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SURVEY OF HISTORICAL GARDENS: MULTI-CAMERA PHOTOGRAMMETRY VS MOBILE LASER SCANNING

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ABSTRACT:

This paper presents an investigation into the characterization of historical gardens by comparing two 3D survey methodologies. In this context, approaches employing terrestrial laser scanning are considered the most accurate, while Mobile Mapping Systems (MMSs) are considered promising due to their extreme productivity. Less common is the use of close-range photogrammetry. This paper compares two approaches based on the use of a wearable MMS and the use of an in-house built photogrammetric multi-camera prototype. The comparison aims to assess the applicability of the two techniques in this field, evaluating their advantages and disadvantages in surveying a historical garden and extracting information for tree inventory, such as the DBH (Diameter at Breast Height) and canopy footprint. We compared the practicality of surveying and processing operations; and the quality and characteristics of the point clouds obtained. Both systems produced a dense representation of the terrain. The multi-camera survey resulted to be more defined due to the lower noise of the point cloud but incomplete in the definition of tree canopies. DBH of tree trunks can be extracted with both systems, except for thinner and finer diameter trunks detected by the MMS approach but not always by the multi-camera. The MMS approach proved more effective thanks to a shorter survey time required to cover an equal area and the fact that the MMS survey alone is sufficient for the geometric description of trees. In contrast, the multi-camera approach cannot avoid integration with an aerial survey for canopy reconstruction.

1. INTRODUCTION

Historical gardens are part of the cultural heritage and can be found in the city centre of many towns. Today, after being closed to the public as private property for much of their history, they also serve a social function as public parks and gathering spaces in the historical centres. Historical gardens require continuous maintenance, often urgent conservation and valorisation interventions. All these interventions first need a preliminary cognitive process to which the geometric survey contributes, that is, the geometric description and subsequent graphic restitution of the site in question. From this process comes the definition of elevation changes, footpaths, park furnishings, plants, vegetation, and their relationships. This process typically flows into drafting technical drawings such as 2D restitution: plans, sections, elevations, orthophotos, or even into GIS (Geographic Information System) information databases and 3D products (Cazzani et al., 2019; Malinverni et al., 2019) that can be used for the garden perioding and long-term maintenance. To this end, the collection of measurements, the instrumental survey, and the surveys aimed at properly annotating the elements of interest, such as the essences in the garden, assume a central role. The total station is the instrument typically used in this application to draft the plan and create the Digital Terrain Model (DTM). More recently, instrumentation capable of producing 3D point clouds model is also employed. Thus, Terrestrial Laser Scanners (TLSs), close-range photogrammetry, and portable Mobile Mapping Systems (MMSs) find great use. These methods allow for the complete description of even intricate terrain geometries and the extraction of data like DBH (Diameter at Breast Height), tree height, and tree canopy width needed for trees and forest inventory tasks.

Approaches that employ TLSs are considered the most accurate by the literature for the estimation of such metrics and are, therefore, most used as ground truth data to compare other approaches against. Liang et al. (2018) summarise a TLS benchmark project comparing algorithms for tree-parameters computation. On the other hand, mobile mapping is today the most promising technology for this application, thanks to its extreme productiveness and time saving of the field survey operations and due to the completeness of the 3D point cloud model. Furthermore, the accuracy required by this application can be met even by using indoor MMSs, which are more manoeuvrable but also use LiDAR (Light Detection And Ranging) sensors distinguished by a low noise performance (2-3 cm). Indeed, the recent literature is rich in analyses on the use of MMSs for the 3D survey of historical gardens and parks as well as for forest inventory applications. In the forest environment, Hyyppä et al. (2020) presented a comparison between multiplatform MMSs: a self-designed backpack, the hand-held ZEB Horizon produced by Geoslam and two UAV (Unmanned Aerial Vehicle) platforms; while Gollob et al. (2020) tested DBH extraction of different diameters from the ZEB Horizon data. In the historical garden context, Pérez-Martín et al. (2021) tested the ZEB Revo hand-held MMS for the extraction of DHB; Hess & Ferreyra (2021) presented an application of garden characterization using the ZEB Horizon; and Del Duca & Machado (2023) compared the performance of the Leica BLK2GO against a TLS. Other authors investigated the use of a terrestrial image-based photogrammetric approach for the

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extraction of stem models and DBH. Liang et al. (2014) tested close-range photogrammetry for forest plot survey, reporting limited capacity in mapping small trees; Forsman et al. (2016) proposed the use of a multi-camera system reporting faster acquisition time but inferior results compared to TLS; Mokros et al. (2021), in a comparison test between low-cost instruments for forest inventory, tested a multi-camera approach reporting the shorter acquisition time while not the best accuracy; and finally, Murtiyoso et al. (2022) tested spherical photogrammetry for stem reconstruction. All terrestrial image-based surveys show a dense reconstruction of the tree stems close to the ground. In contrast, the top part of the trees, leaves, and branches are not reconstructed.

1.1 Paper objectives

In this context, this paper presents an investigation into the characterization of historic gardens by comparing two three-dimensional survey methodologies: the use a wearable indoor mobile mapping system and a multi-camera photogrammetric instrument. The comparison aims to assess the applicability of the two techniques in this field by evaluating their advantages and disadvantages. It focuses on two different aspects: (i) on obtaining the data, i.e., the characteristics of the in situ geometric survey phase as well as the data processing phase; and (ii) on the quality of the data, i.e., the characteristics of the point clouds and the information extracted. Concerning the first aspect, the practicality and speed of the operations and the problems encountered are highlighted. In contrast, in relation to the second aspect, a qualitative comparison of the point clouds obtained is detailed by investigating the completeness of the different geometries acquired, whether architectural structures or trees. The qualitative investigation was carried out by visual comparison of extracted portions of the point clouds and horizontal and cross sections of the trees and terrain.

2. CASE STUDY AND INSTRUMENTATION USED

The case study in which the test was conducted is the historical garden of Villa Burba, a noble villa located in the municipality of Rho (province of Milan, Italy). The garden has a rectangular plan and measures approximately 160 by 100 m; within it there are shrubs and trees of various sizes including valuable century-old trees, a small water basin to some architectural structures both historical and modern (Figure 1). The garden environment meets the needs of the test by allowing the comparison of MMS and multi-camera photogrammetric survey methodologies in terms of the time required to obtain the geometric survey of the entire park and in terms of the three-dimensional description of the architectural structures and trees.

The employed instruments are: the Heron MS Twin Color wearable backpack indoor mobile mapping system (hereafter called Heron Backpack – Figure 2), produced by Gexcel srl, and a prototype of the Ant3D portable photogrammetric multi-camera system (Figure 3), developed as part of a PhD research activity by 3DSurveyGroup (Perfetti, 2022; Perfetti et al. 2022a; Perfetti et al. 2022b). Both instruments allow for surveying on the move, and are used here outside their main field of application. Heron Backpack is a tool developed for use indoors or in environments characterized by strong geometry, while Ant3D is a tool designed for surveying narrow tunnel-like spaces. At the end of the acquisition and processing stages, both instruments produce coloured point clouds. A previous test between these two instruments was performed by Marotta et al. (2022b), where the objects of comparison were instrumental drift in long unconstrained acquisitions and the quality of the acquired data in terms of completeness, measurement range and point cloud noise. The present investigation aims to expand the qualitative comparison.

Figure 1. Photographs of the Villa Burba historical garden.

Figure 2. Images of the survey activities carried out with the Heron Backpack in the Villa Burba Garden.

Figure 3. Survey activities with the Ant3D multi-camera system and a detailed picture of the instrument.

2.1 Heron Backpack – mobile mapping system

Heron Backpack consists of a backpack that houses the instrument sensors and a user interface device: tablet or PDA (Personal Digital Assistant). The backpack houses the measurement unit, control unit, inertial unit, and a panoramic camera for point cloud coloring. The measurement unit consists of two Velodyne Puck LITE sensors of 16 lines each, the first placed horizontally and the second placed at an angle of 45° (Figure 2). The acquisition takes place while walking through the environment to be surveyed. During the data processing, the trajectory of the instrument is reconstructed based on the information acquired from the inertial sensor and based on SLAM (Simultaneous Localization and Mapping) processing in the proprietary Heron Desktop software. The nominal local accuracy is 3cm due to the Velodyne sensors' noise. In contrast, the global accuracy is a function of the presence or absence of constraints such as Ground Control Points (GCPs) and Ground Control Scans (GCSs), the length of the acquisition, and the geometry of the surrounding environment that affects the accuracy of SLAM processing (Marotta et al. 2022a).

2.2 Ant3D – multi-camera system

Ant3D (Figure 3) is a working prototype of a measuring instrument developed for the time-effective and robust surveying of narrow and tortuous spaces. The instrument consists of a hand-held device and a backpack. The hand-held device houses five Flir BFS 50S5 cameras with a 5-megapixel 2/3-inch color sensor (2448 x 2048 pixels, detector pitch of 3.45μm). Each camera has equidistant fisheye optics with a field of view of 190°. The cameras are arranged along the sides of a rectangle directed outward and spaced apart by a baseline varying from 10cm to circa 30cm. The system provides a full hemispheric view except for the side occupied by the operator. LED illuminators and a monitor are also housed on the hand-held device. The backpack houses the device's battery and control unit. The survey is done by synchronized and timed image acquisition; the operator sets the frame rate before starting the acquisition. The system lacks inertial and positioning sensors. Therefore, the three-dimensional reconstruction relies on processing the acquired images by Structure from Motion (SfM) and Multi-View Stereo (MVS) pipelines. This way, a point cloud of the environment traversed during the survey is obtained. In Perfetti et al. (2022a, 2022b), two tests of the accuracy of the multi-camera system in surveying confined spaces without GCPs constraints are detailed. While Marotta et al. (2022b) compare the multi-camera system and Heron Backpack MMS along a mountain trail.

3. DATA ACQUISITION AND PROCESSING

The compared instruments were used with other instrumentation to implement a complete and truly employable surveying procedure that included total station surveying to acquire GCPs. In this way, two approaches to complete surveying were compared, not just the capabilities of individual sensors.
This also allowed to compensate for the already known drawbacks of the two instruments compared: i.e., the high drift error of unconstrained Heron Backpack acquisitions and the poor measurement range of the Ant3D multi-camera (Marotta et al. 2022b). Specifically, a total station survey, a UAV photogrammetric survey, and a terrestrial photogrammetric survey with a DSLR (Digital Single Lens Reflex) camera where conducted. The total station survey support both approaches, in particular the Heron Backpack survey containing its drift; and the UAV and DSLR survey compensate for the short acquisition range of the multi-camera. Thus, the two approaches here compared for the characterization of historical garden include the use of the following instruments:

- Heron Backpack, Total station
- Ant3D multicamera, Total station, UAV, DSLR

Total station network: a provisional topographic network consisting of 5 vertices was materialized, extending throughout the villa's garden. The coordinates of 53 GCPs materialized on the ground were measured from this network. The GCPs were measured with an accuracy of about 1-2cm. The implementation of GCPs constraints during data processing of both the MMS and the multi-camera surveys made it possible to constrain the reconstructions' verticality and contain instrumental drifts.

UAV Photogrammetric survey: The multi-camera survey approach was characterized by a poor measurement range of 4-5m due to the GSD (Ground Sampling Distance) resulting from the multi-camera configuration employed. This led to poor reconstruction of the top portion of trees. Similar behavior is shown in Mokros et al. (2021). It follows that it is necessary to supplement the missing data with additional surveys to complete the tree survey and, thus, the garden characterizations. Therefore, a UAV survey of the entire garden area of the villa and its surroundings was performed. Employing the DJI Phantom 4 Pro v2 UAV, 606 photographs were acquired following an automatic gridded flight plan executed at 50m above ground level. The UAV survey was constrained to the same GCPs materialized for the terrestrial survey.

DSLR terrestrial photogrammetric survey: A terrestrial photogrammetric survey of the perimeter brick walls of the historical garden, which has some entrance portals that surpass 4m in height and features numerous sculptural pieces, was conducted to address the limited measuring range of the multi-camera technique. The survey was conducted with a Nikon D750 DSLR equipped with a 16mm lens, with which 1960 images were acquired. These were processed according to the SfM pipeline together with multi-camera images.

3.1 Heron Backpack survey and processing

For the survey with Heron Backpack, 3 acquisitions were carried out. Each of them had a starting point that was barycentric to the entire park and an ending point that was almost the same as the beginning, ensuring the closure of an acquisition loop. The MMS acquisitions were carried out mainly along existing trails in the park and only exceptionally by walking some sections of the meadow to reach areas otherwise too far from the trails. Figure 4 (a) shows the calculated paths of the 3 trajectories acquired with Heron Backpack, while Table 1 summarises the details of the Heron Backpack survey that took approximately 30 minutes to complete.
The acquired data were processed using the proprietary Heron Desktop software marketed by Gexcel srl.

	Duration	Length	N° of points
Acquisition 1	00:10:03	590 m	262 Mln
Acquisition 2	00:10:28	596 m	261 Mln
Acquisition 3	00:07:14	444 m	193 Mln

Table 1. Summary of the data of the 3 acquisitions performed with Heron Backpack.

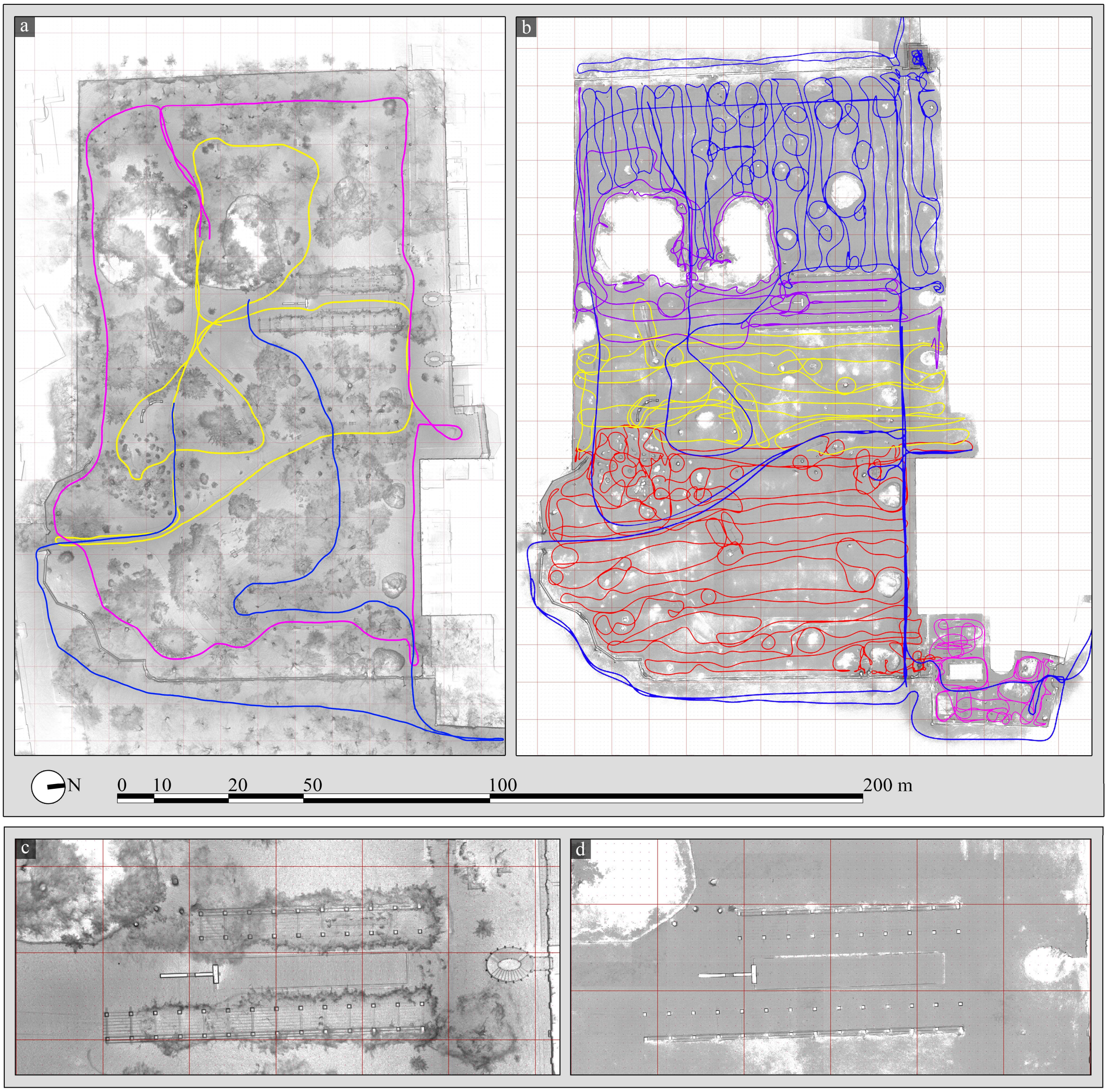

Figure 4. Blueprints of the two obtained point clouds and the respective trajectories followed during the acquisition are highlighted. Heron Backpack survey (a), Ant3D survey (b), zoom of Heron Backpack blueprint (c), zoom of Ant3D blueprint (d). The red grid has a spacing of 10 x 10 m.

The data processing involves, as a first step, the estimation of the path of individual trajectories based on the data acquired from the inertial unit and LiDAR sensors, and secondly, the realization of the so-called “loop closure,” which is a joint optimization of the trajectories of the different acquisitions in which constraints are automatically or manually created between data acquired at different times but pertaining to the same location. In this second phase, it is also possible to realize constraints between manually identified points on the point cloud and the coordinates of the GCPs. The points were identified with an estimated accuracy of about 2cm. The average error on the GCPs at the end of the optimization was about 5cm. Marotta et al. (2022a) describe the Heron Backpack data processing step in more detail. Figure 4 (a, c) shows the data obtained at the end of processing.

3.2 Ant3D survey and processing

For the survey performed with Ant3D, a total of 5 acquisitions were carried out. Unlike the Heron Backpack survey, due to the reduced measurement range of the multi-camera, it was not possible to walk the park paths only. Rather, an attempt was made to maintain a walking pattern of dense parallel passes with which the entire garden area was covered. At larger trees or bushes, a circular acquisition was performed by walking around the obstacle and thus photographing it from all sides. At the end of the last acquisition, the main paths in the park were finally walked with the purpose of linking the different acquisitions together. Figure 4 (b) shows the trail of the 5 different acquisitions, where the difference in density from the Heron Backpack survey is evident.

	Duration	N° of images	N° of points
Acquisition 1	00:18:00	5400	90 Mln Filtered point cloud
Acquisition 2	01:05:00	19570	
Acquisition 3	00:26:00	7860	
Acquisition 4	00:37:00	11240	
Acquisition 5	01:32:00	27730	

Table 2. Summary of the data of the 5 acquisitions performed with the Ant3D multi-camera system.

During the acquisitions, images were taken at 1 fps for a total of 71800 images. However, only one of every four images was later processed, thus a total of 17950. The time required for the multi-camera survey was approximately 4 hours. However, considering the UAV survey and DSLR survey operations that became necessary, the total survey time amounted to about 6 hours. Much higher than what was required for the Heron Backpack survey. The acquired images were processed with Agisoft Metashape until dense point clouds of the entire park were obtained. A single overall SfM alignment of all the Ant3D and DSLR images was performed, and baseline constraints were imposed within multi-camera poses. The enforcement of baseline constraints was carried out as detailed in Perfetti & Fassi (2022a). Manually identified GCPs constraints were also imposed on the photographs; the average error on these points was about 5cm. Then the final point cloud was made by dividing the portion of the park by 10 blocks that were processed separately and then merged.

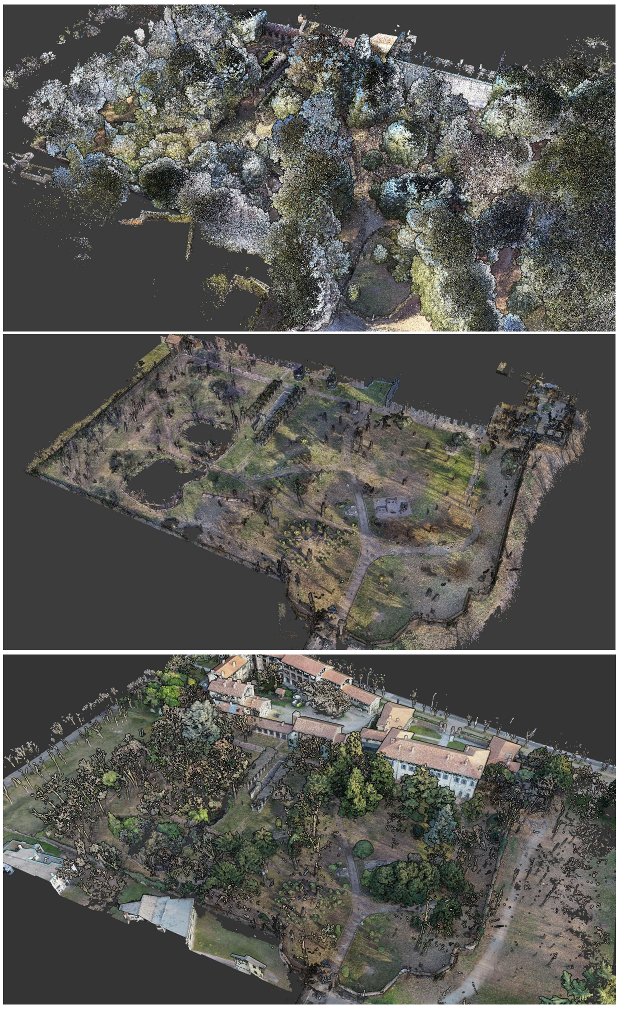

Figure 5. Point clouds obtained for the various survey carried out: Heron Backpack (top), Ant3D (centre), UAV (bottom).

The UAV survey, on the other hand, was processed separately and registered in the same local coordinate system based on GCPs. Figures 4 (b,d) show a plan view of the Ant3D point cloud; it can be seen that compared to the data obtained with Heron Backpack, tree crowns were not detected. Figure 5 (centre) shows the Ant3D point cloud in 3D view.

4. RESULTS AND COMPARISON

At the end of the processing, 3 colored point clouds were obtained (Figure 5): (i) the Heron Backpack survey, (ii) the Ant3D survey, and (iii) the UAV survey. The data acquired with both approaches allow for the extraction of DBH and the planimetric footprint of the canopies, thus characterizing the surveyed trees. However, the obtained clouds present essential differences in describing natural and artificial geometries due to the two instruments' different acquisition ranges and precision. Visual comparisons between the data are presented below.

Point cloud details and noise level: The comparison was performed on portions of the Heron Backpack and Ant3D point clouds, focusing on the architectural geometries found in the park. Figure 6 reports the comparison in these areas: **1a** and **1b** show one of the masonry portals present in the park, the Heron Backpack point cloud (1a) has a much higher noise level than the photogrammetric cloud (1b, the DSLR survey was also performed in this area); **2a** and **2b** show the structure of a gazebo covered with climbing vegetation. Here the photogrammetric cloud (2b, obtained from the multi-camera survey only) shows complete absence of the vegetation while all the architectural structures are correctly reconstructed; **3a** and **3b** show a zoom of the same area. The multi-camera survey point cloud has more details than the MMS one.

Cross-section completeness: a vertical section with a thickness of 6m of the acquired point clouds was extracted. Figure 7 shows the section of the Heron Backpack (top) complete in all its parts. The ground profile, park furniture, trees, branches, and foliage are clearly distinguished. The presence of people in the garden at the time of acquisition is also particularly visible. In contrast, the Ant3D section (bottom, red) was complete only close to the ground, up to a few meters above the ground. However, the details of the branches below the upper surface of the foliage remain undetected. The UAV survey, therefore, allows us to integrate the terrestrial survey with the tree crowns (bottom, pink).

Tree quality, DBH, and canopy description: Some trees with different sizes were isolated for this comparison. Figure 8 shows the planimetric and elevation view of these trees. The data acquired from Heron Backpack (1a, 2a, 3a) turns out to be complete in all its parts, similarly to what is shown in Figure 7 (top); while the photogrammetric data, obtained from the union of the Ant3D and UAV survey (1b, 2b, 3b) turn out to be partially incomplete. However, as visible in the planimetric images, it is still possible to estimate the canopy footprint for a 2D representation. Figure 9, on the other hand, shows the extracted horizontal sections at the 1.3m ground elevation useful for DBH estimation. It can be noticed the greater presence of noise in the Heron Backpack data (1a, 2a, 3a, 4a, 5a). However, the Ant3D data is not without problems; although it shows more precise trunk definition in general (1b, 2b, 3b, 4b), small-diameter trunks are not properly returned unless acquired from a short distance (5b).

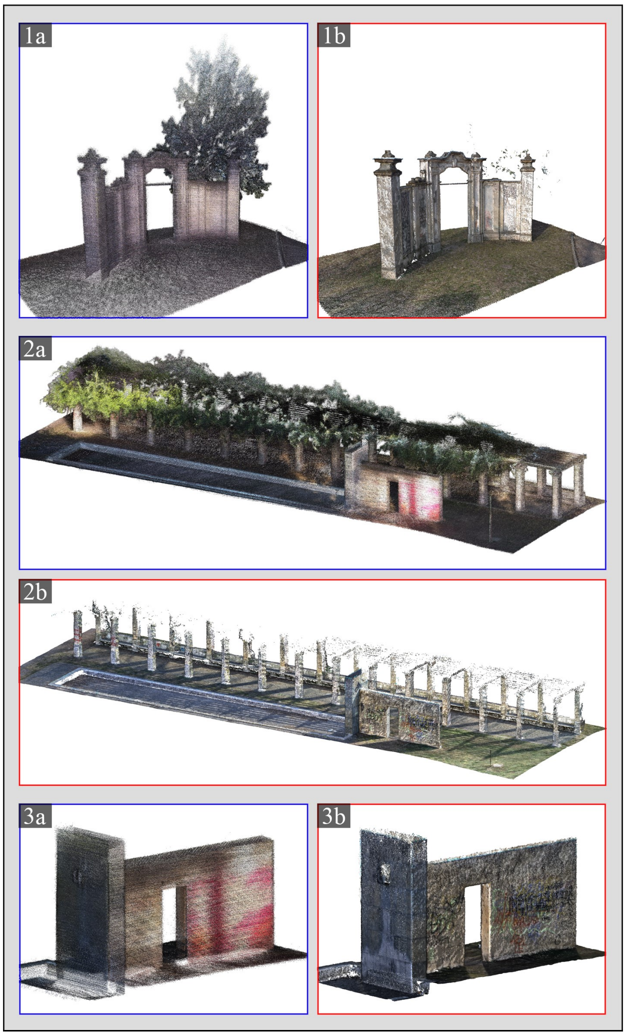

Figure 6. Comparison of the two point clouds obtained of some man-made structures. A portal structure (1a, 1b), a gazebo structure (2a, 2b) and zoom part of the gazebo structure (3a, 3b). Heron Backpack is blue-edged and Ant3D is red-edged.

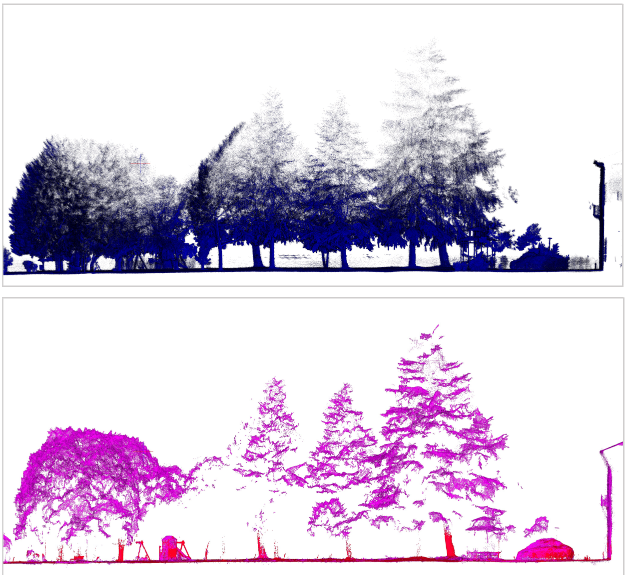

Figure 7. Cross-sections extracted from Heron Backpack (top) and from Ant3D + UAV (bottom). Ant3D in red, UAV in pink.

5. CONCLUSION AND FUTURE WORKS

The results obtained from the two survey approaches are comparable; both methods produced colored point clouds from which various analyses for garden characterization can be derived. The Heron Backpack survey produced a point cloud complete in all its parts capable of describing the trees at both trunk base and crown without requiring the integration of additional surveys. However, the MMS point cloud has higher noise than the photogrammetric one. Survey times were significantly favourable for the MMS approach, with an acquisition time of about 30 minutes, which required a shorter path to cover the entire garden due to the more extensive acquisition range. The multi-camera survey produced a high-resolution point cloud with lower noise and higher detail definition. However, the survey took longer: in fact, due to the shorter measurement range, several parallel passes had to be made at a distance of about 5m, requiring up to about 4 hours to cover the entire garden with the multi-camera survey alone. However, considering that only a quarter of the images were processed, the survey time could have been shortened to about 1 hour by increasing the walking speed, which was indeed relatively slow. Both systems yielded a dense representation of the terrain from which an accurate and detailed DTM can be derived; the terrain sections that can be extracted from the multi-camera survey are more defined due to the lower point cloud noise, but incomplete in the definition of tree crowns. Also, with both systems, the DBH of tree trunks can be extracted, except for thinner and finer-diameter trunks. In this case, the MMS makes it possible to identify the presence of the trunks. However, the DBH estimation might be less accurate, while the multi-camera system sometimes does not provide data. This was also the case for light poles (not shown here), which were found to be poorly identifiable or completely absent in the photogrammetric point cloud. With the photogrammetric data, during the 2D restitution process, identifying thin stems and other fine features is not always possible by looking at a slice of the point cloud into thin horizontal cuts (about 5cm).

In conclusion, the MMS survey approach is more effective than the multi-camera approach in the characterization of historical gardens. The main advantage of the MMS approach lies in the productivity due to the shorter survey time required to cover equal area and the fact that the MMS survey alone is sufficient for the geometric description of the trees. On the other hand, the multi-camera approach cannot avoid integration with an aerial survey for canopy reconstruction, and the greater detail of the point cloud (even in the absence of the DSLR survey, Figure 4 - 3b) is not required for 1:200 or 1:100 scale representations. However, the main advantage of the multi-camera approach lies in the lower cost of the instrumentation used and can therefore be considered for low-budget applications.

For future works, two modifications of the multi-camera device could be attempted to make it more suitable for the garden or forestry context: (i) the first modification could be to increase the resolution of the cameras equipped on the multi-camera system, with the goal of reducing the GSD, increasing the measurement range and consequently simplifying and speeding up the acquisition phase; (ii) the second modification could be to add an upward-facing camera to attempt reconstructing the geometry of the trees branches and canopy from the bottom. However, the authors opinion remains that the main advantage of the multi-camera approach is the lower-cost while a range-based MMS is to be preferred for complete trees description.

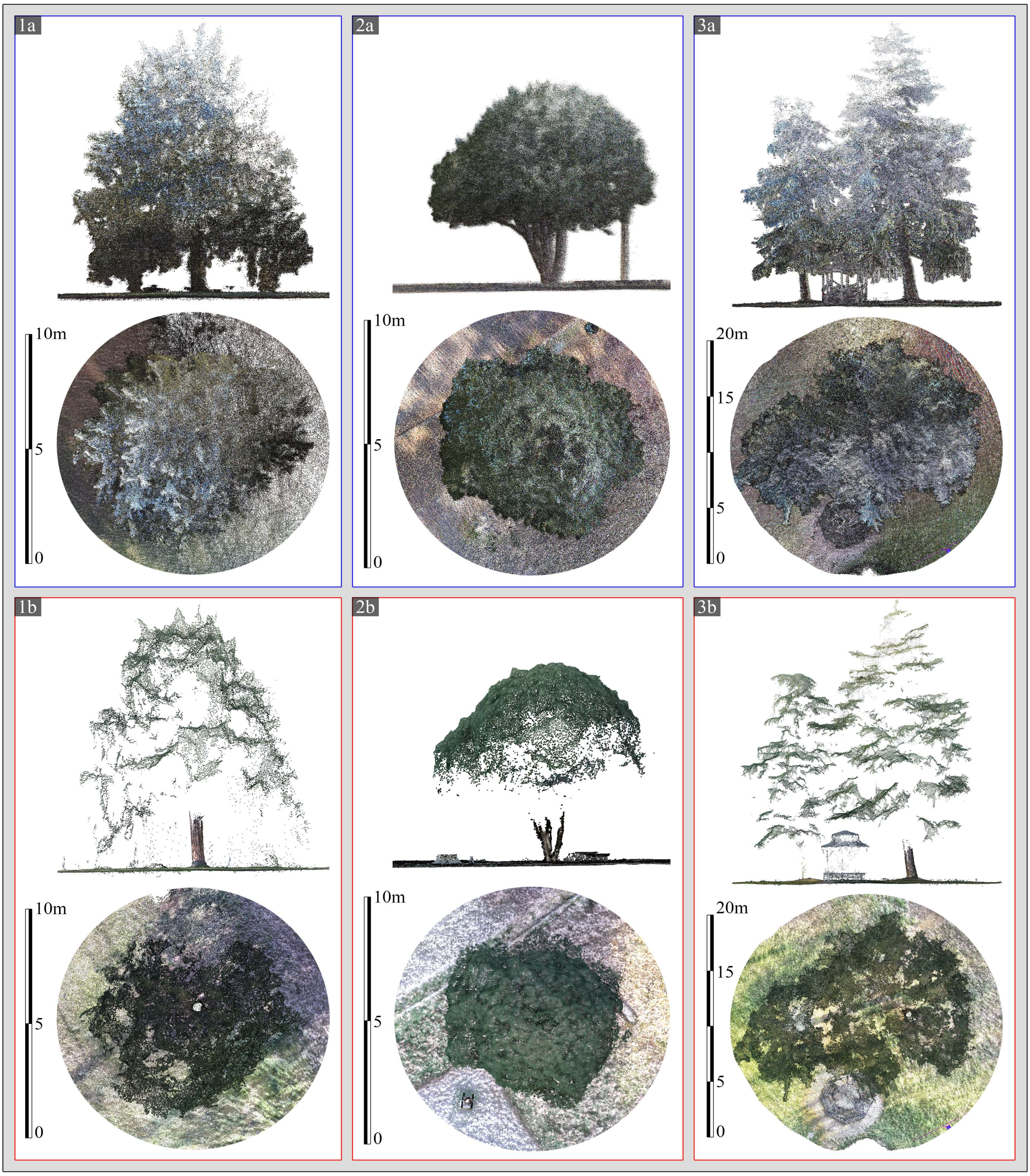

Figure 8. Trees plan and elevation view extracted from the Heron Backpack point cloud (top row, blue edged) and the Ant3D + UAV point cloud (bottom row, red edged).

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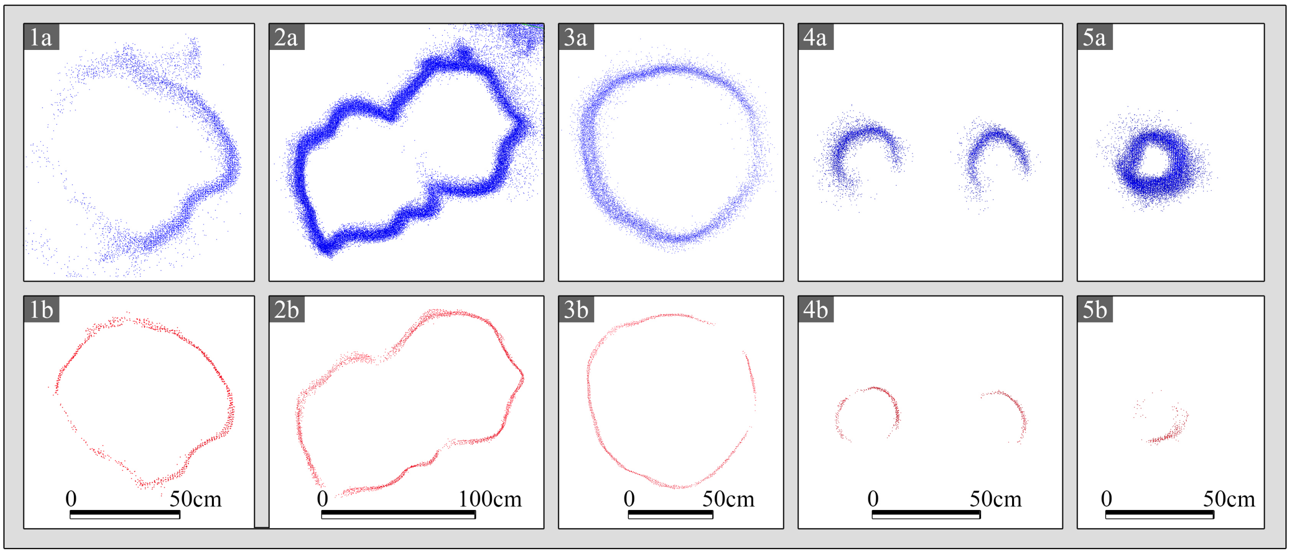

Figure 9. Trees plan section at breast height extracted from the Heron Backpack point cloud (blue) and from the Ant3D point cloud (red).

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