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TARGETLESS REGISTRATION METHODS BETWEEN UAV LIDAR AND WEARABLE MMS POINT CLOUDS

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ABSTRACT:

Fixed-wing Unmanned Aerial Vehicles (UAV) and wearable or portable Mobile Mapping Systems (MMS) are two widely used platforms for point cloud acquisition with Light Detection And Ranging (LiDAR) sensors. The two platforms acquire from distant viewpoints and produce complementary point clouds, one describing predominantly horizontal surfaces and the other primarily vertical. Thus, the registration of the two data is not straightforward. This paper presents a test of targetless registration between a UAV LiDAR point cloud and terrestrial MMS surveys. The case study is a vegetated hilly landscape characterized by the presence of a structure of interest; the UAV acquisition allows the entire area to be acquired from above, while the terrestrial MMS acquisitions will enable the construction of interest to be detailed. The paper describes the survey phase with both techniques. It focuses on processing and registration strategies to fuse the two data together.

Our approach is based on the ICP (Iterative Closest Point) method by exploiting the data processing algorithms available in the Heron Desktop post-processing software for handling data acquired with the Heron Backpack MMS instrument. Two co-registration methods are compared. Both ways use the UAV point cloud as a reference and derive the registration of the terrestrial MMS data by finding ICP matches between the ground acquisition and the reference cloud exploiting only a few areas of overlap. The two methods are detailed in the paper, and both allow us to complete the co-registration task.

1. INTRODUCTION

In Geomatics, fixed-wing UAVs (Unmanned Aerial Vehicles) and wearable or hand-held Mobile Mapping Systems (MMSs) are two widely used platforms for point cloud acquisition with LiDAR (Light Detection And Ranging) sensors. These find applications in various fields, the former enabling aerial surveying of portions of land (1km - 10km) including terrain, structures, urban context, etc., and the latter for rapid terrestrial surveying of smaller areas (100m - 1km) such as urban context, indoor environments, and terrain. Despite using similar sensors, the two platforms produce complementary point clouds, the former describing predominantly horizontal surfaces and the latter primarily vertical. It follows from this that for many applications, it is desirable to employ both instruments to fuse the acquired data into a single point cloud. Thus, the problem of the registration of the two data becomes central.

Data fusion from different sensors is widespread among survey and digitization projects in multiple applications. A typical example is the fusion of terrestrial surveys, made with static, portable laser scanners, or photogrammetry, with aerial surveys, made by UAV using photogrammetric or LiDAR techniques. A more extensive UAV survey can be supplemented with punctual ground surveys to complement structures or areas occluded from above.

However, registering point clouds acquired from distant viewpoints with little overlap and/or different densities is not straightforward. An optimal approach involves the use of double points, preferably of known coordinates identifiable in both data, that would allow simultaneous verification, registration, and georeferencing of point clouds acquired by the different methods. However, this approach has the disadvantage of requiring the materialization of some targets before the survey phase or being able to locate homologous points a posteriori by manually recognizing them among the surveyed elements, provided there are sufficiently recognizable structures. In addition, measuring control points using standard topographic techniques (total station and Global Navigation Satellite System, GNSS) requires additional effort and time.

Another possibility for registering aerial data with terrestrial data is the use of algorithms that operate in the absence of markers. These find abundant application in forestry for registering point clouds acquired below and above canopies. The forest scenario, in fact, makes it more difficult to position and measure Ground Control Points (GCPs) and thus more attractive to perform targetless registration of terrestrial point clouds with UAV LiDAR surveys that have already been georeferenced thanks to the GNSS sensors on board the UAVs.

Targetless registration methods include "2D" approaches, which are based on identifying 2D homologous points among two-dimensional representations of the point clouds, and "3D" approaches, which are divided into registration by object-correspondences and by 3D point-correspondences. Persad and Armenakis (2017) propose a "2D" method based on the use of depth maps generated from point clouds; this approach is most effective in the presence of 3D scenes rich in artificial object geometry. Kelbe et al. (2016) and Polewski et al. (2019) propose a "3D" method based on object matching developed for forestry applications in which tree trunks are used for the matching. Shao et al. (2022), propose a multi-step mixed method that relies on "3D" terrain matching for vertical alignment and "2D" matching between point cloud image reductions for planar alignment. The latter approaches were specifically developed for forest contexts

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and require the presence of trees. On the other hand, 3D point matching approaches, such as the use of Iterative Closest Point (ICP) algorithms, are the most classic targetless registration methods and are flexible, applicable in different scenarios, both natural and man-made. However, the ICP approach requires comparable point clouds with good overlap and a rich and recognizable common geometry. Ultimately, the ICP approach is usually discarded in forestry since there is little overlap and much-repeated geometry between aerial and terrestrial point clouds in this scenario.

Finally, all registration approaches compute the relative position between different rigid point clouds and therefore fail in the presence of non-negligible deformations inherent to the point clouds themselves. The influence of deformations is reduced or nullified in the case of UAV acquisitions supported by relative GNSS positioning and small terrestrial TLS or MMS acquisitions. On the contrary, it cannot be neglected in the case of unconstrained aerial surveys and in the case of extended terrestrial MMS acquisitions. Marotta et al. (2022b) analyze the magnitude of deformation of unconstrained terrestrial MMS and multi-camera photogrammetric acquisitions in the forest environment arriving at an estimated drift error of 0.2 m per 100m for the MMS instrument. While Marotta et a. (2022a) present an application in the urban environment where the use of GCPs was found to be essential for containing deformation.

1.1 Our approach

This paper presents a case study integrating UAV and mobile ground-based LiDAR measurements to comprehensively survey a mixed outdoor environment, including forest areas and artificial structures. The article describes the survey phase with both techniques. It focuses on the processing and the coregistration strategies to blend the two methods. The area under study is a vegetated hillside landscape with occasional structures and/or areas of interest. However, the approach is suitable for all those contexts where an extensive aerial UAV survey needs to be complemented by punctual terrestrial surveys.

This paper illustrates and compares two aerial and terrestrial point cloud data registration strategies that aim to be efficient and rapid and do not require GCPs. The LiDAR aerial survey was conducted with a fixed-wing UAV equipped with GNSS RTK (Real Time Kinematic) positioning. However, it was impossible to acquire the data in precision mode during the acquisition, so the aerial survey was not free from deformation. The terrestrial survey was conducted with a wearable MMS that allows rapid acquisition of 3D data describing vertical surfaces and above-occluded parts of areas of interest. Despite the deformations, the aerial data are more reliable than the unconstrained MMS survey and were therefore considered the reference. The terrestrial MMS data must be constrained to the aerial data to prevent the drift of the former from leading to significant deformations. This is particularly critical for mobile mapping platforms without RTK positioning sensors (such as Geoslam Zeb, Kaarta Stencil, Gexcel Heron, etc.) or, more generally, when surveying is conducted in GNSS denied areas (such as urban environments, vegetated regions, etc.).

Our approach is based on the ICP method by taking advantage of the data processing algorithms available in the Heron Desktop post-processing software for handling data acquired with the Heron Backpack MMS instrument (by Gexcel srl). Two coregistration methods are compared. Both methods use the UAV point cloud as the reference and derive the coregistration of ground data by finding ICP matches between the ground acquisition and the reference cloud. The MMS acquisition is not treated as a rigid block; the trajectory of the instrument is calculated at each point to ensure the best match. The two methods can be described as (i) post-processing adjustment and (ii) continuous tracking adjustment.

In summary, the first method performs trajectory registration and optimization of Heron Backpack data based on ICP registration between portions of the MMS point cloud called "Local-maps" and the reference UAV point cloud. While the second method is based on continuous adjustment of the MMS trajectory based on the "tracking" of Heron Backpack movements relative to a starting point in the known environment of the UAV point cloud. The first method requires more manual intervention in defining and controlling ICP connections between adjacent local maps and between local maps and the reference point cloud. The second method requires defining an injection point from which epoch-by-epoch tracking of the system's movements relative to the known environment will be performed.

1.2 Case study

The acquisition was conducted in Collebeato (Brescia, Italy), a hilly context characterized by patchy vegetation, unpaved paths, crops, and the presence of the convent of Santo Stefano (Figure 1). The goal was to explore possible synergies between two instruments and relative data types: an aerial LiDAR survey with a fixed-wing UAV platform mounting a Livox Avia LiDAR sensor and terrestrial surveys conducted with the Heron MS Twin Color indoor MMS manufactured by Gexcel srl.

The UAV-generated point cloud is considered more accurate. It therefore is treated as the reference data, while the data generated with the indoor MMS needs to be registered and constrained with the reference data exploiting only a few overlapping areas.

Figure 1. Images of the area of interest, the convent of Santo Stefano in Collebeato (Brescia, Italy).

2. DATA ACQUISITION

Data acquisition for the test took place in a single day. At the same time, the UAV survey was carried out to cover the entire area of interest of 800 by 400 m from above, while a series of acquisitions with the wearable MMS system were carried out around the architectonic structure and protruding under the woods. No GCPs were placed and measured.

2.1 UAV LiDAR survey

The UAV survey was conducted by the Max Planck Institute of Animal Behavior – Advanced Research Technologies DroneLab and Airborne Remote Sensing. A vertical take-off fixed-wing UAV platform was used (Figure 2) on which an Applanix APX-15 UAV positioning unit and a Livox Avia LiDAR measurement unit were mounted. The measurement unit, used in Repetitive Line Scanning mode, has a longitudinal field of view of 4.5° and a transverse field of view of 70.4°, acquires at a rate of 240,000 points per second, and has a nominal accuracy of 3cm. The positioning unit allows RTK positioning with an accuracy of 2-3cm; however, data could not be acquired fixing the position with high precision, and this caused inherent deformations to individual measurement passes. Once the home point was established, the acquisition was started with vertical take-off reaching the survey altitude. The flight plan setup is a grid type consisting of 5 parallel swipes in the longitudinal direction and 6 in the transverse direction.

The acquired point cloud was provided to us pre-processed in two versions: merged into a single point cloud and divided into the individual swipes of the survey. The acquired data fully covers the area of interest but still has suboptimal features. First, the lack of precision RTK positioning led to deformations in the different strips that produced double surfaces (Figure 3). In particular, deviations of about 30-50 cm can be found on the roofs of the convent building and variations up to more than 1 m in some areas of the terrain. Second, the data provided to us has few terrain points surveyed in the denser forested areas, these are sufficient to obtain the Digital Terrain Model (DTM) of the area of interest, but they are not sufficient to ensure a match with the data acquired from the ground with the MMS instrument (Figure 4). Finally, the UAV point cloud is not complete on all vertical surfaces of the convent structure (Figure 5).

Of these three limitations/characteristics of UAV data, the sparsity of points measured on the ground and vertical surfaces is most easily overcome. Coregistration algorithms can rely poorly upon these areas. Thus, for example, the MMS survey performed under dense vegetation may be untethered from the reference and thus be prone to instrumental drift. For the present case study, where the densely vegetated areas are few, and the MMS survey does not extend too far into the undergrowth, this does not produce significant deviations. On the other hand, the presence of double surfaces in the reference data is more critical, as the ICP can confuse the two surfaces and lead to incorrect registration. Double surfaces mainly affect one of the two proposed methods: the continuous tracking adjustment. Therefore, it was necessary to reprocess the registration of the point clouds of the individual swipes to reduce the final deviations.

Figure 2. The fixed-wing UAV used during the survey phase.

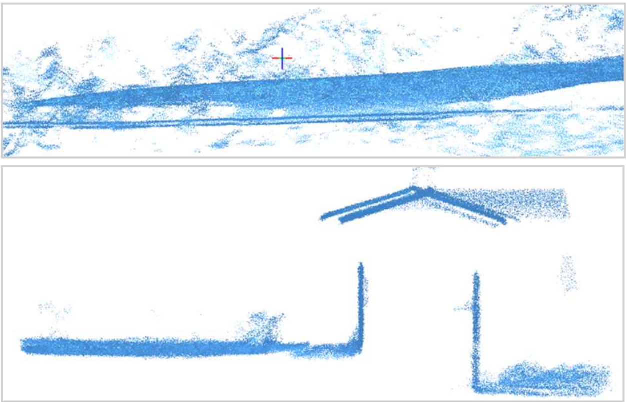

Figure 3. Examples of double surfaces in the original aerial data: a footpath (top) and a portion of the roof (bottom).

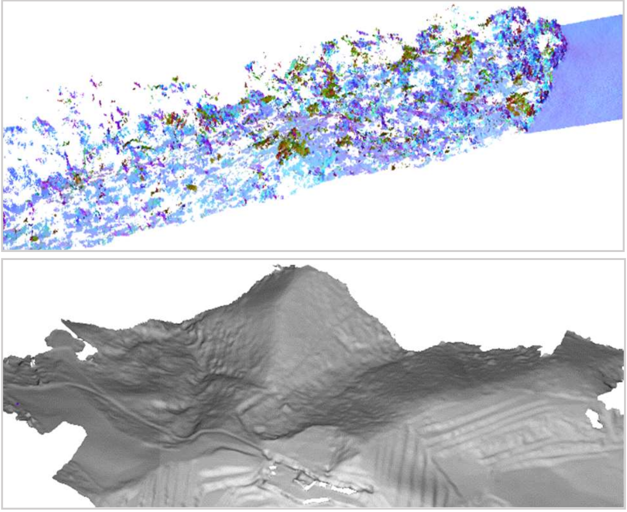

Figure 4. A portion of the UAV point cloud showing few ground points detected (top), and the DTM extracted (bottom).

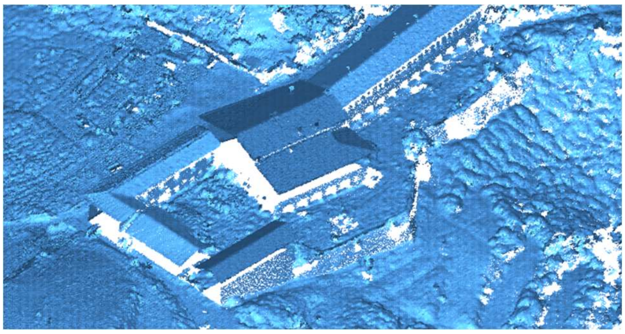

Figure 5. UAV point cloud showing few points detected on the vertical survey of the convent structure.

Each of the point clouds of the individual swipes were segmented into 2 or 3 blocks of comparable size. The segmentation yielded 29 blocks; 16 were discarded because were considered redundant or lacking significant information for the coregistration with the MMS system. The 13 blocks that were considered significant were re-registered with each other in the Reconstructor software using the ICP registration algorithm. The registration procedure was performed in several stages, linking one block at a time to the previous blocks already registered. The first block of the registration held stationary was chosen based on the presence of abundant man-made geometry, the convent, and the fact that it is barycentric to the overall survey. At each registration stage, the average ICP error was checked at the addition of each block; it ranged from 6 to 12 cm. In addition, a visual cross-section check was performed to verify the correct alignment or extent of deviations. Once an overall registration of all selected blocks was obtained, it was possible to verify how the increased flexibility provided by dividing the starting data into smaller portions had the effect of decreasing the distance between the double surfaces to a maximum of about 15 cm. At this point, a bundle adjustment was performed between all the pre-aligned blocks. The average error of the registration is 6.5 cm, and the maximum distance between double surfaces was reduced to a maximum of about 10 cm. The resulting registration produced a new point cloud with satisfactory accuracy suitable for forest survey applications, Figure 6 shows the final reference point cloud obtained.

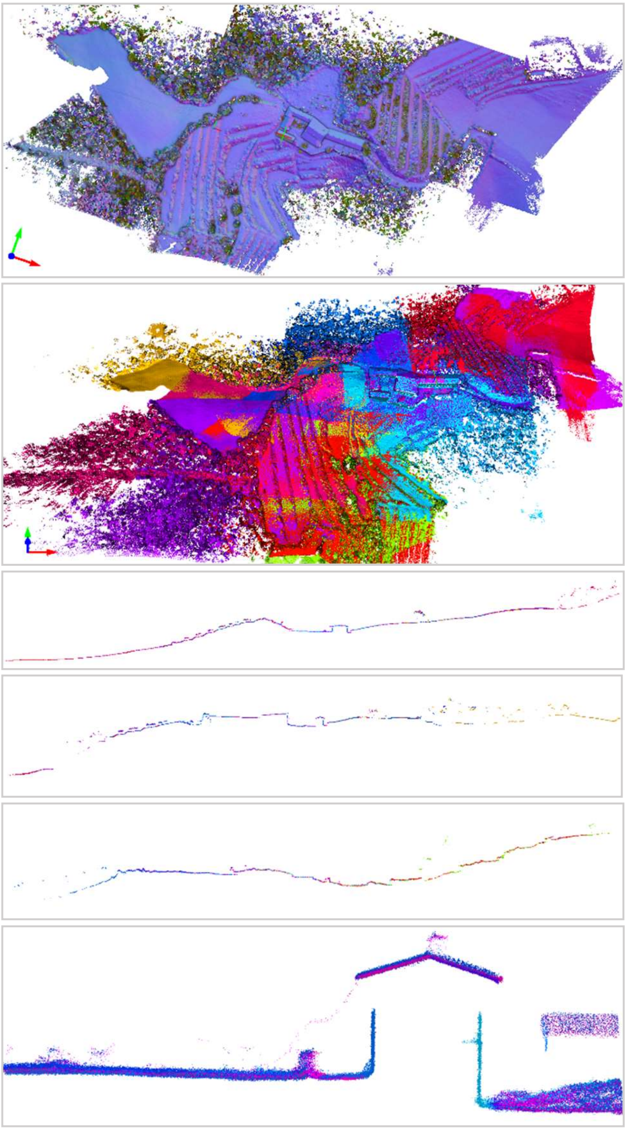

Figure 6. Reference aerial LiDAR point cloud obtained after reprocessing, top and 3D views (top two), and sections view (bottom four).

2.2 Terrestrial mobile mapping survey

The land survey was carried out with the Heron MS Twin Color MMS (later named "Heron Backpack") manufactured by Gexcel srl (Gexcel, Brescia, Italy). It is a portable wearable backpack system a single operator uses while walking in the environment to be surveyed (Figure 7). It offers the advantage of being easily deployable even in steep and uneven terrain, making it ideal for acquisitions in vegetated areas. Heron Backpack mounts a mapping unit, a positioning unit, a control unit connected to a hand-held screen, and a panoramic camera. The measurement unit consists of two LiDAR Velodyne Puck LITE sensors, each with 16 scanning lines: one sensor is positioned horizontally and rotates around the vertical axis. The second is placed at 45°. Heron Backpack acquires 600,000 points per second with an omnidirectional 360° x 360° viewing angle and has a nominal local accuracy of 3cm. The positioning unit consists of a compact IMU (Inertial Measurement Unit): Xsense MTi. It lacks a GNSS receiver since the instrument is designed primarily for indoor use. The device acquires data in motion and quickly surveys large areas. Accurate data processing is done in post-processing employing the software Heron Desktop. The data processing uses a SLAM (Simultaneous Localization And Mapping) approach to estimate the trajectory traveled by the instrument (Figure 8).

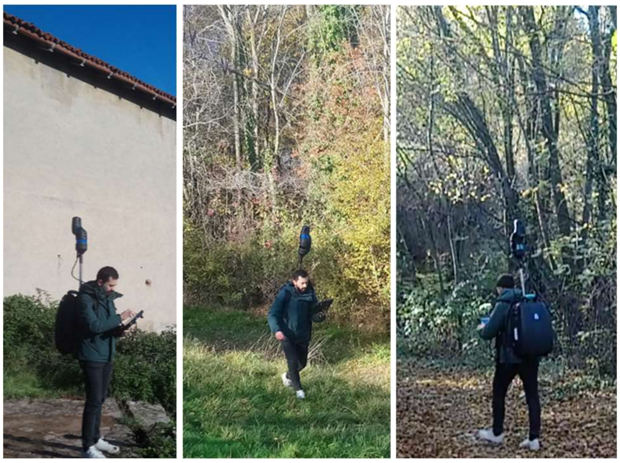

Figure 7. Images of the survey phase with the Heron Backpack.

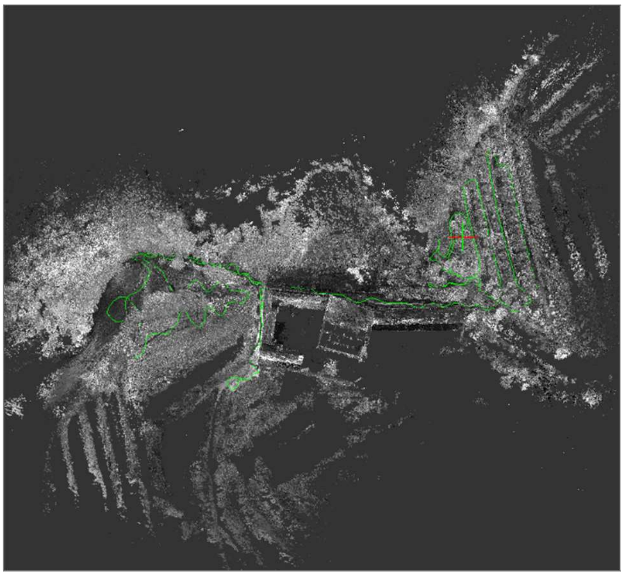

Figure 8. Heron Backpack data are registered together after the initial pre-processing.

At this stage, it is also possible to impose different constraints, such as GCPs or ground control scans (Marotta et al., 2022a). The result of the processing is a point cloud with associated reflectance information and possibly RGB color information derived from the panoramic camera.

A total of 6 acquisitions were made in the field with Heron Backpack for about 40 minutes of survey time. The individual acquisitions cover different areas of the hilly landscape, but all include portions of the Santo Stefano Convent structure. Of the 6 acquisitions, 4 were selected as significant and processed further for coregistration with UAV data, while the others were discarded. Figure 7 shows Heron Backpack during field acquisition operations, Figure 8 shows the merging of the 4 selected trajectories.

Before proceeding with the coregistration process, it is advisable to pre-process the Heron Backpack data to reasonably estimate the trajectories traveled by the instrument by employing only the data it acquired. This step is partly optional if the "post-processing adjustment" is used as the coregistration method and totally optional if the "continuous tracking adjustment" method is used. However, starting from a better estimate of trajectories traveled than the one obtained from the positioning unit alone allows for simplification and improvement of the subsequent steps. The pre-processing of Heron Backback data is done in Heron Desktop in three stages:

- Odometer computation
- Local maps computation
- Global optimization

Odometer computation: It is calculated for all individual acquisitions; it consists of estimating the trajectory considering the data acquired by the mapping unit for which an incremental ICP alignment is calculated. A single turn of the LiDAR sensor acquisition constitutes one laser sweep. Heron Backpack's acquisition is therefore subdivided into a series of sweeps that must be registered with each other. The Odometer calculation process consists in aligning by ICP the second sweep to the first one, the third to the first two, and so on. Each new laser sweep is registered with a "Local-reference-map" composed of the sum of *n* sweeps already registered. Periodically the Local-reference-map is updated to include the last registered sweeps instead of the first ones and keeping the total number of sweeps equal to *n*. Updating the Local-reference-map is necessary whenever the instrument, as it moves, reaches new areas. The more frequently the Local-reference-map is updated, the more the trajectory estimation is subject to drift. At the same time, the less often the Local-reference-map is updated, the more we run the risk that the last laser sweep will not find sufficient common geometry to be registered. The Odometer calculation allows these and other parameters to be modified according to presets or by manually setting the desired values. The most important ones are:

- "Minimun-Maximum distance," the range considered for LiDAR data in terms of distance from the sensor. For example, it is possible to exclude the closest points to the instrument if there is the frequent passing of people and thus many non-stationary points can be filtered out;
- "History size," the number of laser sweeps that constitute the acquisition segment or Local-reference-map to which the last laser sweep is aligned via ICP, the Local-reference-map consists of *n* laser sweeps already registered where *n* is the history size;
- "Update map min. distance", controls how often the Local-reference-map is updated, it is expressed in terms of distance, the map update is triggered when the instrument moves *m* meters from the time of the last update. If Heron Backpack is kept stationary, the local map is not updated despite the elapsed time. Each new laser sweep is registered on the same data preventing the accumulation of instrumental drift.

A metric of the correctness of the Odometer calculation is provided by the agreement between the information obtained from the positioning unit and the information obtained from the incremental ICP. For each point of the trajectory, the two methods provide an estimate of the instrument displacement vector. When these two estimates agree, the trajectory is colored green; when they disagree, it is colored orange or red. Suppose there are local errors in the trajectory estimate. In that case, these may result in deformations or double surfaces at the end of the process. To solve problems in any critical areas, Heron Desktop allows the Odometer calculation parameters to be changed for each trajectory segment. Therefore, it is up to the operator to define the parameters or presets for each given portion of the acquisition depending on the survey conditions.

Local maps computation: It is calculated for all the individual acquisitions made. It consists of extracting, from a Heron Backpack trajectory for which the Odometer has been processed, a series of point clouds known as "Local-maps," which consist of the set of data acquired by the mapping unit in a given trajectory segment. Several parameters can be changed when calculating Local-maps, among them are:

- "Map length," specifies the length of the trajectory segment considered for adding the individual laser sweeps to the local map;
- "Number of overlapping maps," a value of 1 corresponds to a 50 percent overlap; the overlap between adjacent maps is essential for the next step in the process;
- "Minimum translation-rotation to add a cloud," two parameters to exclude redundant data from the Local-maps, should the instrument remain relatively stationary for a period of time, the acquired laser sweeps are not added to the Local-maps.

The Local-maps thus obtained can henceforth be treated as a static point clouds.

Global optimization: it is the last step of the process. It aims to link the different acquisitions and their trajectories to each other and accomplish the so-called "loop closure" by binding together areas where the single trajectory returns to previously visited sites. It is applied once for the whole set of trajectories. It consists of computing an ICP bundle adjustment among all Local-maps computed during the previous step for all trajectories, implementing constraints among all Local-maps that insist on the same area. During processing, the operator checks the correctness of the automatic extraction of links between Local-maps and makes manual links if required. The result of the global optimization is a new and improved estimate of the individual Heron Backpack trajectories that are part of it (Sanchez et al., 2020). For this case study, the Odometer was processed for the four selected trajectories by modifying the parameters from time to time according to the “outdoor survey” presets and manually intervening on them for the most critical areas.

Once a estimates of the Heron Desktop trajectories were obtained with the Odometer computation, a double step was performed:

- Computation of short Local-maps of length 10m, then processed in a Global optimization from which a better estimate of the trajectories was derived;
- Computation of new longer Local-maps of length 100m from the result of the previous Global optimization, then processed in a second Global optimization.

The double step allows first "local" and then "global" optimization of the trajectories, thus avoiding that slight local deviation cause non-negligible deformations on longer path sections. The result of this pre-processing of Heron data alone is shown in Figure 8.

3. TWO COREGISTRATION METHODS

At this point, we tested two approaches, two co-registration methods that take advantage of the data processing algorithms available in the Heron Desktop. These are (i) post-processing adjustment and (ii) continuous tracking adjustment.

3.1 Post-processing adjustment

The first method is the classical approach proposed by the software itself. It is again based on the process of Global optimization. In fact, in this phase, it is possible to import "external" clouds, not coming from Heron Backpack, such as, for example, static scans or point clouds from aerial acquisitions, and it is possible to impose ICP constraints between these and the Local-maps obtained from Heron Backpack trajectories. These external point clouds can be left unconstrained or bound at their original positions. In the former case, they behave like a regular Local-map. In the latter case, they are named Ground Control Scans (GCSs) and allow the passage of the MMS trajectory to be constrained on the fixed position of the GCS.

The aerial LiDAR point cloud obtained from the UAV survey was divided into two blocks. These were employed as GCSs in a Global optimization subsequent to those performed during pre-processing. Since the GCS is meant by the software to be a static ground cloud, this method involves an initial step of preparing the reference point clouds for them to have the following characteristics: (i) they must be small in size, in the order of tens of meters; and (ii), the origin of the point clouds must be approximately barycentric to the cloud itself. Linkages between Heron Backpack Local-maps and GCSs were made manually (Figure 9). Figure 10 gives a summary of the process steps.

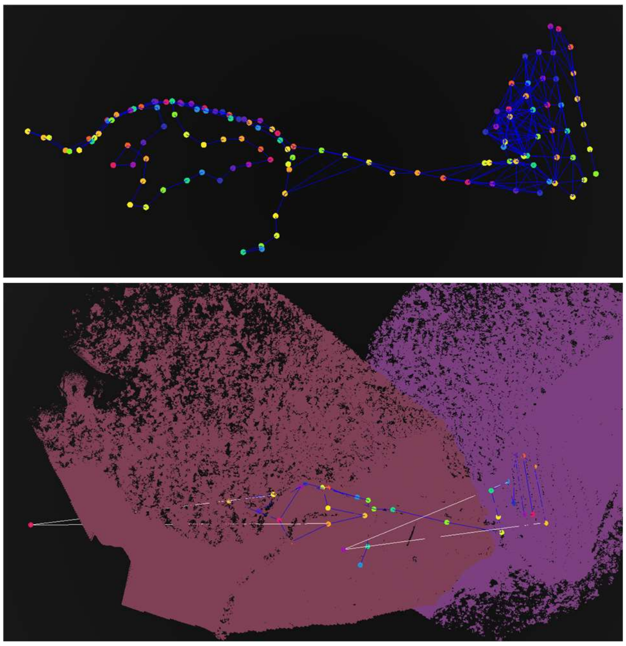

Figure 9. Images of the global optimizations of the Post-processing adjustment method. Heron Backpack data only (top), and with connections to the reference point clouds (bottom).

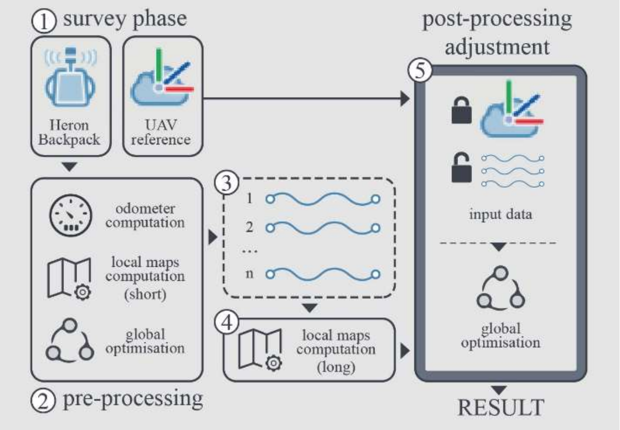

Figure 10. scheme of the post-processing adjustment method. Heron Backpack survey data (1) is pre-processed (2), getting an initial estimate of the trajectories (3), long Local-maps are computed (4), and finally, the global optimization is performed between the Heron Backpack Local-maps and the reference (5).

3.2 Continuous tracking adjustment

Instead, the second method uses another feature in the Heron Desktop software called "Tracking odometer". This tool was developed for change detection applications and is based on recognizing abundant common geometries between newly acquired and previously known data (Sanchez et al., 2016). This is a condition that is not easy to guarantee between two point clouds acquired from different viewpoints.

This feature has the potential to significantly shorten data processing time and produce a better result than the classical method. In fact, under ideal conditions, the Tracking odometer makes it possible to completely replace the pre-processing described in Chapter 2. It replaces Odometer computation by allowing obtaining an estimate of the trajectory based on continuous tracking of the individual laser sweeps by computing the ICP registration between them and the reference point cloud. In this case, the reference point cloud performs the function of the Local-reference-map, and all sweeps are registered on it. It also replaces the steps of Local-maps computation and Global optimization since the trajectory estimate resulting from the process already provides the best fit to the GCS.

The process consists of two steps: (i) Identification of a first matching point, or tracking injection point; and (ii) continuous tracking processing throughout the trajectory extent. The first matching point between a portion on the MMS trajectory and a portion of the reference UAV point cloud must be determined manually; it can be chosen at any point on the trajectory, preferring areas characterized by abundant geometry. At this point, the rigid rototranslation between the entire MMS trajectory and the reference is calculated based on the ICP between the two identified portions. This operation can be attempted several times until a satisfactory initial alignment is obtained. At this point, continuous tracking processing can be initiated from any point on the trajectory, scrolling from the injection point to the desired point. From the moment continuous tracking is initiated, the current laser sweep is registered on the reference point cloud and the relative position of subsequent ones is adjusted accordingly.

The whole process produces good results in all those cases where there is extensive and continuous overlap between the two data; an example of the efficacious use of this method in forestry is described in Marotta et al. (2022b) where the reference point cloud is derived from a terrestrial photogrammetric data acquired along the same trajectoryof the Heron Backpack. However, two main critical issues emerge in non-ideal situations such as this case study:

- Inaccurate trajectory. The use of a raw trajectory estimate obtained from the IMU sensor alone makes it difficult to establish an injection point in an optimal area and then start continuous tracking from the beginning of the trajectory. In the case of significant deformations in the raw trajectory, in fact, from the point where the match between the two clouds was found, to the starting point of the trajectory, the accumulated drift can lead to the two point clouds no longer aligning and thus the inability to start tracking.
- Loss of tracking, should continuous tracking no longer find a match between the point clouds because, for instance, an occluded area has been reached, the trajectory calculation relies on the IMU data, in this case once an area common to the two surveys is reached again the accumulated drift may lead to a significant deviation between the MMS cloud and the GCS, restarting continuous tracking from this point will result in an abrupt discontinuity in the estimation of the MMS trajectory.

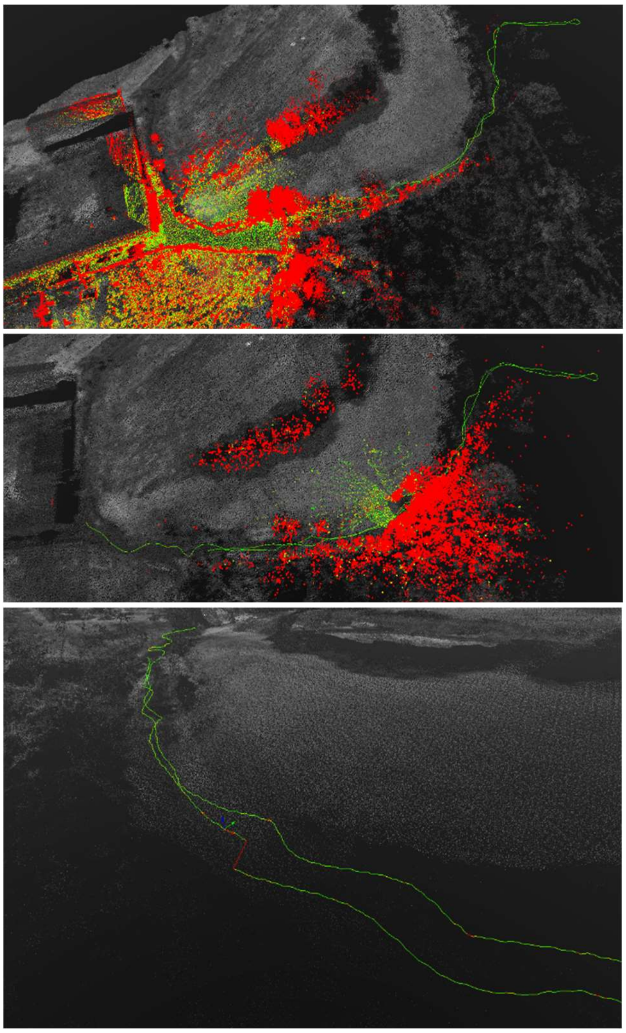

Figure 11. Example of the tracking odometer: good tracking on significant geometry (top), tracking on poor geometry (centre), and trajectory error due to two poor trackings (bottom). The green points lie close to the reference point cloud while the red points do not.

In the present case study, the injection point can only be chosen near the convent structure; however, not all trajectories start in this area. Therefore, it is necessary to find the first match and then start continuously tracking at a different point. To overcome the problem of the accumulation of IMU drift present in the raw trajectory, it was decided to pre-process the Heron Desktop data as described in Chapter 2. The continuous tracking was then processed based on a better estimate of the MMS trajectory. Figure 11 (top) shows tracking near architectural structures, while Figure 11 (middle) shows tracking on poor geometry. The latter was still satisfactory when performed on a pre-processed trajectory. In contrast, the issue of loss of tracking is more challenging to resolve. As shown in Figure 4, the reference point cloud has few terrain points in densely vegetated areas. In practice, they constitute occluded areas where one can only rely on the previously calculated trajectory. Figure 11 (below) shows the error accumulated at the exit of an occluded area when tracking on the UAV cloud is resumed. In this case, the "post-processing adjustment" method using Global optimization allows the drift error to be distributed uniformly along the occluded trajectory avoiding abrupt discontinuities.

As shown in Figure 12, the process that was performed was, therefore, more complex to avoid the problems mentioned above. After pre-processing, the four selected MMS trajectories were sub-segmented into smaller portions, dividing the areas characterized by the presence of good geometry and therefore by the architectural structure from the occluded areas. A total of seven shorter trajectories characterized by strong geometry were obtained, and four trajectories for which there is no significant overlap with the UAV point cloud. The formers were processed utilizing the "Continuous tracking adjustment" method resulting in point clouds adherent to the reference. The second ones were added later in a final post-processing adjustment. In the final optimisation, the previous seven trajectories were used together with the UAV point cloud as GCSs.

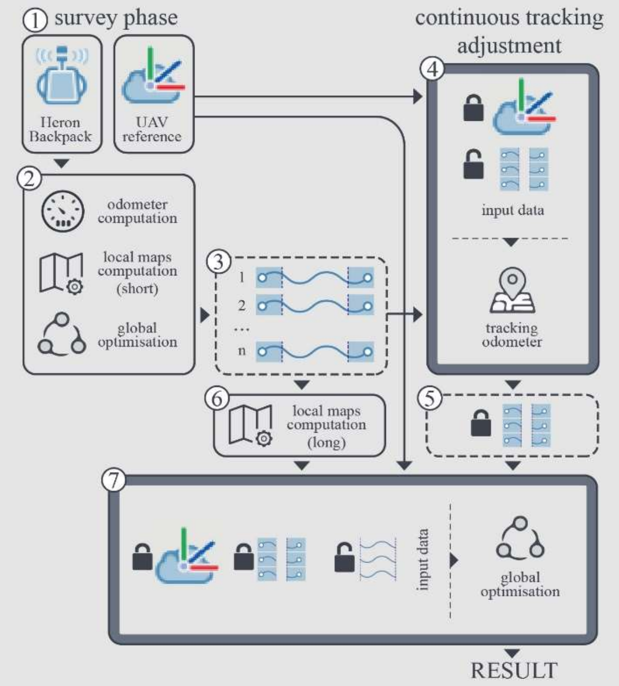

Figure 12. scheme of the continuous tracking method. At stage 3 the estimated trajectories are divided in portion with good and poor geometry. The good-geometry portions are processed with continuous tracking (4) resulting into new GCSs. For poor-geometry portions new long Local-maps are computed (6) and later processed in a final post-processing adjustment (7).

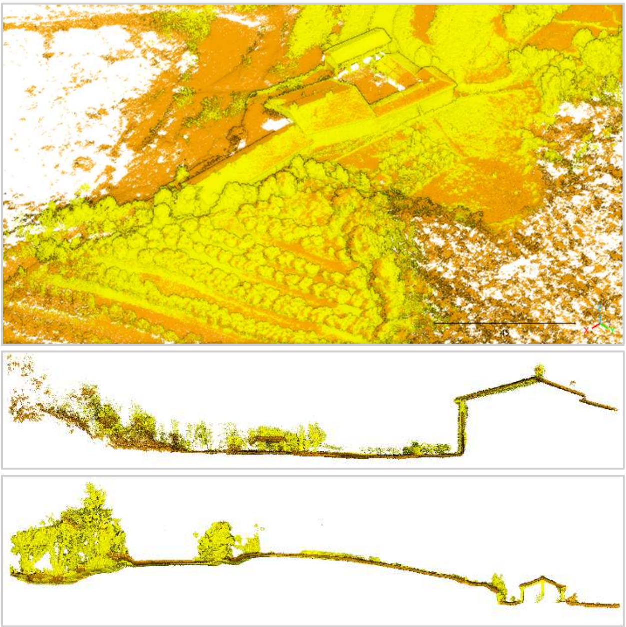

Figure 13. 3D view (top) and cross-sections (centre, bottom) of the post-processing adjustment method registration. Yellow: Heron Backpack point cloud, orange: UAV point cloud.

4. RESULTS AND DISCUSSION

In this paper, we tested two methodologies to achieve targetless co-registration of aerial and terrestrial LiDAR data using the functions available in the Heron Desktop software. The objective was to constrain a terrestrial MMS survey acquired with Heron Backpack on a UAV survey considered as reference. The application area is rapid spatial surveying of natural environments such as forests and meadows punctuated by structures or places of interest that require the integration of a terrestrial survey. For this scope, the global target accuracy is in the order of centimeters. Still, local precision is needed to ensure the absence of double surfaces or visible registration errors.

The first method, the post-processing adjustment, has produced good results by creating a coregistration of data free of significant detectable deviations. This method consists of the classic Heron Backpack data processing method, where GCPs or GCSs are essential to achieve centimeter-order global accuracy. This case study involved the use of two GCSs derived from the UAV point cloud and covering the entirety of the area of interest and thus effectively constraining MMS trajectories within the global accuracy of the reference. Only for areas of dense vegetation was the Heron Backpack data subject to its own instrumental drift.

The second method tested: continuous tracking adjustment, has the potential to speed up and simplify the data processing procedure by directly computing the best estimate of MMS trajectories by performing continuous and direct tracking of the MMS survey on the reference. However, some limitations of the UAV data made it necessary to precede the continuous tracking adjustment with a pre-processing of the Heron Backpack data. In addition, it was only possible to perform continuous tracking when there was overlap between the MMS survey and the UAV survey making it necessary to use the classical post-processing adjustment method to complete the registration of all the acquired MMS data. The main limitation of the UAV LiDAR data that did not allow the continuous tracking method to be applied for the entirety of the acquisition turned out to be the poor penetration under tree canopies of the sensor employed. Despite the limitations, it was possible to obtain a final coregistration as good as that obtained by the previous method but without speeding up the process. Figure 13 shows some 3D views and cross-sections obtained from the first registration method.

In future work, increasing the density of information acquired from the UAV survey under tree foliage is recommended by using a different sensor that can penetrate more or make more passes. In addition, planning continuous tracking injection points from the beginning and acquiring more information in these areas can simplify and increase the accuracy of tracking operations.

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