range photogrammetry. Grussenmeyer et al. (2012) propose a CH documentation approach that involves using the two techniques and validating the goodness of fusion based on visual cross-section checks and quantitative checks using topographic measurements. Fassi et al. (2011) present an approach aimed at three-dimensional modeling that integrates TLS survey with high-resolution close-range photogrammetry of decorated elements. Achille et al. (2015) present an approach that combines an interior TLS survey with an exterior Unmanned Aerial Vehicle (UAV) photogrammetric survey of a bell tower to obtain a complete 3D model; Achille et al. (2020) and Perfetti & Fassi (2022a) demonstrate the effectiveness of integrating indoor TLS, outdoor photogrammetry, and multi-camera surveys for narrow spaces. Other authors have also proposed the possibility of using a specific survey technique as a “bridge” for registering other surveys made with different instrumentation (Murtiyoso et al., 2019); and have investigated the issue of effectively merging source point clouds into unified data: by simply superimposing the information acquired by different instruments (Pulcrano et al., 2021) or by analysing geometric features such as density and roughness of point clouds (Chiabrando et al., 2022).

1.1 Paper objective

This paper presents a multi-sensor approach to survey complex CH architecture and share the obtained 3D data with different stakeholders to support an ongoing conservation project. Specifically, the case of study is the 3D survey of the two bell towers and the apsidal portion of the Cathedral of Aosta (Italy). Different survey techniques were employed to acquire the different surfaces and to obtain a complete point cloud model of the area under investigation. The final aim of the survey was to

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produce data that could be shared with the professionals working on the project.

We detail (i) the techniques employed for the data acquisition; (ii) the method used to validate and merge the source point clouds into the final one; and (iii) the strategy used to make the data available for subsequent phases using the web platform FlyVast.

1.2 Case study – the Cathedral of Aosta

The historical complex subject to survey and study are the two bell towers and the apse of the Cathedral of Santa Maria Assunta and San Giovanni Battista, located within the historic fabric of Aosta (Italy). The cathedral shows a complex and articulated historical stratification due to the sequence of interventions distributed over a considerable time. Its foundation seems to date back to the end of the fourth century. The articulated shape and complexity of the architecture and its many elements have posed difficulty in carrying out comprehensive maintenance and conservation activities; in fact, the part of the cathedral that is more easily visited and accessible has undergone a significant number of interventions over the years, while the secondary areas, including the bell towers and the apse complex, present to this day several criticalities and advanced decay. The current state of the cathedral can be ascribed to the action of atmospheric agents, associated precisely with a lack of maintenance over time. Therefore, once the initial priorities were defined, a work plan was implemented to gather knowledge about the current state of deterioration of the architecture and to deploy a conservation project aimed at conserving the existing material, the visible surfaces, the masonry complexities, the irregularities, the artisanal nature of the structures and the diversity of various types of materials. The restoration interventions in progress concern: the external and internal walls in stones and mortars; the consolidation of the walls and structures; the contrast to the phenomena of rising damp; the restoration of the spire; the restoration of the crowning element of the roof; the fixing of the metal elements of the top part of the spire with the presence of the cross.

The restoration program is divided into three phases. The first phase of the geometric survey, the second one related to material and state of decay characterization, carried out through in-depth investigation practices aided with the indispensable contribution of the study of architectural archaeology. The third phase is the investigation of the constructive/structural components, aimed at assessing their state of conservation.

This work concentrates on the method used for the geometric survey, made thanks to the combined use of traditional and experimental geomatics survey techniques, and on the data post-processing and management to make it accessible for the subsequent phases of the project.

1.3 Our approach

As part of the ongoing inquiry, it was necessary to investigate the present state of conservation of the two square-based bell towers. Specifically: the towers’ masonry surfaces, including their external and interior faces, as well as all spaces that were close to the masonry, such as basements, attics, stairs, and tiny passageways. Given the complexity of the case study and very different environments (Figure 1), it was decided to adopt a multi-sensor approach.

The following survey techniques were employed during the project: (i) terrestrial laser scanning, (ii) terrestrial DSLR (Digital Single Lens Reflex) close-range photogrammetry, (iii) UAV photogrammetry, (iv) multi-camera photogrammetry, and (v) total station survey to materialize a supportive network for the whole activity.

Figure 1. Images of the Aosta’s Cathedral: exterior area of the apse (1, 2, 3), belfries (4), naves (5, 6), indoor view of the south tower (7, 8), attics (9, 10) and archaeological area (11).

TLS and terrestrial and UAV photogrammetry were used to acquire the larger areas and easy-accessed surfaces indoors and outdoors. At the same time, multi-camera photogrammetry was used to digitalize all the hard-to-reach narrow spaces. The distinctive feature of our approach lies precisely in the multi-camera photogrammetric survey conducted using the prototype Ant3D (Perfetti & Fassi, 2022a). This type of survey was here used to link and co-register various acquisitions separated by distribution elements and characterized by poor accessibility, solving the problem of registering disconnected areas and replacing more traditional techniques, like topographic referencing, that are impractical in those locations.

2. 3D SURVEY

The survey aimed to produce a point cloud with a point-spacing resolution of 5 mm and an accuracy of 1-2 cm compatible with the 1:50 scale of representation.

The larger interior spaces of the cathedral (altar, apse, sacristies, bell room, and some exterior surfaces) and the outer walls of the apse were acquired by TLS survey. The exterior surfaces were obtained by photogrammetric survey using a DSLR camera with different fixed optics and two UAV platforms. Finally, all confined spaces, including cellars, attics, stairs, and passageways, were acquired with the Ant3D multicamera system (Perfetti & Fassi, 2022a). A total station was also used to materialize a topographic network to record all data and verify its accuracy. However, due to their inaccessibility, topographic measurements could not reach all the acquired environments. Therefore, in the present case, it was necessary to rely on the accuracy of the survey and the robustness to drift error of the multi-camera system, which connects all the other surveys. The expected drift error for the multi-camera system was estimated based on previous tests conducted and detailed in Perfetti & Fassi (2022). In those tests, the instrument measured a drift error of about 3-5cm per 100 meters of unconstrained trajectory traveled. Figure 2 shows a scheme of the apsidal area of the cathedral, indicating the areas in which the various instruments were deployed.

2.1 Total station survey

Topographic support is the best way to combine surveys from different sensors into a single coordinate system and verify their accuracy. However, the characteristics of the narrow spaces in the cathedral (Figures 1) did not allow the network to be extended inside the two bell towers. Nor to reach the top of the towers. Therefore, a topographic network was set up outside the apsidal area connected to the interior through the sacristy rooms and then extended to the altar area. All Ground Control Points (GCPs) that could be measured were located on the apse's and towers' exterior surfaces and inside the cathedral at the ground level. Therefore, the acquisitions made inside the towers are untethered and free of constraints except for a few targets located at the openings of mainly the North Tower. The multi-camera acquisitions (Figure 2 – #4) remain mostly untethered from the topographic network, as do the TLS scans made at the base (Figure 2 – #2) and top of the towers (Figure 2 – #1).

2.2 TLS survey

The TLS survey was conducted using three different laser scanners: Leica C10, Leica RTC360, and Leica HDS7000, employed to survey different types of areas.

The C10 TLS was used outdoors at ground level to capture the exterior surfaces of the apse and the two bell towers. Scans were acquired at high resolution: up to 3mm at 40m, to describe the top of the spires with great detail. However, the C10 survey could only capture a limited portion of the towers due to the impossibility of moving around them at the ground level before encountering obstacles. Therefore, the exterior TLS survey was insufficient to reconstruct the whole geometry and needed to be complemented by the UAV survey. Thus, the C10 TLS data was used as a geometric reference to orient and scale the aerial photogrammetric block.

RTC360 and HDS7000 were used indoors with a maximum resolution of 3mm at 10m.

The RTC360 TLS was used for the cathedral's interiors to survey all large accessible areas. These can be divided into three separate acquisitions: (i) the survey of all indoor spaces at ground level (Figure 2 – #3), (ii) the survey of the rooms at the base of the bell towers, including the larger attics (Figure 2 – #2), and (iii) the survey of the belfries at the top of the two towers under the spires roofing (Figure 2 – #1). These three acquisitions are separated by narrow spiral staircases connecting the ground level to the base of the towers and the base of the towers to the belfries. Only incomplete portions of the spiral staircases were included in the RTC360 surveys, thus rendering the three areas unconnected. Moreover, while acquisition (i) is connected to the topographic survey, acquisitions (ii) and (iii) are not, therefore, their registration in the shared coordinate system depends solely on the multi-camera connection.

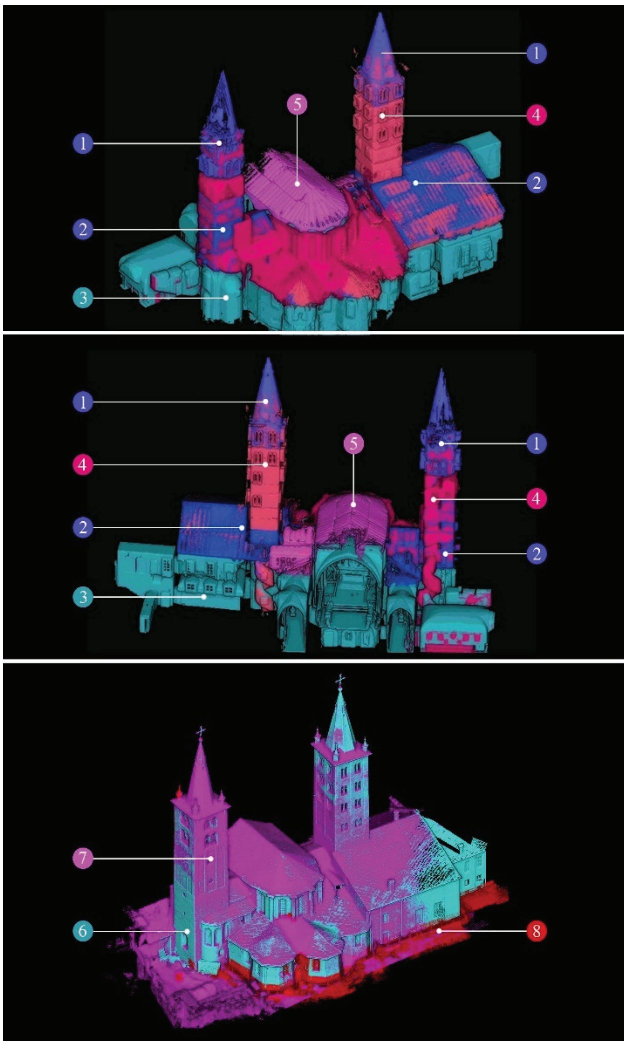

Figure 2. Acquisitions scheme. In the inside (top and centre), TLS surveys: of the belfries (1), the base of the bell towers (2), and indoor areas (3); and Ant3D surveys: of the towers (4) and attics (5). In the outside (bottom), TLS survey of the apse and portions of the bell towers (6), UAV survey of all outside surfaces (7), and DSLR + Ant3D survey of the apse and moat.

The HDS7000 was used to survey the underground archaeological part. The final number of scans for all the TLS surveys is 174.

The scans acquired from the various instruments were registered with the Leica Register360 software, using only the cloud-to-cloud method. The final registration accuracy of the single scan-to-scan registration was between 1 and 6mm, depending on the dataset. A final target-based referencing in the topographic reference system was performed for the ground-level datasets, at the end of the process achieving an absolute error of around 7 mm using 15 well-distributed GCPs. An error of 1,5 cm is estimated for the manual picking of distant targets on top of the towers. The result suits the 1:50 representation scale and the complexity of the case study and surveyed spaces.

2.3 DSLR and UAV photogrammetry

The photogrammetric survey was carried out with a DSLR camera and two UAVs. The photogrammetric acquisition allowed the complete surface description of the roofs and bell towers, which otherwise could not be reached from the ground.
The DSLR survey was carried out with the Nikon D810 camera by making several acquisitions with different fixed optics to maintain a GSD (Ground Sampling Distance) of about 4 mm for all surveys. The exterior surfaces of the apse and the exterior surfaces of the towers were acquired by employing a 105mm optic from ground level and a 50mm optic from one tower pointing to the other. However, similar to the TLS C10 survey, the ground photogrammetric survey allowed the apse to be surveyed. Still, it was incomplete in describing the geometry of the towers.
The UAV survey was conducted with DJI Mini 2 and DJI Mavic Pro drones. The former was used to capture the roofs, while the latter was used to survey the vertical faces of the bell towers. The image-capturing scheme employed for the survey of the towers was carried out similarly to what was described in Achille et al. (2015) by acquiring images by columns.
The two datasets, terrestrial and UAV, comprise a total of 973 and 2230 images, respectively, that were processed separately in the Agisoft Metashape software, from which orthophotos of all exterior faces were also obtained (Figure 3).

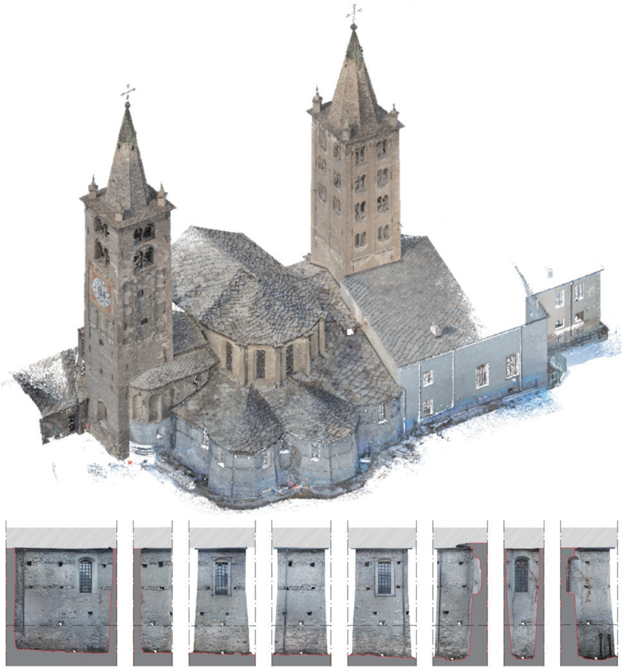

Figure 3. 3D views of the photogrammetric point cloud generated from the union of the DSLR ad UAV surveys (top), and orthophotos of the apse (bottom).

2.4 Multi-camera survey

The multi-camera survey was carried out with Ant3D (Figure 4), a prototype of an image-based measurement device developed as part of the activities of a doctoral thesis (Perfetti, 2022). The multi-camera instrument was specifically designed for agile and rapid surveying of confined spaces. It comprises a hand-held device with five cameras equipped with fisheye lenses. Data acquisition is made on the move, recording a sequence of synchronized images at a predetermined frame rate during the operator walks through the environment, carrying only the compact device. The set of images thus acquired is then processed by SfM (Structure from Motion) and MVS (Multi View Stereo) until a scaled, colored point cloud of the surveyed object is produced. Because of the instrument’s wide field of view (Figures 5), the number of frames required to reconstruct extensive interior environments is reduced compared with a classic DSLR photogrammetric survey. Because of the a priori known distances between cameras, a scaled model is obtained. The instrument’s characteristics make it ideal for the case study at hand, where it is required to survey the complete geometry of narrow spaces characterized by poor accessibility in which it is difficult to operate with bulkier instrumentation. In Perfetti et al. (2022b), the survey of narrow tunnels carried out with Ant3D for high-resolution 3D reconstruction is described, while in Perfetti and Fassi (2022a) a drift robustness test carried out in the CH field is detailed from which an average error of about 3-5 cm per 100m traveled by the instrument is shown.

Figure 4. Ant3D survey activities: north tower (top row), apse attic (bottom left) and underground area (bottom right).

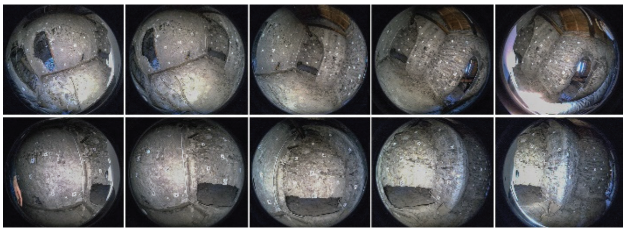

Figure 5. Multi-images acquired with the Ant3D multi-camera. Each row is a pose of the multi-camera during calibration.

Using Ant3D, all the narrow spaces present were surveyed, specifically (i) the north tower, (ii) the south tower, (iii) the low level of apsidal attics, (iv) the high level of apsidal attics, (v) the foundation of the north tower, (vi) two underground areas in the apsidal area, and (vii) an external moat running along the perimeter of the apse.

For both tower surveys, the acquisition was started in the altar area. The respective first-level spiral staircases leading to the base of the towers were traversed, and here, all rooms were acquired. From here, the survey of the north tower proceeded by navigating the various levels of the floors using the wooden ladders until reaching the top (Figures 4 - top row). On the other hand, the survey of the south tower proceeded in two directions: (i) coming out on the low roof of the apse, the roof was traversed until reaching the north tower, and (ii) from the base of the south tower, a second-level spiral staircase was taken up to the belfries. The acquisitions of the two bell towers are thus tied together at the start and at the low roof level of the apse. They are constrained on GCPs at the beginning of the trajectories, on the ground floor, and on all levels of the north tower and the top level of the south tower, which feature large openings where targets have been placed and measured from the outside. All portions of the trajectories along the spiral stairs are unconstrained. Figure 6 shows the result of the alignment of the south tower.

The surveys of the apse attics were carried out starting from the rooms at the base of the north tower. Some narrow connections (Figures 4 - bottom row on the left) were traversed until the respective attics were reached and acquired. These two acquisitions are constrained solely at the starting point, based on the location of the rooms from which the acquisitions were started, which in turn is dependent on the accuracy of the survey of the north tower.

The survey of the north tower's foundations and the apse's two underground areas were also unconstrained. These acquisitions were registered based on cloud-cloud registration with the TLS surveys by taking advantage of common overlapping areas at the beginning of the acquisition.

Finally, the exterior moat survey was performed to facilitate the photogrammetric survey operations of the exterior. In this case, the Ant3D acquisition is constrained to its full extent on GCPs.

Acquisitions	Duration [hh:mm]	N° of images
North tower	02:08	12,900
South tower	01:44	10,550
Attics	00:47	6995
Undergrounds	00:19	2880
External moat	00:28	4220

Table 1. Summary of the main data of the acquisitions carried out with Ant3D.

A total of five significant acquisitions were performed over two survey days for a total survey time of approximately 5 hours and 30 minutes and a total of 37,545 images processed. All acquired data were processed using the Agisoft Metashape software, constraining the baselines between the cameras composing the multi-camera. Table 1 shows the main data of the surveys performed with Ant3D while Figure 8 shows the 3D view of the trajectories of the main acquisitions. Figure 7 shows the mesh model of the first-level spiral staircase of the south tower obtained from the survey images and Figure 6 and Figure 9 shows the resulting point cloud of the two towers.

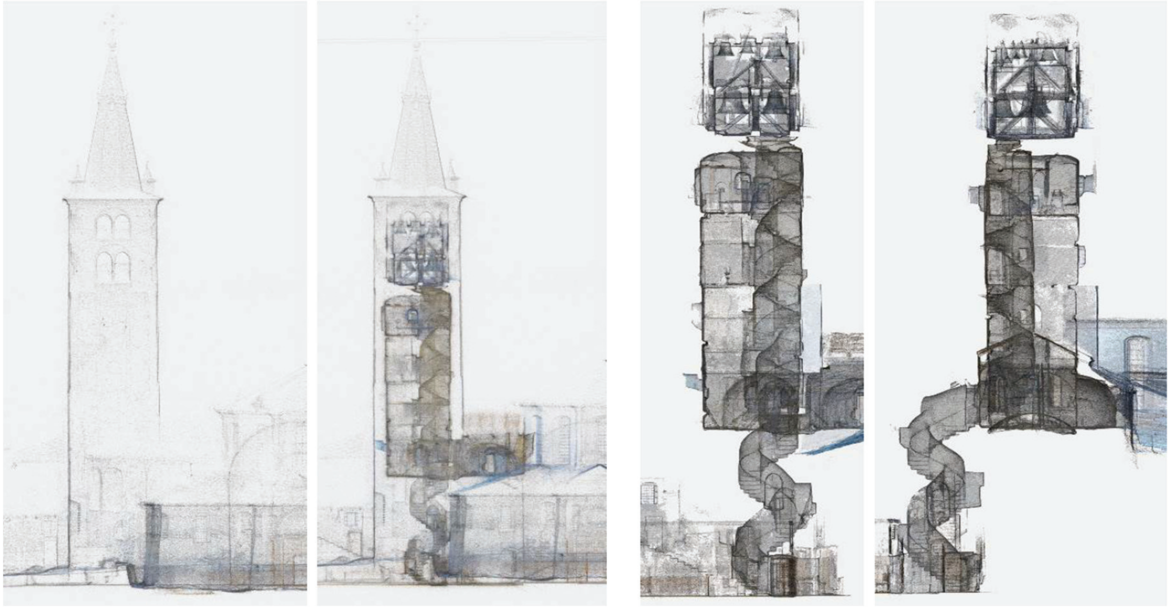

Figure 6. Images of the south bell tower survey. On the left: sparse point cloud of only the exterior surface from close-range photogrammetry (first image) and with the narrow spaces (second image); On the right: two views of the dense point cloud.

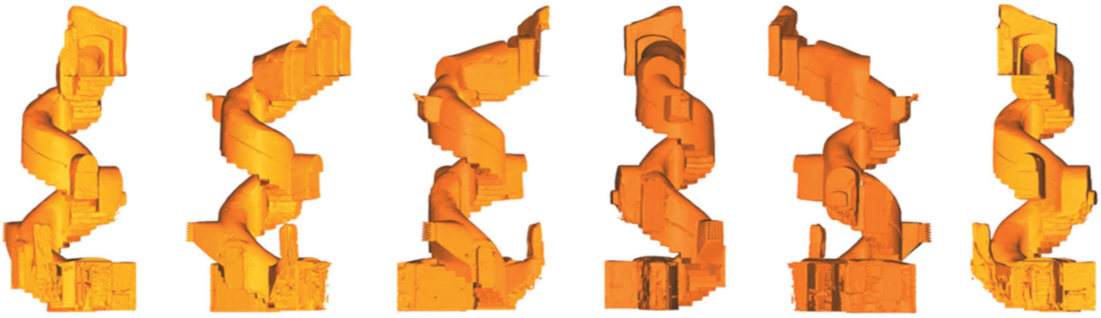

Figure 7. 3D model views of a portion of a spiral staircase surveyed with the photogrammetric multi-camera technique.

Prior to the survey operations, a calibration of the baselines between the cameras was performed similarly to what was described in Perfetti & Fassi (2022a). A small room inside of the south tower was identified on which some photogrammetric targets were attached and measured by a total station (Figure 5). Subsequently, a redundant Ant3D acquisition was performed, from which an estimate of the baselines was derived with an estimated accuracy of around 0.1-0.2 mm.

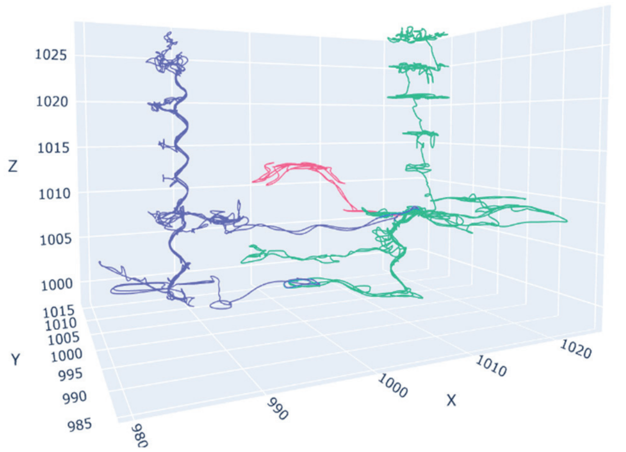

Figure 8. 3D view of the trajectories of the three main indoor acquisition with Ant3D: south tower (blue), north tower (green), and attics (red).

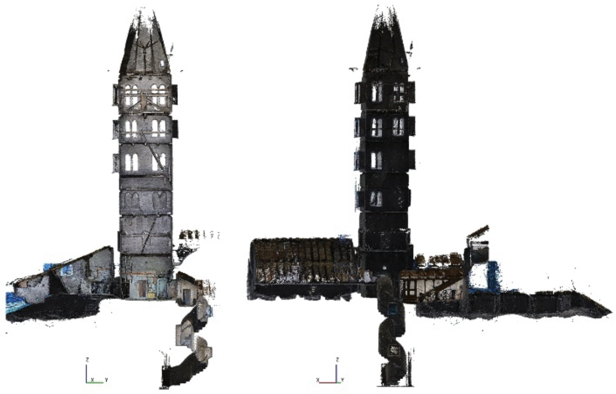

Figure 9. Views of the point cloud of the north tower and lower attics. Section (left) and complete (right).

3. VALIDATION AND ASSEMBLY

The multi-sensor survey and processing phase resulted in a set of point clouds in the same coordinate system that may overlap entirely or only partially in some areas. The point clouds are found to be homogeneous and comparable with each other. Each has, in fact, undergone a process of data cleaning and sub-sampling to the spatial resolution of 5mm.

The point clouds superimposed on each other were used to validate the survey using a visual method of checking on cross sections, which aims to highlight deviations between the different surveys produced and measure their magnitude. Although manual and punctual, this method is necessary as an aid to error control on GCPs since, in the present case study, many point clouds were registered on the basis of other point clouds rather than on the basis of GCPs. For example, the multi-camera and TLS acquisitions of the south tower are weakly constrained on GCPs, given the small number of them that could be surveyed from the inside and measured from the outside. The GCPs themselves, however, are sufficient to rigidly constrain the UAV photogrammetric survey of the exterior. Consequently, a visual cross-section check between the point cloud of the interior with one of the exteriors constitutes an indirect validation of the point cloud of the interior of the tower.

Once the point clouds were mutually validated through this method, the different parts were merged to obtain a unified model by selecting the clouds, or areas of them, most appropriate for each area or surface of the cathedral.

3.1 Cross section validation

Visual validation based on cross-sections was carried out by slicing the towers in the transverse and longitudinal directions and in horizontal planes at various significant levels. Special care was taken for the stair connection areas, on which multiple acquisitions insist. During the check, the extent of deviations was measured, verifying that this was within the tolerance range given by the scale of representation. This is the final check on the various datasets, which were previously processed and mutually registered using the GCPs measured with the total station and, in their absence: based on common targets or cloud-to-cloud registration exploiting common areas.

Deviations between point clouds describing the same environment and acquired with different instruments and techniques are expected and unavoidable due to inherent differences between sensors, processing techniques, and final noise (Figure 10).

The dimensional tolerance for the present survey’s reference representation scale, i.e., 1:50, is a maximum of 2 cm.

The average discrepancy shown during the validation phase was about 15 mm. The value obtained is compatible with the tolerances of the scale of representation.

The visual validation method was preferred to the cloud-to-cloud distance calculation available as a tool in various processing software because it is faster and also considered a helpful tool for assessing the quality of the data locally on an area-by-area basis. In fact, the cross-section verification phase helped to become aware of the characteristics of the various point clouds in the different areas of the survey and thus aided the subsequent data selection phase for final assembly.

Figure 10. Example of the verification through cross-sectioning of the clouds. Horizontal cut of the north bel tower. C10 TLS point cloud (yellow), UAV photogrammetric point cloud (green), and Ant3D point cloud (blue).

3.2 Point cloud assembly

Once the verification that the deviations present did not exceed the established dimensional tolerance was completed, the following operation was to assemble the overlapping data into a single point cloud. This was done by making a selection and segmentation of the most significant areas reconstructed by the various tools, choosing area by area the data to keep and those to discard. This selection was made by considering the noise of the specific point cloud or a portion of it, the completeness of the cloud, the presence of areas of sparse or poor-quality data, and, in general, preferring the most reliable and descriptive data.

The assembly of the point cloud was done manually, segmenting the various datasets according to the selection criteria. Generally, the joins between the different parts of the final point cloud are located at the edges or transition areas between different rooms, such as a door or window thresholds, stair steps, manholes, etc. Figure 11 shows a detail of the assembly of the apsidal area.

The result is a mosaic of point clouds free from extended areas of overlapping data and homogeneous, obtained by selecting the most suitable portion of the data, optimized for visualization and use for 2D representation.

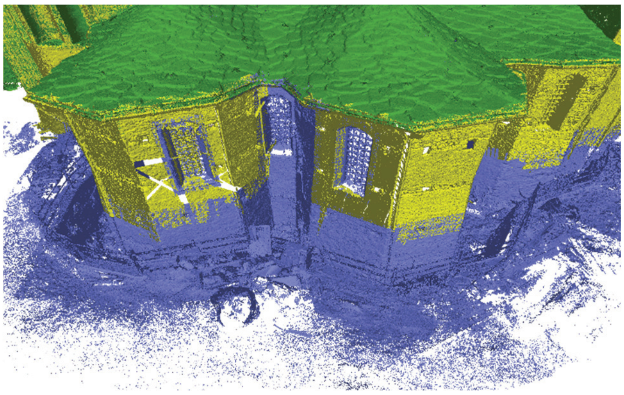

Figure 11. UAV photogrammetry (green), outdoor C10 TLS survey (yellow), and terrestrial DSLR + Ant3D point cloud (blue). Example of the assembly of the final point cloud from the available datasets.

3.3 Data sharing in FlyVast

The final point cloud was finally uploaded to the FlyVast web platform (Geovast 3D, 2022) to be shared with the various professionals involved in the project.

FlyVast is a platform accessible through a website (Web App) that provides users with various tools for viewing, navigating, and interacting with point cloud data. The user can interact with the point cloud by taking annotations, measuring distances, areas, and volumes, cutting cross-sections, and consulting information through databases related to the point cloud objects.

The Cathedral point cloud was provided through FlyVast because of the need for seamless data sharing and remote collaboration on the same dataset. This latter aspect was crucial because of the number of professional figures involved as stakeholders in the restoration project, as architects, restorers, surveyors, archaeologists and the Chapitre de la Cathédrale as management of the cathedral. The platform specializes in using and sharing 3D data, has smooth visualization performance, and provides practical annotation tools that allow users to visualize, query, and enrich the point cloud with information and data, enhancing the 3D user experience.

This system proved particularly efficient for the scenario considered for the following reasons. The efficient rendering of the point cloud makes it possible to allow a performant viewing of the whole model and, at the same time, clear, detailed visualization in a unique system without the need for specific high-performance hardware. The final point cloud has 300 Mln points with a final resolution of 5mm, resulting in a single 9Gb E57 file (Figure 12, top). The rendering module allows individual users to manually adjust, via a slider, the number of points rendered to achieve the desired level of smoothness in navigation, depending on the task at hand. Available annotation tools support interaction and information sharing among users and allow specific areas to be highlighted for investigation. In addition, the sectioning tools provided by the platform allow users to create cross-sections by drawing the section line or specifying coordinates for more precise cutting. This tool is particularly valuable because it enables users to quickly extract a 2D representation from the point cloud (Figure 12, bottom two).

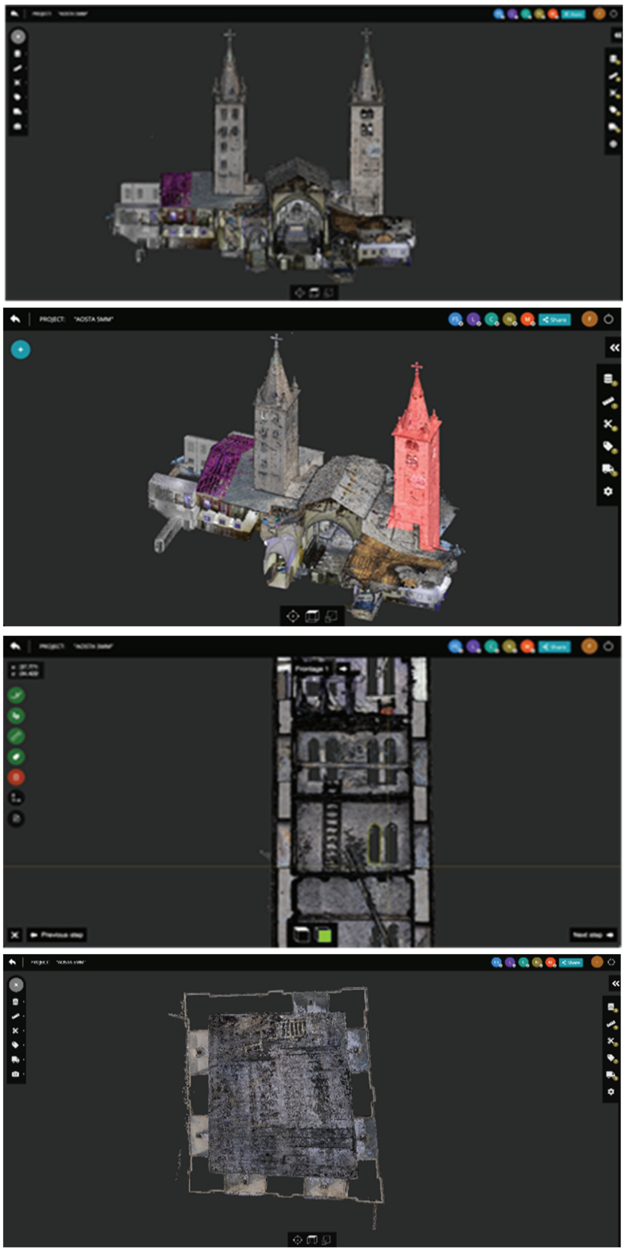

Figure 12. The cathedral point cloud was uploaded to the FlyVast web platform. Top: a general overview of the point cloud with a resolution of 5mm. Below, the south tower is highlighted by a bounding box allowing users to isolate the cloud portion or download the selected points. Bottom two: a vertical and a horizontal section of a tower, sliced into the sectioning tool.

One of the primary needs expressed by designers and conservators is to easily have the 3D geometric survey available at each project stage. It is also possible to download the point cloud or a portion of it in LAS format using intuitive bounding boxes (Figure 12, second). Finally, it is possible to create selected project views that anyone can share via a Web link.

4. CONCLUSION AND FUTURE WORKS

In this paper we presented the multi-sensor survey of the two bell towers and the apse of Aosta’s Cathedral. The case study is complex, it is characterized by heterogeneous environments and by the presence of numerous narrow spaces: the very object of the survey activity. The poor accessibility of the interior spaces made it impossible to reach all the surveyed rooms with a total station network. Moreover, the TLS survey operated on the ground floor of the cathedral was not extended along the narrow spiral staircases. Therefore, it was decided to employ an experimental survey methodology by surveying the cramped spaces using a self-built photogrammetric multi-camera, which would simplify and shorten the field survey phase. Only a few constraints were possible. For the south tower in particular: the multi-camera survey was constrained at the beginning of the acquisition, at the ground floor. No other constraints were possible before the first level of the roofs and then before the top at the belfries. In this way, the accuracy of the survey of the first winding staircase (Figure 7) and of the second depended on the robustness to drift of the multicamera system. In turn, the registration of TLS scans made in the belfries for the complete description of the spire intrados depended on the local accuracy of the multicamera point cloud. The agreement between the interior and exterior geometry of the south tower (Figure 6) and, more generally, the cross-section verification of the internal point clouds with the external UAV point cloud indirectly validated the goodness of the multi-camera survey and multi-sensor registration.

This survey experience has thus shown how multi-camera photogrammetric surveying is a viable option for surveying confined spaces and as a “bridge” to TLS point cloud registration in all those practical situations where, for various reasons, a more rigorous but also slower surveying approach cannot be implemented.

In the post-processing and assembly phase, the manual segmentation of the point clouds took time. Thus, strategies to speed up this phase could be explored, such as classifying the point cloud based on geometric features to aid the manual process.

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