# Mobile mapping for architectural survey.
# The case of Doge's Palace in Venice: Challenges and lessons learn.

Francesco Fassi [1], Massimo Dierna [3], Laura Taffurelli [1], Jacopo Mario Helder[1], Luigi Fregonese [1], Giorgio Vassena [2]

[1] Department of Architetture, Building and Construction (ABC), Politecnico di Milano, Via Ponzio 31, 20133 Milano, Italy (francesco.fassi, luigi.fregonese, laura.taffurelli, jacopo.helder)@polimi.it
[2] Department of Civil, Architectural, Environmental Engineering and Mathematics (DICATAM), Università degli Studi di Brescia, 25123 Brescia, Italy – giorgio.vassena@unibs.it
[3] Gexcel srl, Via Branze 45, 25123 Brescia, Italy – consulting@gexcel.it

**Keywords: Mobile Mapping, Cultural Heritage, 3D, digitalization, backpack scanner**.

**Abstract**
This paper discusses the utilization of a wearable Mobile Mapping System (MMS) (Gexcel HERON MS TWIN Color) for an extensive 3D survey of the Doge's Palace in Venice, highlighting both the potential and the challenges of employing such technology in architectural contexts to achieve architectural accuracy standards. In under seven hours, a trajectory over 17 km was documented, resulting in 101 scan pathways and over 30 billion data points. To attain the necessary architectural precision (1–5 cm), the MMS was integrated with static laser scans utilized as Ground Control Scans (GCSs), and data processing was performed using Heron Desktop, involving extensive parameter calibration and manual trajectory optimization to reduce SLAM-induced drift and misalignment. The study identifies significant issues such as the evaluation and mitigation of drift errors, as well as extensive data management, providing practical solutions and underscoring the essential role of human experience in the processing phase. Although wearable MMS demonstrates significant potential for swift, extensive architecture documenting, the necessity for hybrid methodologies and meticulous preparation is crucial to achieving the elevated accuracy requirements mandated in cultural heritage contexts.

## 1. Introduction

In recent years, the Mobile Mapping System (MMS) has been revolutionizing the surveying sector, allowing for faster and more comprehensive data collection compared to traditional methods. The continuous development of advanced sensors, artificial intelligence, and data fusion techniques (Nebiker et al., 2020) has made Mobile Mapping an increasingly widespread tool in the world of infrastructure, mining (Zlot et al., 2014), tunnelling (Sun et al., 2020; Fan et al., 2025), railway surveying (Kremer et al., 2012), and road and urban environment surveying (Arseni et al., 2024).
The development of smaller, lighter, and more affordable portable sensors is promoting the use of these systems even in different sectors that require more economical, versatile tools with greater accuracy and resolution, such as the documentation and preservation of architectural heritage. In particular, the use of wearable Mobile Mapping systems is gaining increasing popularity in architectural surveying thanks to their versatility and ease of use. These systems, mounted on backpacks, allow operators to dynamically acquire data even in complex environments with uneven terrain and the presence of stairs, such as historical buildings, caves, tunnels, or areas with limited access. The main advantages of using these systems are particularly access to confined spaces, greater agility compared to systems mounted on vehicles or trolleys because they allow data collection while walking, without the need for a bulky mobile platform. They allow for continuous and real-time data acquisition, significantly reducing survey time, and they are also very easy to use. The technology is increasingly user-friendly, making architectural surveys more accessible to a wide range of professionals.
However, many challenges remain to be addressed, especially related to the quality of the data, which is currently not suitable for detailed architectural surveys at large scales of representation typical of architectural surveys (from 1:20 to 1:100), the overall measurement accuracy affected by inherent deviations in the measurement systems are difficult to be avoided or corrected, and the management of a huge amount of acquired data, which requires advanced processing and storage techniques that are not always easy and economical.

### 1.1 State of art.

The state-of-the-art in mobile mapping, which is used to map and digitize complex indoor environments, demonstrates a substantial advancement in technology that is primarily focused on resolving issues like data fusion, trajectory drift, geometric accuracy, and managing the massive amount of data generated.
According to recent research, mobile systems have reached a certain level of maturity specially in the mining sectors and in urban environments. The ideal measurement accuracy in the mining area is usually between 5 and 10 cm. This is required to guarantee the safety of operations, exact computation of mined volumes, and correct structural monitoring. Wang et al. (2023) and Trybała et al. (2023) use low-cost mobile instrumentation to analyze relatively short and confined segments, ranging from 120m to 500m, with generally high accuracy, often below 5 cm. Chang et al. (2022), on the other hand, provide an important case study including multi-robot SLAM systems that cover pathways that range from 1.2 to 2.2 km apiece, for a total of up to 6 km. The study's overall accuracy in this instance falls between 0.65 and 1.01 meters, indicating a trade-off between the precision attained and the managed path's extent. Even in urban settings, portable mobile mapping systems (handheld or backpack) behave similarly to those used in the mining industry: they can achieve very high precision (<5 cm) over short distances (100–500 m), but on longer routes (>500 m), accuracy deteriorates and can reach sub-metric values (0.5–1 m) depending on the correction technologies used (loop closure, GCP, auxiliary GNSS) and environmental conditions. Marotta et al. (2022) demonstrate that overall accuracy might decrease to metric levels, ranging from 0.5 to 1.5 m using the old version of Gexcel Heron MS Twin color demonstrating how constraints are essential to improve the trajectory reconstruction and correct

the drift error on routes longer than one kilometer, confirming the pattern seen even in the mining setting.
In the indoor environment the situation is not so different as Salgues et al. (2020) and Tucci et al. (2018), demonstrate confirming similar accuracies on short segments, reporting local errors of less than 5 cm in building environments tests using SLAM systems over close routes of roughly 200–300 m.
They examined and evaluated the effectiveness of handheld and backpack tools, pointing out their local accuracy and density limitations when compared to traditional static systems. They highlighted the possibility of having geometric deformations and the challenge of maintaining constant accuracy along both indoor and outdoor or mixed paths particularly in environments that are particularly large and complex.
According to Campi et al. (2018), despite the growing interest in architectural applications, a certain reluctance still persists—mainly due to concerns about accuracy and the stringent standards required for the precise representation of architectural and historical heritage. The required general accuracy in the architectural field is normally less than 1-2 cm for 1:50 and less than 5 cm for 1:100 that are the classical architectonic representation scales, so much smaller than the environmental cases presented before. That means that in this field not only the general accuracy must be centimetric, but also local accuracy and the resolution of the data must make it possible to visualize and analyze details of the order of magnitude of a centimeter.
From the local resolution and point cloud quality the mobile mapping systems are rapidly increasing accuracy with the introduction of new sensors but remain obviously less accurate as static instruments as stated by Conti et al (2024) and Tucci et al (2028). Yiğit et al. (2023) put in relation the noise of the data with the speed of acquisition demonstrating that 3D point cloud data are particularly noisy in areas where walking speed is slower with consequent difficulties to recognize objects smaller than 3 cm. Moreover, as almost all the authors write on the topic (Keitaanniemi et al, 2023, Tucci at al. 2018) the output of slam processes is provided "as is" by the vendors. The post-processing software gives the user few or no options, and the output is essentially controlled by the system as a "black-box" so that the user cannot access intermediate steps or intervene, allowing them to make adjustments or fine-tune the output affecting de facto the possibility to use multiple acquisitions, extra data or redundant passages to improve the results.
Such more studies on the general accuracy in extensive architectural environments have been further extended to historical architectural contexts by Vassena (2022) and Perfetti et al. (2023) where they confirmed the need to heavily post-elaborate the data integrating the mobile sensors with static lidar scans. Ground Control Scans (GCS) and or GCP or to support the mobile acquisition with photogrammetric techniques. The employment of hybrid approaches—which combine data from mobile and static systems—is motivated by the requirement for high accuracy (sub-centimetric), typical of the architectural field.
For all these reasons the mobile mapping is still a relatively unexplored in the construction and Cultural Heritage (CH) field specially when the areas and very extensive although these devices would be ideal in terms of acquisition speed, agility, and ease of use.

## 2. The case of study

### 2.1 The aim

The case study presented here is the survey of the Doge's Palace in Venice. The survey was conducted to obtain a complete 3D overview of the complex to be able to make seismic assessments investigation. For reasons of time and the complexity and extent of the survey to be conducted in a short period, it was not possible to carry out a classic survey with static technology. Therefore, it was almost mandatory to use dynamic lidar survey technology that allowed for an extremely fast survey of spaces. The requested tolerances and resolutions were typical of a scale from 1:200 to 1:100 because only the main structural elements were interested from the investigation. The occasion therefore allowed us to push indoor mobile mapping technology to its limits and evaluate the methods of obtaining an architectural survey in this way.

### 2.2 The place

The Doge's Palace in Venice is a formidable edifice featuring expansive halls, ceremonial chambers, administrative offices, and confined spaces including concealed corridors, service sections, prisons, and attics. The pedestrian zone encompasses around 23,000 m², whereas the entire volume is roughly 150,000 m³.

Figure 1. A few photos from the survey with mobile mapping at the Doge's Palace and surrounding area.

## 3. Mobile mapping survey

### 3.1 Surveying instruments

All vertical parts, both external and internal, have been fully surveyed with the Backpack Gexcel HERON MS TWIN Color instrument. The instrument allows for an acquisition of 1,280,000 points per second with a local accuracy of 4mm. The instrument has a very wide range (Minimum laser range 0.05 m and Maximum laser range 300 m) which allows for acquisitions in both very confined environments and outdoors.

### 3.2 Challenges and on field solutions

The primary challenges encountered were diverse in nature. Initially, the complexity arose from the division of the building among multiple managing entities, necessitating meticulous planning concerning the opening of spaces, deactivation of alarms, and other accessibility-related factors. In this context, the utilization of mobile equipment demonstrated a significant advantage: the rapid acquisition facilitated operations within brief timeframes, thereby minimizing disruption to the regular use of the spaces. An additional challenge involved the requirement to conduct the majority of surveying operations during the evening and nighttime hours to circumvent the presence of numerous tourists, which would have rendered the work impractical during the day. This facilitated an acquisition devoid of human interference; however, it led to complications in color

rendering due to inadequate lighting conditions and the presence of disparate artificial lights along the route.
Notwithstanding these complexities, the primary objective – specifically the precise acquisition of geometries – has been completely realized. The survey project has been structured in such a way as to try to solve some others numerous more technical challenges:

- Overall size of the survey.
- Completeness and local and general accuracy of the work required
- Very large noble spaces and extremely narrow and complex spaces
- Very intricate and labyrinthic paths

The work was therefore set up by dividing the overall environment into areas and sub-areas that allowed for acquisitions of no longer than ten minutes. Despite the capability of the equipment to record significantly longer trajectories (theoretically some hours!!), the decision was made to segment the spaces into shorter trajectories. This approach facilitates the operator's meticulous monitoring of trajectory reconstruction during post-processing, thereby expediting the identification of potential issues that may compromise the trajectory, such as information loss from the IMU sensor, the occurrence of repetitive geometries that obstruct the SLAM process, or the presence of glass, mirrors, and other reflective surfaces that generate false planes and objects, further complicating the trajectory reconstruction process. From a perspective of elaboration, the establishment of smaller trajectories accelerates import-export operations, despite augmenting the volume of files to be managed in the subsequent processing phase.
The categorization into areas and sub-areas adhered to the natural configuration of the environments, structured into macro-areas according to the available openings, ownership of the spaces, and their dimensions. Smaller and adjacent environments were documented separately when access was not contextual or when entrances and exits posed substantial challenges, such as pronounced elevation changes, excessively narrow passages, or circumstances necessitating abrupt movements, such as sudden drops. During the acquisition process, we endeavored to prevent these abrupt movements, which are primary contributors to the degradation of the inertial sensor and can jeopardize the quality of the recorded trajectory, rendering it less comprehensive and fluid. To address these situations, targeted acquisitions were executed, modifying the instrument's configuration accordingly each time. The "backpack" mode, typically employed in outdoor settings or expansive areas, has been supplemented with “pole” configuration: in this instance, the scanning head is handheld and affixed to a pole, a notably efficient solution for confined spaces, low heights, or areas physically unreachable by the operator.
Following the recommendations of Vassena (2022) and Perfetti et al. (2023), a series of support surveys were conducted using a static laser scanner. These acquisitions pursued two main objectives. The first was to help achieve the desired overall accuracy, minimize the drifts by constraining the mobile mapping trajectories within a limited set of Ground Control Scans (GCSs), referenced to the established survey control network. The second objective was to validate the results, particularly in key areas of the building where geometric consistency was most critical. A total of 108 scans were acquired using the RTC360 laser scanner. These were strategically positioned at significant locations within the building to ensure efficient referencing to the topographic control network—measured with a Leica TS30 total station—and to optimize the spatial constraints applied to the mobile mapping trajectories. So, almost all the walks performed closed loops, passing in covered areas to static support scans or intersecting paths that pass through these GCSs.

A total of 17 km of walking path, considering the interiors, exteriors, and acquisition from the boat, yielded 101 scan trajectories in precisely 7 hours of SLAM survey.

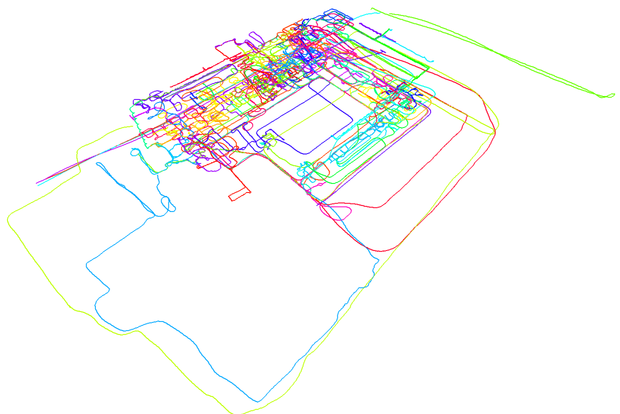

Figure 2. The 17 km of the 101 trajectories registered in the same reference system.

### 3.3 The data elaboration

The mobile mapping data was elaborated with Heron Desktop software. The uniqueness of the software lies in the ability to manage the entire process both automatically and manually: from the import of the trajectories to the generation of the point clouds, to the filtering and export of data. All phases can be executed step by step, with the possibility of modifying processing parameters according to specific needs. This approach represents one of the key elements that contributed to the success of the project.

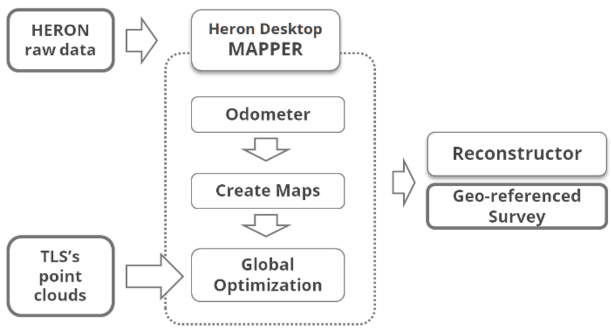


Figure 3. HERON data processing workflow schema for static scan reference.

Unlike static laser scanning, mobile acquisition does not allow for the definition of initial acquisition parameters. The operational modes remain constant, but the quality and characteristics of the detected data vary significantly depending on the path taken, the geometries encountered, and the materials present in the environment. For this reason, it is not possible to apply a completely automatic and uniform processing: it is necessary to adapt the parameters to the different acquisition conditions.
Precisely for this reason, as already mentioned, the survey was divided into as homogeneous areas as possible, separating those that are more complex or characterized by criticalities. This subdivision has made subsequent processing easier, allowing for greater automation in the trajectory reconstruction process, thanks to the use of more consistent parameters within each segment and along with the different steps of the mobile data processing workflow in Heron Desktop. Given the unique nature, dimensions, and specific characteristics of the different areas, each stage requires meticulous parameter fine-tuning. The

most critical parameters and their values, particularly those employed in challenging environments, are detailed below for each stage.

**3.3.1 Data Import.** The process, completely automatic, will import the panoramic videos (4K resolution: 3840 x 1920 pixels, 12 FPS), the point cloud data of two head, and the IMU data. All sensors mounted on the acquisition head are synchronized using a timestamp. A noise-masking filter has been applied to the LiDAR data to eliminate disturbances caused by the structural pillars supporting the camera and the oblique LiDAR sensor. The point cloud generated by a complete rotation of the laser sensors—referred to here as a *single-sweep scan*—is then rectified to correct the distortions introduced by the operator's movement during data collection.

**3.3.2 Odometer.** This process calculates the trajectory by registering the clouds between each other. The fine-tuning of odometry reconstruction parameters was crucial in order to mitigate drift, "hinge" and "treadmill" effects caused by challenging environments like narrow passages, corridors, and crowds. To tackle the challenges mainly posed by narrow or small environments, the main critical parameters to be modified (mainly following the experience!) are:

**Point Acquisition min and max Distance:** that are two parameters that fix the minimum and maximum distances of the points acquired by the scanner considered in the process. This helps to isolate points with the best range, to be used by the SLAM process. After several tests, the most effective setting proved to be a minimum distance of 1 meter and a maximum of 20 meters, for large environments.

**Odometry Map Resolution:** it is the resolution of the map, used as a temporary reference for odometry reconstruction. It was setup at 2 cm, using a significantly finer value compared to the default of 5 cm normally used in urban or environmental areas.

**Correspondences:** This parameter represents the number of correspondences that the SLAM algorithm seeks between the single-sweep cloud and the Local Map. In this case, its value was doubled relative to 20000 respect the standard setting to obtain a larger sample for a challenging alignment.

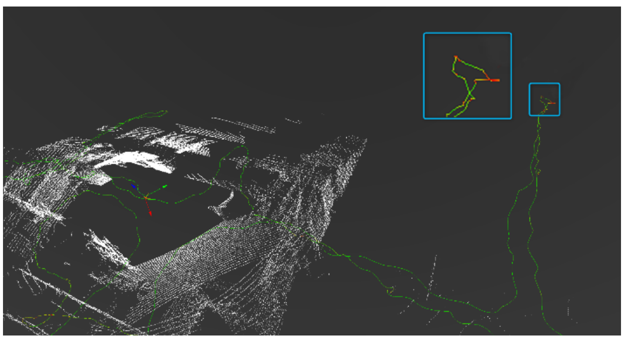

Figure 4. The reconstructed trajectory. The trajectory inside the box is color-coded by its Confidence. In Red the low confidence piece of trajectories normally due to fast rotation or change of heigh.

**3.3.3 Create Maps.** This process creates the "rigid local maps" to be used in the later Global Optimizations stage. These maps are accumulations of several single-sweep clouds that have been registered together in the SLAM process.

This intermediate phase is probably the key phase of the process because transforms the fluid sequence of trajectory frames into rigid local maps, forming a kind of "backbone" for the overall reconstruction. The goal, that is achieved in the next step, is to optimize the trajectory by performing cloud-to-cloud registration between the local maps themselves. This step is crucial to achieving the intended outcome because it ensures a cleaner point cloud by efficiently distributing errors along the trajectory and creating a final point cloud with no ghosting effects due to inaccurate alignment.

The process splits the initial created point cloud into 3D maps that are as the classical static scans 3D point clouds and that can be considered internally locally and globally correct in function of the geometry and the dimension of the place. For this reason, they can vary the sizes based on site characteristics. Finding the ideal balance between the number of maps to register together and the maps' dimensions (measured in lengths along the trajectory) is the most difficult task that must be evaluated case by case in function of the spaces dimension and object characteristics and, in the software, we use can be set a unique value for each trajectory.

There are three fundamental parameters that are crucial to adjust for optimization. In a similar way as in the previous odometry settings, it is necessary to define the **minimum and maximum point distances** from the centre of the scanner. This parameter defines the interesting region used for the future ICP optimization defining de facto the dimension of the maps and the dimension of the overlap region between the maps. The idea is to have more overlap as possible in order to connect more maps together but, in the same time, to eliminate too far regions of the maps, normally too sparse and with lower vertical accuracy, and the too close because under the 1,5m the point cloud coming from this type of sensors can be very noisy both situation could affect the result. In this case, 40 meters as maximum distance are normally needed to achieve greater overlapping regions and have more robust registration.

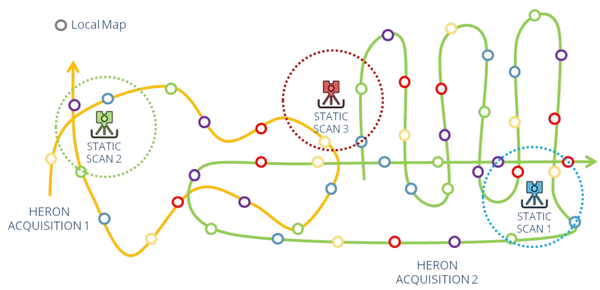


Figure 5. Schematic representation of the combined use of mobile and TLS maps. (Gexcel srl, 2024)

Another critical parameter is the **distance between the different maps**, which was adjusted based on the environment size: 5 meters for restricted spaces (like stairwells and very small rooms), 10 or 20 meters for conventional indoor areas, and 30 meters for outdoor environments. Finally, the **spatial resolution** of the map plays an equally important role and requires careful calibration. It determines the detail represented and thus the quality of the geometries on which the ICP can be anchored but also can increase enormously the elaboration time if too small.

**3.3.4 Global Optimization.** This goal of this step is to registers all the local maps in a unique graph-based optimization process. In this phase, the objective is to establish a complex network of connections to be solved and adjusted.

This is done in different steps: first creating links among the maps generated inside each individual trajectory, then connecting the maps of different communication or intersecting trajectories, and finally, connecting these maps with the static scans (GCSs), which are held fixed and used as immovable reference points. The process to link the maps can be completely automatic but must be carefully monitored and manually corrected to add and remove links that can create misalignments. Important here during the phase manually add links between maps of different trajectories not automatically added by the software and at the same time to remove links with no significant 3D overlaps to prevent an uncontrollable automatic process. The idea was to proceed in a way that made errors easy to identify and fix, keeping automated only the steps that wouldn't cause issues. In this case, the first step (linking the maps trajectory by trajectory) was done completely automatically. A small number of trajectories were then grouped automatically, with results monitored periodically. The full integration of all the maps was completed manually.

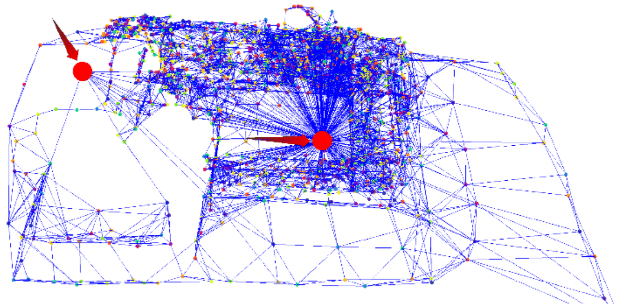

Figure 6. 1874 maps in graph connections and, at the top of them, the two "Super-References" GCS.

To prevent an excessive number of connections, the **maximum link distance** which refers to the distance between the centroids of the two maps, was lowered to 20 meters.

The static scans are introduced only at the end into the bundle adjustment process and manually connected to their overlapping local maps. To simplify the process and for pure visual clarity in the manual selection of the connecting maps al the static scans, registered together in external software and referenced in the same reference system were imported merged as single big clouds (here called "Super-Reference") decimated to 5 cm. Once all the links are established and optimized two by two, a general graph optimization algorithm is run to find the best alignment among the HERON's local maps to achieve the best possible alignment with the fixed static point clouds; thereby enhancing the absolute accuracy of the mobile model.

**3.3.5 Data Export**. This stage enables the export of the point cloud, with options to select the resolution (via the voxel size parameter) and apply filtering. The main goal of the filtering process is to reduce noise by removing spurious points—such as those generated near edges or resulting from excessive laser beam incidence angles. Average parameter values were chosen to maintain sufficient surface coverage while eliminating lower-quality points.

Interesting feature the possibility to avoid in the export the points corresponding to bad trajectory reconstruction, so points corresponding to the yellow and red sections of the trajectory, where the alignment was sub-optimal, using the **confidence parameter** (Figure 4). The software also permits a "**Clean Data**" filter, which removes moving objects, that was not utilized due to long processing times needed and because a subsequent manual editing for point removal (e.g., moving people, reflections) was planned post-export.

### 3.4 The results obtained from the different steps

Due to the huge amount of data, the "create map" process was run again after the optimization using 20-meter length map distance parameters to reduce the number of the maps to be registered with the static ones, otherwise, the total number of maps would have been too large to be handled by the workstation. For the trajectory captured by boat in the exteriors, a length of 30 meters was selected. So the final optimized dataset contains a combination of coexisting map lengths: 5, 20 and 30 meters. Totally 1874 maps were included in the single bundle adjustment with more than 6000 connections, approximately 400 were performed manually. The Root Mean Square Deviation of these connections' averages 1.35 cm

The software, during the Global Optimization phase, provides the Root Mean Square Deviation (RMSD) of the closest point distances but also gives detailed statistics about the errors of all maps-to-maps alignments. This value given in (m+rad) is useful for sorting matches based on their compatibility with the current state. Typically, a value of 0.05 is considered sufficient, but in this project—aiming for architectural-level accuracy—an average threshold of 0.01 was deemed acceptable. This, however, required additional effort to filter matches above this threshold and manually reprocess them. In some cases—such as external environments, like the trajectory along the canal—achieving such precision was not feasible, and a higher threshold of around 0.4 was considered acceptable.

| Phase | Parameter | Stairs | Indoor | Outdoor |
|---|---|---|---|---|
| Odometer | min/max distance [m] | 0.5<br>20 | 1.5<br>40 | 4.0<br>100 |
| | local map resolution [m] | 0.02 | 0.05 | 0.10 |
| | registration correspondences [#] | 20,000 | 10,000 | 10,000 |
| Map Creation | min/max distance [m] | 1.0<br>10.0 | 1.5<br>20.0 | 4.0<br>100.0 |
| | map length [m] | 5 | 20 | 30 |
| | map resolution [m] | 0.05 | 0.10 | 0.10 |
| Global Optimization | max distance for valid matches in batch selection [m] | 20 | 40 | 100 |
| Export | min/max distance [m] | 1.5<br>20 | 2.0<br>40 | 4.0<br>100 |
| | min collinearity angle [deg] | 10 | 10 | 10 |
| | max incidence angle [deg] | 88 | 88 | 88 |

Table 1. The key parameters and their values chosen in relation to the surveyed spaces.

The point clouds were exported at a spatial resolution of 1 point per cubic centimetre, striking a balance between keeping the dataset manageable in size and preserving enough detail for information extraction at a 1:100 representation scale. The final part of the elaboration was performed inside the software Reconstructor performing the final filtering, point cloud cleaning and data exchange.

After the final reduction at 1 cm resolution, the entire number of points, which was 30 billion, is now just 5 billion.

The general accuracy of the final cloud tested on the areas covered by static scans is from 2 cm to 5 cm, comparing the 2 different clouds in the software Reconstructor. Areas not encompassed by static scans cannot be examined in such detail. The quantitative analysis of optimization, the number of static scans, and the execution of highly constrained paths suggest that the scenario remains within the intended tolerances, even in uncontrollable areas. Following post-processing, certain vertical sections and plans of the point cloud were juxtaposed with pre-existing CAD drawings. In most instances, there was a global concordance among the various representations within acceptable limits, with a few discrepancies usually attributable to errors in the pre-existing historical representations.

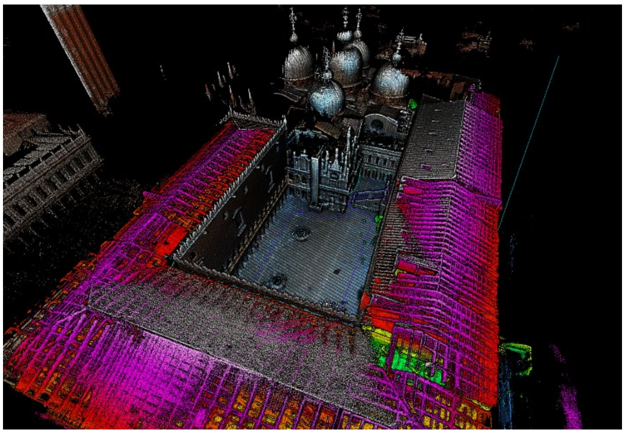

Figure 7. An overall point cloud of the Doge's Palace, with focus on the complex attic structures.

### 3.5 The 3D point cloud data final use

The final point cloud is now accessible for further structural work on the Flyvast platform, facilitating seamless online navigation and measurement of the extensive data set, along with options for total or partial data export for the end user. Concurrently, multiple architectural sections have been generated or revised. Several blueprints were also extracted from the point cloud. A blueprint is an orthographic projection of the point cloud onto a reference plane, automatically generated to produce a measurable 2D view of the 3D building. The extraction of the blueprints is a straightforward technique, requiring only the selection of the cutting plane, depth, view direction for data visualization, and the resolution in pixels per meter of the desired image. While the technique for floor plans is instantaneous, different cutting planes must be selected for vertical sections and views of both internal and external architectural facades, contingent upon the configuration of the Palace's internal rooms. By assembling the several retrieved photos, a coherent and legible final image is produced that precisely represents the intricate architecture of the Doge's Palace in Venice.
This process eliminates the need for manual drawing, streamlining documentation and analysis. The extracted blueprints were all at the 1:100 scale and were used also to help the verticalization of the architectonic plan and sections required by the projects.

## 4. Discussion issues, solutions, lesson learns

In addressing the challenges of 3D mobile scanning of complex architectural environment, as well as the subsequent data management, several key issues have been identified, together with the solutions implemented and potential directions for future development.
One significant problem encountered is working in confined small spaces during surveying. To mitigate this, the chosen system was designed and used configured in multiple ways, such as a backpack allowing fast and smoother acquisition in largest places or pole-mounted setup allowing narrow spaces investigations.
Making sure the entire region is covered during surveying is another important factor, which is now dependent on the operator's spatial mobility and memory of past paths. Paths that are linear are not a major issue, but in complex landscapes that are highly articulated, if not labyrinthine, there is a risk of forgetting sections or becoming overly redundant while spending too much time in the same location. In this project, the only solution to the issue was manual paper tracking. In the future the development of trajectory real time viewer and optimization algorithms that allow for more accurate acquisition planning will allow us to save time in the field and in the elaborations. (Al-Kamil et al, 2024)

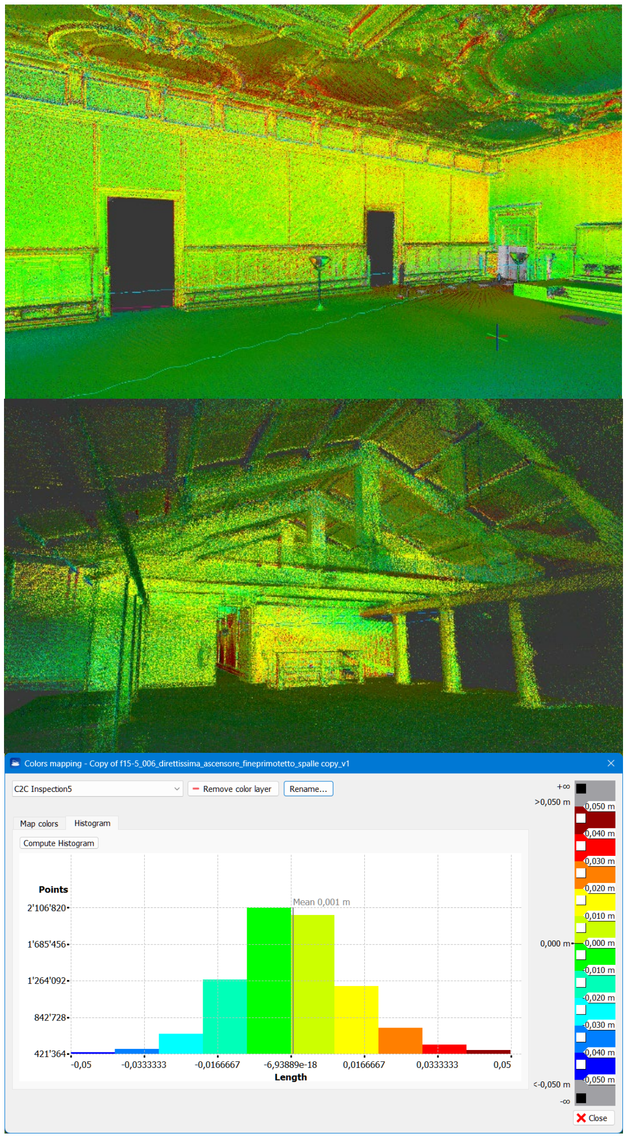


Figure 8. SLAM point cloud of the Grand Council Hall (on the top) and of a part of the attic (in the middle) colored by distance to the reference cloud. On the bottom the rainbow colour scale applied to the SLAM cloud, depicting its distance from the reference cloud. The inspection range was 5 cm.

Drift errors in SLAM are a persistent issue in three-dimensional reconstruction. Especially indoors, employing two sensors with an extensive field of view significantly reduces drift overall. Moreover, the accuracy was improved through the utilization of multi-trajectory intersections and static constraints. The program employs an algorithm that can "stiffen" the 3D wall by segmenting the point cloud into local maps, derived from the aggregation of multiple single-sweep laser scans. The process is predominantly automated; however, meticulous human intervention is necessary to comprehend the reasons behind certain connections exhibiting elevated alignment errors, to eliminate problematic connections, and to incorporate others that current automated systems cannot autonomously identify. The software typically identifies and associates trajectory segments with substantial 3D overlaps (Sánchez-Belenguer et al., 2020); however,

it often fails to adequately recognize common points across multiple trajectories with minimal 3D overlap, which is essential for their intersection and linkage and crucial for the accurate constraining process of the trajectory. The volume of maps and data to navigate do not help this task. The current solution involves manually memorizing key links and subsequently identifying them within the intricate 3D model. In the future, an automated method may be employed, maybe utilizing on field targets ad hoc positioned in strategic places and identifiable from camera images, or more effectively, from the laser sensor.
The data verification is another big challenge. A ground truth with static reference data to rigorously verify alignment is mandatory in the architectural field but it is not feasible to do too many static scans because mobile surveying would lose its main characteristics of immediacy and flexibility. The solution to this problem lies in the mode of acquisition, the observance of closed loops as per literature or always having one or more intersections with other mobile trajectories, maybe passing through the GCS. If this constraint is absent, it's not possible to make definitive statements regarding accuracy, only visual inspection of the cloud can report some alignment problems as shown in Figure 11 problems sometimes only solved repaying again the acquisition to join it better with more constrained geometries or with nearby GCS. The issue of data validation is still the main open issue in mobile mapping specially when with mobile mapping high accuracy is required.

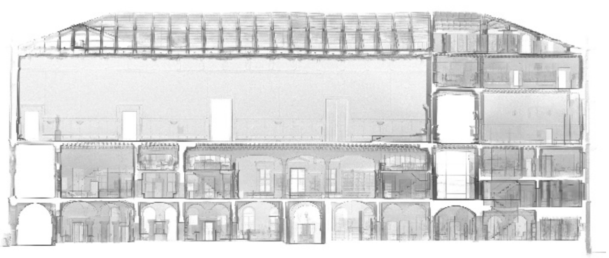

Figure 9. "X-Ray" orthophoto extracted from a vertical section plane and generated by the union of 3 images with different depths of view.

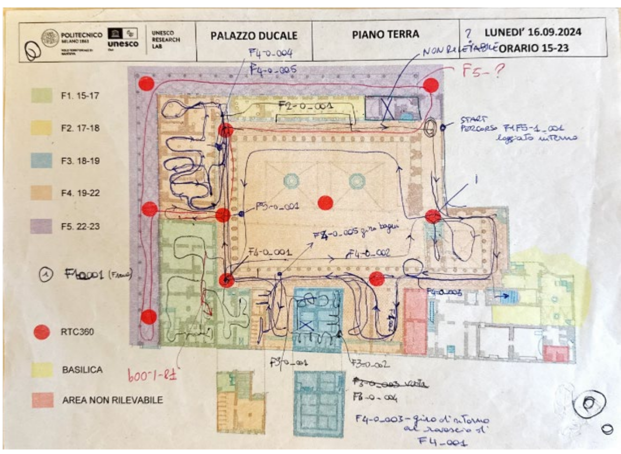


Figure 10. A paper map illustrating the detection trajectories.

The sheer volume of data generated presented a substantial management challenge especially during elaborations. This subject lacks definitive solutions: however, it is crucial to recognize that mobile mapping entails extensive data collection, necessitating substantial storage capacity and considerable computational power for both data processing and end-user utilization of the generated data. The complete project reached here 3 TB starting from the initial 200 giga of the raw files. To tackle this, we relied on a fast and high-capacity internal processing hard drive, specifically a 4 TB M.2 PCIe NVMe MP400 SSD, with sequential read speeds up to 3,400 MB/s and sequential write speeds up to 3,000 MB/s. This setup was complemented by an 8 TB mechanical external hard drive, providing substantial capacity for storage backup. Other main characteristics of the used workstation used include AMD Ryzen 9 5950X 16-Core Processor at 3.40 GHz, 128 GB of installed RAM (mandatory to manage all trajectories in a single global optimization), NVIDIA RTX A4000 graphics card.

## 5. Conclusion

This study at the end has shown how portable mobile mapping technologies are rapidly allowing to achieve results comparable to static approaches, particularly in architecture, where local accuracy often demands less than 1 cm and global accuracy is approximately a few centimetres.
The acquisition was quick; however, contrary to common belief about these technologies, it is not true that they do not require specialized skills from the operator or that the acquisition can be completely automatize. The precise planning of trajectory intersections, the strategic placement of an appropriate number of Ground Control Stations (GCSs), and the tailored division into areas and sub-areas were critical factors for the project's success. This experience clearly illustrates that potential SLAM errors are greatly affected by the geometry of the surveyed object, and that planning the appropriate path and trajectory, along with correct subdivision, are essential initial steps to address issues that cannot be resolved at the elaboration level.

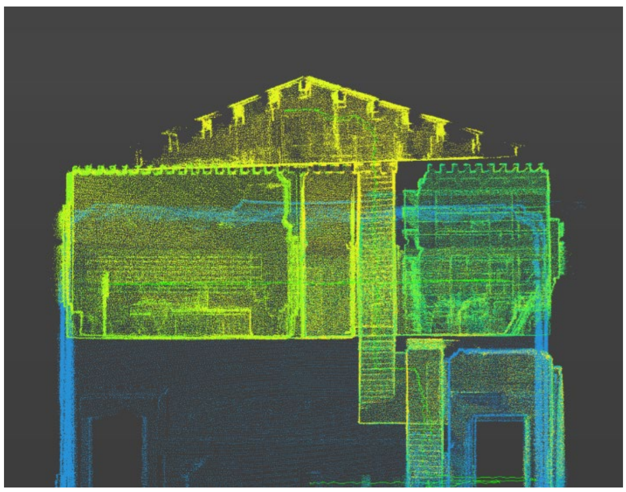

Figure 11. Cross-section view where is evident a big misalignment of the upper part. Solved repeating the acquisition.

The processing phase was protracted and frequently necessitated manual intervention by the operator. This was essential to attain the desired outcomes, which cannot yet be entirely automated using a mobile survey. The processing phase is the crucial process, surpassing the instrument itself, that facilitates more precise findings. The potential to decompose the cloud into sub-maps and execute optimization on the 3D surfaces was the crucial stage in the procedure (Fassi et al, 2019).
Additionally, it is necessary to point out that correlating the data with static scans and a topographic support network is an essential and indispensable step when addressing complicated and extended situations.
Numerous future projects exist, some pertain to the use of the final point cloud, while others focus on the advancement of data processing software. The major purpose, in this instance, is to categorize and organize the point cloud to provide enhanced

navigation and querying, equivalent to the treatment of a genuine 3D model, hence increasing its usability for the operators who will use it shortly. The second purpose is to provide tools or algorithms that facilitate more automated and assisted processing and validation of the data while managing an exceptionally huge volume of trajectories and sub-maps.

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