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PRELIMINARY SURVEY OF HISTORIC BUILDINGS WITH WEARABLE MOBILE MAPPING SYSTEMS AND UAV PHOTOGRAMMETRY

L. Perfetti [1]*, G.P.M. Vassena[1], F. Fassi[2]

[1] DICATAM, Civil Engineering, Architecture, Territory, Environment and Mathematics, Università degli Studi di Brescia, Italy (luca.perfetti, giorgio.vassena)@unibs.it
[2] ABC, Architecture, Built environment and Construction engineering, Politecnico di Milano, Italy, francesco.fassi@polimi.it

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ABSTRACT:

In cultural heritage, three-dimensional documentation of historic buildings is fundamental for conservation and valorisation projects. In recent years, the consolidated tools and methods: Terrestrial Laser Scanning (TLS) and close-range photogrammetry, have been joined by portable Mobile Mapping Systems (MMSs), which can offer significant advantages in terms of speed of survey operations at the price of reduced accuracy. The reduction of survey times and, therefore, costs makes the application of MMS techniques ideal for the preliminary stages of analysis of historical artifacts, when a rapid survey is indispensable for estimating the costs of conservation interventions.
In this paper, we present a methodology for the expeditious survey of historic buildings and the surrounding urban fabric that is based on the use of an MMS and an Unmanned Aerial Vehicle (UAV). The MMS is the Gexcel Heron MS Twin color. It was used to survey two architecture of interest and the urban context surrounding them from the ground level. The UAV is the DJI Mini 2, used to integrate the terrestrial survey by acquiring the buildings' roofs. The case study presented in the paper is the survey of San Clemente and San Zeno al Foro churches, two historic churches in the city centre of Brescia (Italy).
The result are a complete point cloud of the two buildings and a metric virtual tour of all spaces. These results were made available to the architects through the Cintoo web platform to plan future activities.

1. INTRODUCTION

In Cultural Heritage (CH), three-dimensional documentation of historic buildings is a cognitive process underlying a series of actions and interventions affecting structures. It is nowadays almost fundamental for conservation and restoration interventions, but it is also increasingly employed for purposes of cultural enhancement and promotion of the built heritage. The tools and methods most widely used in historic building digitization projects, whether small or large, are Terrestrial Laser Scanners (TLS) and close-range photogrammetry. These well-established techniques result in three-dimensional products, such as point clouds and mesh models, that can provide the desired geometric description of the artifact under consideration. In recent years, these established techniques have been joined by portable scanners: hand-held or wearable Mobile Mapping Systems (MMSs) that, at the price of reduced global accuracy, compared to static scanners, can offer great advantages in terms of speed of survey operations. MMSs are an ideal choice for all those applications benefitting or requiring a rapid survey. Di Filippo et al. (2018) show the effective use of the MMS Zeb Revo made by Geoslam to rapidly survey a damaged structure where traditional TLS survey operations would have been hazardous. Campi et al. (2022) presented a CH survey comparing a TLS approach to using the NavVis VLX MMS, highlighting the rapid survey capabilities of the latter as ideal for continuous monitoring of the architecture. At the same time, other authors proposed accuracy assessment tests of different commercial MMS solutions (Tucci et al., 2018; Sammartano & Spanò, 2018), finding great potential in the efficiency and productiveness of the acquisition phase, well suited for 1:100 – 1:200 representation scale requirements.

The reduction of survey times and, therefore, costs, combined with the ability of some MMS to record high-resolution panoramic images of the scanned environment, makes the application of MMS techniques also interesting for facilities management purposes or the preliminary stages of analysis of built heritage. For the former, a rapid geometric survey complemented with panoramic images allows efficient object/building-features recognition for model annotation (Cantoni & Vassena, 2019). For the latter, the same data allow for the preliminary assessment of the building conservation status and estimation of the costs of conservation interventions.
Moreover, today's practice commonly sees using more than one technique/instrument for a single digitization project. The final products, the point clouds, are fused together to achieve the final result (Remondino, 2011). In this context, MMS approaches are commonly complemented with UAV (Unmanned Aerial Vehicle) photogrammetry that shares the advantage of effective data acquisitions while enabling the survey of complementary parts of the building: the roofs. Sammartano (2018) proposes a combination of MMS and UAV photogrammetry for rapidly mapping damaged structures in emergencies. Chiabrando et al. (2019) and Patrucco et al. (2019) show effective integration of terrestrial surveys carried out with the Geoslam Zeb Revo with aerial ones carried out with UAV photogrammetry at the building scale. At the same time, Marotta et al. (2019) show MMS-UAV integration at the urban scale. Overall, MMS, combined with UAV photogrammetry, offers an effective workflow for documenting the built heritage in the preliminary investigation phase and during continuous building management.

* Corresponding author

1.1 Paper objective and case study

In this paper, we present an efficient methodology for the expeditious survey of a historic building based on using an MMS and a UAV. Compared with the more classical integration of UAV survey with TLS survey, MMS-UAV integration offers some interesting opportunities that we exploit in the present investigation:

- the shortening of survey operations in the field,
- the opportunity to rapidly survey the urban context in which the building is embedded,
- the opportunity to acquire panoramas during the MMS acquisition allowing the creation of immersive virtual navigation of the building and the surrounding,
- the opportunity to rapidly extend the survey to include squares and open areas where measurements can be made with the GNSS receiver.

The case study presented in the paper is the survey of the churches of San Clemente and San Zeno al Foro, two historic churches in Brescia (Italy), dating back to the 14th and 12th centuries, respectively, and no more than 200m apart. The two churches are, to this day, fully inserted into the city's urban context: adjacent buildings incorporate their masonry, and the streets of the historic centre on which they are located are extremely narrow.

The proposed survey methodology exploits the speed of MMS and UAV surveys to obtain the preliminary survey to estimate the costs of the conservation and restoration interventions planned for the two churches. The preliminary survey aims to achieve an accuracy of 3-4cm suitable for representation at a scale of 1:100 and, at the same time to acquire abundant photographic valuable documentation regarding the actual state of conservation of the two structures and their urban context, as well as for planning the following stages of the conservation project. The photographic documentation includes the images acquired during the UAV flights, aimed at producing the orthophotos of the roofs, as well as the hemispheric images obtained during the MMS survey, both in the interior and exterior spaces. In particular, acquiring panoramic photographs as part of the geometric survey allows the creation of a metric immersive virtual tour. Through this, it is possible to derive measurements and observe the state of preservation of the various parts of the buildings, thus minimizing on-site inspections in favor of virtual ones.

During the survey, the two churches were acquired, the church of San Clemente, both inside and outside, and the church of San Zeno al Foro, only outside. The roofs were acquired by UAV survey. The MMS system was also used to acquire the urban context of the two structures by walking some streets in the historic city centre along a closed-loop route (Figure 2). Finally, the MMS survey was extended to two areas with less dense urban fabric and, therefore, less occluded by the presence of the buildings (Figure 2 – GCPs 1 and 2 areas). Extending the survey to these areas allowed it to be georeferenced by measuring some points on the ground with a GNSS receiver.

The acquisitions made beyond the specific survey of the churches are made possible by the portability and speed of MMS acquisition. They are intended to create a single connected virtual tour and, at the same time, allow convenient referencing of the data. However, Marotta et al. (2022) show that poorly constrained MMS acquisition of urban context suffers from significant instrumental drift. An estimate of the overall accuracy of the urban survey was made by surveying a few Check Points (CPs) with GNSS (Figure 2 – CPs area); from the outset, this was expected to be on the order of a few meters.

Figure 1. Photographs of the two churches under study, San Clemente (left) and San Zeno al Foro (right).

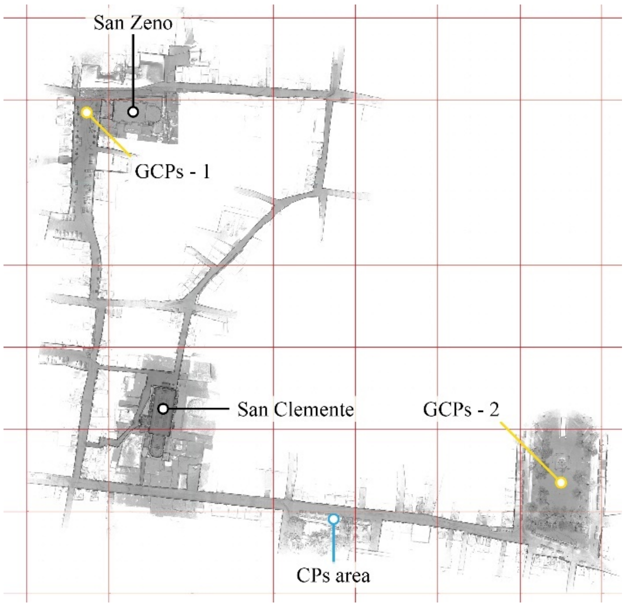

Figure 2. Scheme of the survey areas. Red grid is 50 by 50 m.

2. DATA ACQUISITION

The mobile mapping system used for the survey is the Heron MS Twin Color manufactured by Gexcel (hereafter referred to as the Heron Backpack – Gexcel srl, Brescia, Italy). This backpack device houses two Velodyne LiDAR (Light Detection And Ranging) sensors, an IMU (Inertial Measurement Unit), and a panoramic camera capable of capturing, simultaneously with LiDAR acquisition, an image stream useful for point cloud colouring and for creating virtual metric tours. The operator controls the acquisition via a hand-held device. It is done by simply walking through the environment to be surveyed at the normal walking pace.

In the present work, two versions of the Heron Backpack have been used at two different times. A version mounting two 16-line Volodyne sensors, one placed horizontally and the second placed at a 45-degree angle, and also equipped with the Garmin Virb 360 5k camera. The other mounting a 32-line Velodyne sensor placed horizontally, a 16-line sensor placed at a 45-degree angle and a Gexcel MG1 8k camera. The version with the 5k camera was used for capturing the interiors of the San Clemente church, this version simultaneously allows capturing the images to colour the point cloud and, upon operator input, allows capturing the high-resolution images for the virtual tour. The version with the 8k camera, on the other hand, requires that a choice is made at the beginning of the acquisition whether to acquire Full-HD resolution fast-sequence images, useful for colouring the point cloud, or to acquire 8k high resolution images upon operator input. Two acquisitions are therefore necessary if one wants to obtain both the coloured data and the high-resolution panoramas.

This second version was used for the outdoor acquisitions and for the walkthrough in the urban context; initially, it was planned to perform the two acquisitions in the two modes, but it was then preferred to process exclusively the survey with the high-resolution 8k panoramic acquisitions.
For the UAV survey, the DJI Mini 2, a lightweight commercial drone (weight within 250g) capable of capturing 12-megapixel images, was used. Two captures were made with the UAV, limited to the area of the roofs of the two churches.
Figure 3 shows the survey operation with the MMS and with the UAV.

Figure 3. Survey operations. Heron Backpack survey (top), UAV photogrammetric survey (centre), Heron Backpack pole tagging (bottom – left), and GNSS survey (bottom – right).

Figure 4. 8k panoramic images acquired with Heron Backpack. City centre crossing (top) and entrance to San Clemente (bottom).

2.1 MMS survey

The MMS survey was carried out on two different days; on the first, the survey of all the interior rooms and exterior surfaces of the Church of San Clemente was carried out using the 5k camera version of Heron Backpack. The capture surveyed all the interior rooms and exterior surfaces of the building. It also surveyed the small square on which the facade of the church with its main entrance stands, as well as a part of the street that runs along the side of the church and on which a secondary entrance stands. Finally, from the interior spaces, the acquisition extends along an interior passageway that leads to a third connection with the outside, opposite the main entrance. The acquisition of Sa Clemente took around 30 minutes to complete.
During the second day of acquisition, instead, the survey of the exterior of the church of San Zeno al Foro was carried out, the survey of the exterior of San Clemente was repeated, and the urban context was surveyed. In this case, the 8k camera version of Heron Backpack was used. Two acquisitions were made on the same route, the first in "streaming" mode, i.e., acquiring a video aimed at point cloud colouring, and the second in "single shot" mode, i.e., acquiring 8k panoramic images when determined by the operator. The first acquisition in "streaming" mode was later discarded to shorten the data processing time. The panoramic images of the "single shot" acquisition (Figure 4) were acquired at a distance of about 10 meters from each other.
Subsequently, two shorter acquisitions were made with the same instrument, without spherical image acquisition, aimed at surveying the more open areas where GNSS acquisition was carried out (Figure 2). During these acquisitions, Ground Control Points (GCPs) were surveyed using the "pole tag" mode (Figure 3), which involves the MMS capturing head being mounted on a pole held stationary on the points to measure for a few seconds.
The trajectory acquisition in "single shot" mode took around 30 minutes, while the two acquisitions for surveying GCPs took about 10 minutes. Table 1 summarizes the main data of all acquisitions; overall, the MMS surveys took around 1 hour and 10 minutes to walk a total of 2 km of trajectory length.

	Length [m]	Duration [hh:mm:ss]	Number of points
San Clemente	503	00:29:44	94 Mln
Surroundings	1304	00:30:39	280 Mln
GCPs 1	97	00:04:09	36 Mln
GCPs 2	150	00:06:57	67 Mln

Table 1. Details of the Heron Backpack acquisitions.

2.2 UAV Survey

The UAV survey was carried out on the same day as the second MMS acquisition. It was divided into two areas of the two churches. The DJI Mini2 drone was used to manually fly while maintaining visual contact with the UAV the whole time (VLOS - Visual Line Of Sight). 758 images were acquired for the survey of the San Clemente roof, and 596 images were acquired for the survey of the San Zeno roof. The resolution of the images, the reference GSD (Ground Sampling Distance), is 5 mm, which is sufficient for a 1:50 scale representation of the orthophotos of the roofing. The photogrammetric survey could be scaled by deriving the coordinates of some architectural points from the MMS survey conducted outside the churches to be imposed as constraints in the SfM (Structure from Motion) process. However, it was preferred to make a rapid topographic support survey employing a total station for each of the UAV acquisitions, each consisting of only two vertices from which some GCPs were measured on the vertical faces of the structures.

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The two topographic surveys were carried out without materializing any network points on the ground. This approach made it possible to constrain the verticality of the UAV survey and to scale the acquisitions with higher accuracy to be able to extract the orthophotos at a scale of 1:50. The two UAV surveys are thus referenced on two arbitrary and independent local coordinate systems and therefore need to be merged with the MMS survey.
Table 2 summarizes the main details of the UAV photogrammetric acquisitions.

	Number of images	Duration [hh:mm:ss]	Number of points
San Clemente	758	00:32:00	55 Mln
San Zeno	596	00:21:00	37 Mln

Table 2. Details of the UAV photogrammetric survyes.

3. DATA PROCESSING

Post-processing of the acquired data was done using commercial software: (i) Heron Desktop and Reconstructor (by Gexcel) for Heron Backpack data processing and management; and (ii) Agisoft Metashape for the photogrammetric process. Overall, discarding redundant processes, errors, and testing, the processing of all data until the final product is estimated to take about one week of work.

3.1 MMS processing

The Heron Backpack data process involves calculating the trajectory traveled by the instrument based on the information recorded by the IMU and based on a SLAM (Simultaneous Localization And Mapping) method. The SLAM method exploits the abundant geometry detected at each rotation of the range-based sensors (the single "laser sweep") thanks to the 2 Velodyne multi-beam sensors equipped on the instrument. It is based on the registration of the data acquired by the LiDAR sensors using ICP (Iterative Closest Point) matching between consecutive "laser sweeps" and between data obtained in the same area but at different times, thus performing the so-called "loop closure" (Sanchez et al., 2020).
The data processing in Heron Desktop is divided into three main phases:

Odometer, odometer calculation provides an initial estimate of the trajectory traveled by the MMS by calculating the ICP registration of the single laser sweep with the previous ones already registered. This is done by controlling various parameters or choosing the most suitable existing presets. The operator's work and experience are crucial at this stage. The process can lead to different results depending on the parameters used since the operator has complete control over the ICP registration and can adjust the settings at any point as needed. For example, it is crucial to exclude the data closest to the instrument in case there is the frequent passage of people or cars; or it is necessary to include the most distant, even sparse data in the case of acquisitions in environments with poor geometry or in the case of very long acquisitions to contain instrument drift.

Create Maps, after the first MMS trajectory estimation, we segment in detected data into "Local-maps." Local-maps consist of the sum of laser sweeps acquired in a given trajectory segment. They each constitute a point cloud comprising great geometry comparable to a point cloud obtained using TLS. Longer segments produce geometrically richer point clouds but there is a risk that these Local-maps are affected by inherent deformation due to instrument drift in long trajectory segments. The operator controls the length of the trajectory segment used to segment the source data into different Local-maps.

Global Optimisation, is the final process consisting of a bundle adjustment between the ICP connections of the different Local-maps. The connections are made either automatically or eventually manually by the operator. Different types of constraints can be included in the optimization at this stage: (i) constraints via GCPs manually identified in the Local-maps or already recorded in the field using the "pole tag" function; and (ii) constraints via GCSs (Ground Control Scans), i.e., by creating ICP correspondences between the Heron Backpack data and other point clouds from other instruments that can be imported.

The Heron Backpack data from the San Clemente acquisition was processed according to a two-step pipeline: Odometer > Create Maps (short) > Global Optimisation > Create Maps (long) > Global Optimisation. Local-maps were first created of a length of 10 m. After an initial optimization, they were recalculated to 25 m and then connected in a second optimization process. This process can be suggested as a standard for interiors or narrow areas in the exteriors. In both cases, the Local-maps were extracted considering a LiDAR data range of 5-40 m, excluding the data before 5 m and after 40 m. This made it possible to include, in each Local-maps of the church's interior, the entire geometry of the church itself, excluding interference close to the instrument due to other people present during the acquisition. The result obtained from this process is a reasonable estimate of the trajectory in an arbitrary local coordinate system since no constraints were included during optimization.
Similarly, the data acquired for the urban context survey and the two short acquisitions for the GCPs acquisition were processed in the same way, by a two-step process. Shorter Local-maps were first extracted, at 10 and 25 m lengths for the GCPs- and urban context- acquisitions, respectively. And subsequently, after the first optimization, longer Local-maps of 40 m length each were extracted.

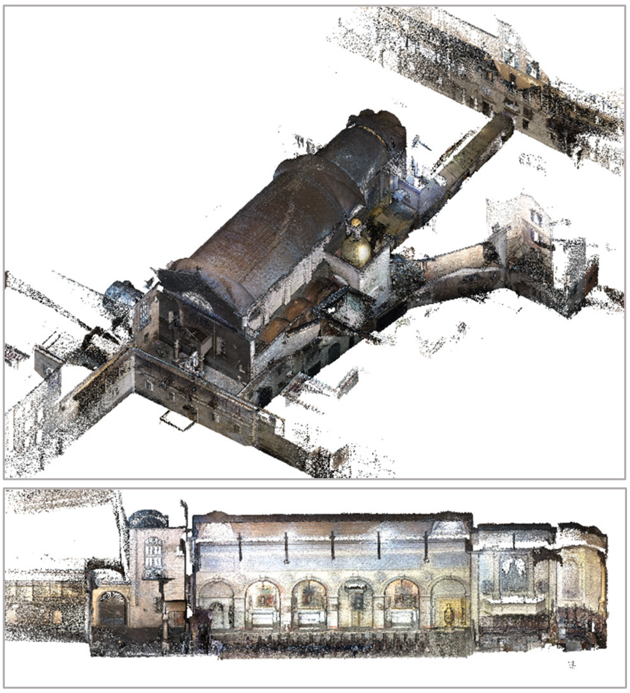

Figure 5. Heron Backpack point cloud of the San Clemente acquisition. Whole (top) and section (bottom).

In the second Global Optimisation, the coordinates of GNSS-measured GCPs were also constrained. The result obtained from this second process are the three trajectories of the three acquisitions, georeferenced according to the GCPs. The registration error is around 3 cm, consistent with the accuracy of GNSS points and "pole tag" acquisition.
At this point, the Heron Backpack data have been pre-processed, and to complete the registration, it is necessary to connect in a subsequent Global Optimisation the external survey with the internal survey and both with the UAV survey.

3.2 UAV processing

The photogrammetric surveys were processed separately in Agisoft Metashape using a simple pipeline. First, the images were oriented using the SfM process. Then markers were created by manually identifying the architectural corners measured during the total station survey. It was verified that the maximum error on the estimated points was within the tolerance of the 1:50 scale. Finally, the point clouds of the roofs were obtained at 5mm resolution. The data obtained is thus scaled and correctly oriented according to the verticality, thanks to the topographic survey. It needs, however, to be registered with the Heron Backpack data to pass from the local coordinate systems of the two surveys into the global system. Figure 6 shows the photogrammetric point clouds of the two churches and the photogrammetric image network.

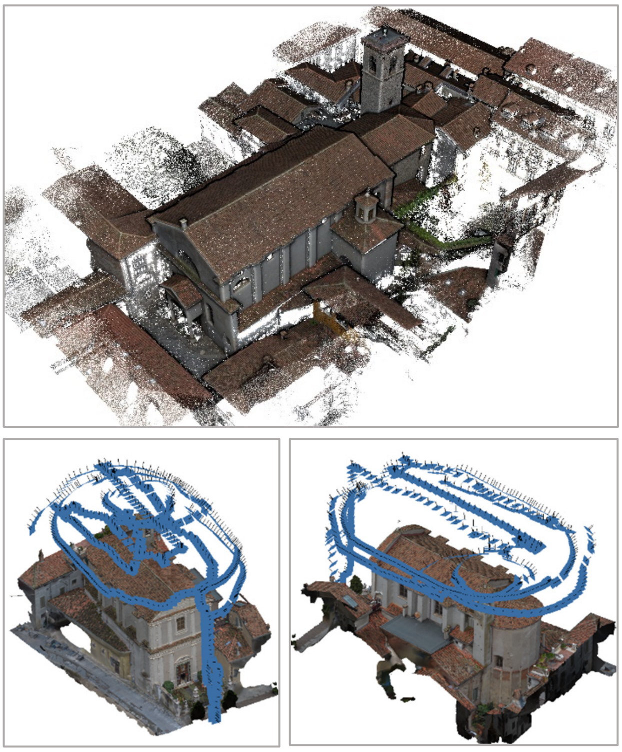

Figure 6. UAV survey: point cloud of San Clemente (top), and textured mesh model of San Zeno with image network (bottom).

3.3 Data fusion

The UAV photogrammetric survey data registration on the MMS data was first attempted using a cloud-to-cloud ICP registration performed in the Reconstructor software. However, this strategy proved unsuccessful since the poor global accuracy of the MMS survey produced point clouds of the two churches that were not correctly leveled. As a result, the ICP registration of the UAV data on the MMS data created a tilted survey and therefore clearly not acceptable. This error is due to the extension of the MMS survey and the distance of the GNSS constraints. In fact, the MMS survey of San Clemente alone has no observable tilt with respect to the vertical axis.
To overcome this problem, an ICP registration with constrained Z was performed, thus locking the vertical axis of the UAV survey. This allowed us to derive the approximate position of the UAV point clouds in the global coordinate system while maintaining the horizontality defined by the topographic survey. Figure 7 shows the UAV point cloud in red positioned in the global coordinate system and the MMS point cloud in cyan. Noticeable deviations around one meter are visible due to the deviations of the MMS survey.

The total station survey verified the local accuracy of the photogrammetric point clouds, which amounted to about 1-2cm. The global accuracy is much worse, around a meter, depending on the MMS data. At this point, these point clouds were imported into Heron Desktop to be used as a GCSs constraint in further optimization.
The last Global Optimisation performed combines all the MMS paths processed so far and uses the UAV point clouds as an immovable constraint. The operator, manually made the ICP connections between the Local-maps of Heron Backpack with the UAV point cloud, thereby constraining the verticality of the MMS acquisitions in the area of interest of the two churches on the reference point cloud.

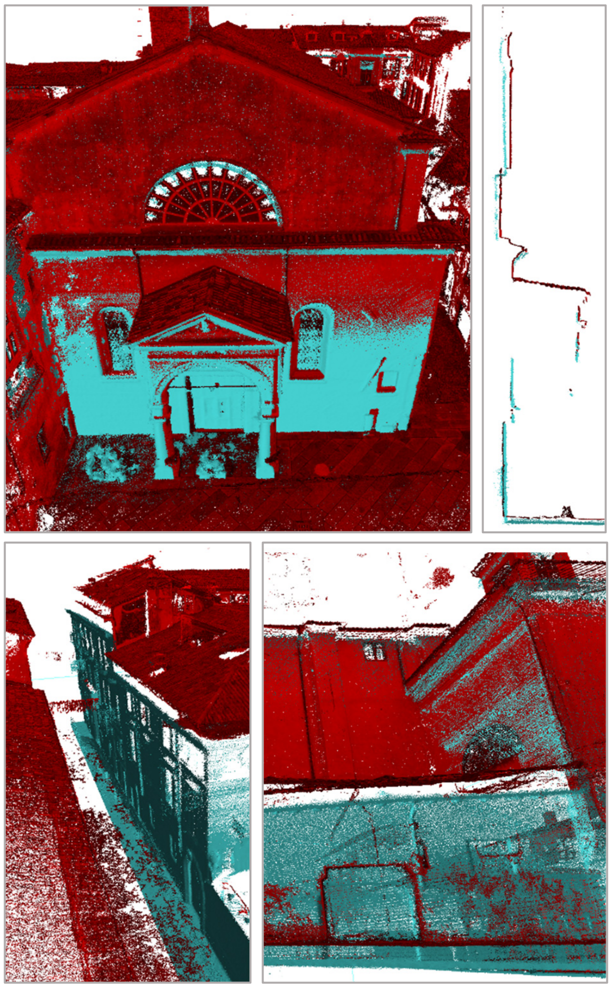

Figure 6. View of the UAV (red) and MMS (cyan) point cloud after the ICP with the UAV Z axis locked. Deviation are clearly visible since the MMS is tilted with respect to the vertical axis.

The final Global Optimisation also made it possible to constrain the survey of the interior of San Clemente with the exterior at three points, corresponding to the three entrances to the church. This allowed the connections between the trajectories to be reinforced by realizing loop closures.

4. RESULTS

The registration obtained at the end of the process thus fulfills the requirements set for the preliminary survey of the two churches. The local accuracy of the data is about 3cm due to the noise of the Heron Backpack point cloud. At the two churches, the verticality is constrained based on the photogrammetric surveys. In contrast, the global accuracy is worse and was estimated based on some CPs acquired along the unconstrained path.

4.1 Validation

Due to the long unconstrained MMS path from the location of the "GCPs 2" survey to the location of the San Clemente church, the trajectory indeed accumulates drift (Figure 2). Some GNSS points acquired along this path, that were never constrained during the previous processes (Figure 2), derived a global accuracy measure. As Figure 8 shows, the error found at this point on the trail is about 45 cm, thus providing a measure of the global accuracy of the survey made.

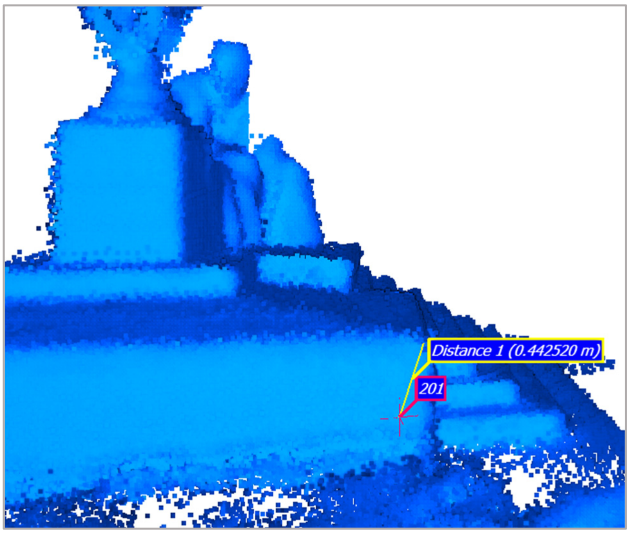

Figure 8. Global accuracy check. deviation of around 45cm between the MMS point cloud and the CPs placed along the trajectory.

4.2 Virtual tour in cintoo

The panoramic images acquired during the interior survey of San Clemente and the urban context survey (Figure 4) were used to create a metric virtual tour. This can be accessed offline in the Reconstructor software (Figure 9 - top) or online via the Cintoo web platform (Figure 9 - bottom). The virtual tour allows the users to navigate all surveyed spaces, observing and annotating the attributes, materials, and state of decay of the two structures. Moreover, it is possible from this to extract measurements directly from the obtained point cloud, but without using any specialized tools or technical processes. This data-sharing methodology, which allows intuitive multi-platform web-based data consultation, thus proves particularly effective for sharing the survey products with the professionals responsible for preparing the cost estimate for the conservation project.

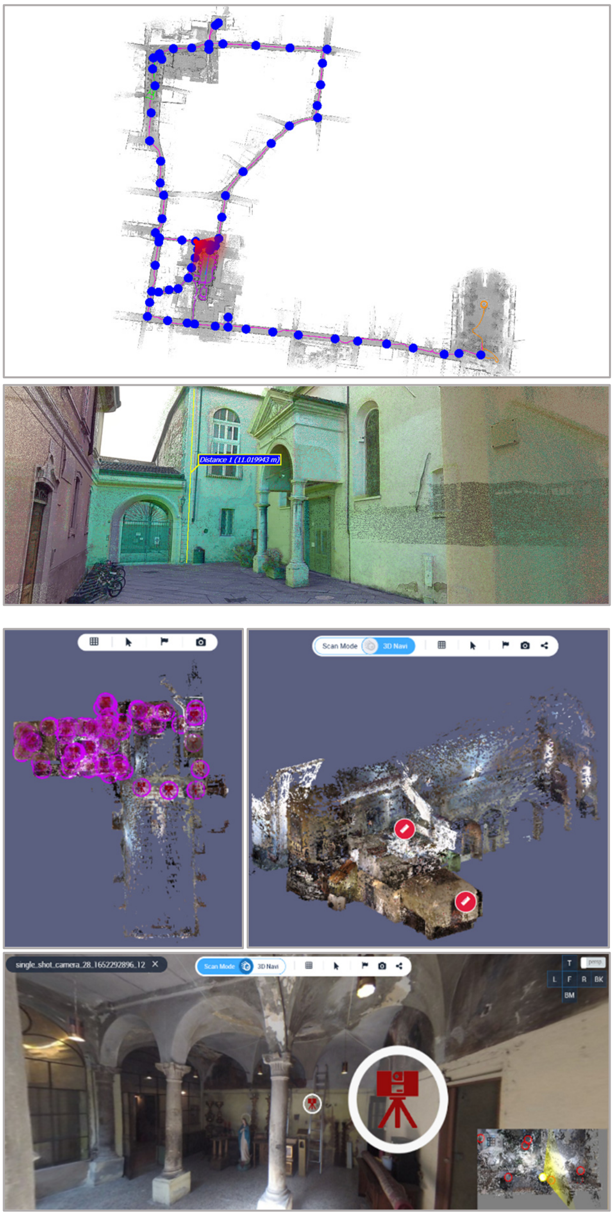

Figure 9. Images of the virtual tour. In Reconsructor (top - two), plan and immersive view with pano image superimposed on the point cloud. In the Cintoo web platform (bottom - three).

5. CONCLUSION AND FUTURE WORKS

In this paper, we presented a methodology for the rapid survey of Cultural Heritage aimed at the preliminary investigation of the state of preservation of two churches in the historic Roman centre of Brescia. The methodology employed is based on the MMS survey with Heron Backpack, which simultaneously allows the acquisition of high-resolution panoramic images of what was surveyed. This is then integrated with a UAV photogrammetric survey to acquire the roofs. The methodology employed has its main advantage in the reduced time of field operations, which took, for the presented case study, a total of about 4 hours to complete the acquisition of (i) all MMS data, (ii) all photogrammetric surveys, and related topographic measurements, and (iii) the GNSS measurements. The post-processing phase of the data, adjusted for some initial errors and other tests performed, required approximately one week of work to go from the raw data to the final point cloud (Figure 10).

Figure 10. Some images of the survey results. X-ray plan view of the point cloud (left), San Clemente (centre) and city context (right).

The accuracy in the survey of the two architectural structures is on the order of 3cm. Photogrammetric surveys, constrained by rapid local topographic measurements, proved important to correctly define the horizontality of the reconstruction at the areas of interest. The overall accuracy of the data was verified to be on the order of 50cm. However, this is not of primary importance for the application presented and does not affect the measurements that can be derived locally. Rather, the possibility of quickly capturing the urban context of the historic centre of the surveyed buildings allows for enriching the documentation of the preliminary survey by facilitating eventual evaluations regarding the relationship between the architectures under investigation and the urban fabric of which they are part.
Finally, the metric virtual tour shared via the web with professionals and clients represents a powerful means of making survey data intuitively available, consultable, and usable accompanied by classic products such as digital point cloud files, images, orthophotos, and more.
For future work, the use of a UAV capable of working in relative RTK positioning can further speed up and simplify the survey and data processing phase, simultaneously allowing: (i) to obtain the photogrammetric survey already correctly sized, (ii) to georeference the survey without the need to acquire GCPs with GNSS and the "pole-tag" function, (iii) to define the verticality, and (iv) to improve the global accuracy of the whole survey, at least at areas of interest.

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