ACCURATE 3D MODEL OF VENICE: PRESERVING HISTORICAL DATA AND INTRODUCING SLAM IMMS FOR CHANGE DETECTION AND UPDATING PROCEDURES

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Abstract

The Municipality of Venice, through Insula srl (Insula, 2024), started the RAMSES (Rilievo Altimetrico, Modellazione Spaziale E Scansione 3D) project in 2005 with the unprecedented intention of conducting a static laser scanner survey of an entire city. The authors of this paper, who have been involved in the project on behalf of the client, including drafting general contract technical specifications, wished to revisit the survey’s findings nearly two decades later. This contribution illustrates the procedures implemented to guarantee the future accessibility of the surveyed data. It is interesting to highlight how the detailed technical specifications outlined in the general technical contract section have facilitated the retrieval of the historical three-dimensional laser scanner measurements archive. Tests have been conducted to determine how the existing mobile mapping technologies may be utilised to update the three-dimensional historical data obtained in the Ramses project efficiently. Furthermore, the paper describes the surveying approach that has never been adequately described in the literature. The surveying and geo-referencing methodologies continue to have several interesting and relevant aspects, especially regarding how the topographic network has been implemented. The Ramses three-dimensional model represents an extraordinary, valuable digital archive containing portraits of the city’s conditions at the time of the mapping. Ramses 3D model, when enriched with field activities conducted using more updated technologies, can provide interesting and unique evaluations of the evolution of Venice’s landscape.

1. INTRODUCTION – THE RAMSES PROJECT

The problem of “high water level” (“Acqua alta” in Italian) directly affects the liveability of the city of Venice, and several solutions have been sought over time to minimise the impact of high tides on the accessibility of Venice, both by inhabitants and tourists. Depending on the height reached by the water, to make the city walkable, it is necessary to place walkways that allow the population to move around even in high water conditions. Historically, the elevation of the city of Venice was periodically measured with accuracies of the order of 10 cm, referenced with respect to the tidal zero of “Punta della Salute” (ZMPS) (Todaro, 2011), with a sparse point density, i.e. on the order of one point every 8 meters.

The RAMSES project aimed to conduct a laser scanning survey of the complete historic centre of Venice (Todaro, 2011) (Vassena, 2012), ensuring a planimetric accuracy of 2 cm and an altimetric accuracy of 1 cm. Additionally, the density of the city pavement needed to reach a minimum value of 25 points per square meter. The project started in 2005 and possessed great originality and innovation characteristics. Although the survey’s primary objective was to examine the city’s pavement, the general tender specifications also stated that the acquired three-dimensional point cloud and colour information captured by the sensor via a mounted camera must be provided. The colour information was also crucial for the recognition of several items present on the city pavement. The three-dimensional model of the pavement includes accurate contour lines and a topographic survey with standardised accuracy, simple to use, and a denser mesh. The accurate 3D model significantly lowered the possibility of assessment errors related to water level, transitability of the pavements, estimated walkway routes, and overflow limit elevation. The accuracy of the city’s digital model is important in this regard. In the case of a city DTM with a 10 cm accuracy or 2 cm, the estimation of extension of the flooded area changes significantly (see Figure 1).

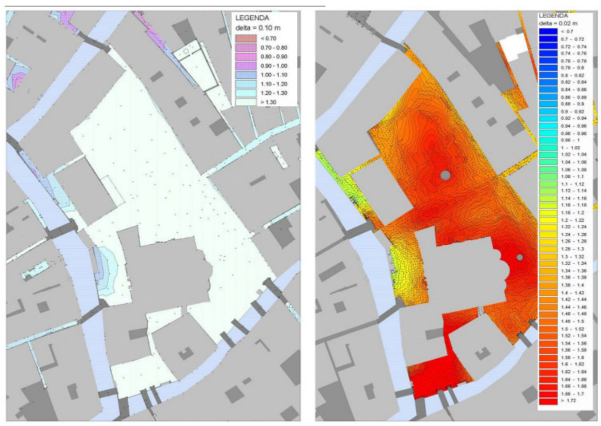

Figure 1: The estimated flooded area changes significantly if the resolution of the 3D pavement model has a 10 cm (left image) or 2 cm accuracy (right image). (Todaro, 2011)

This can cause great inconvenience to the population, particularly regarding estimating which routes are passable to avoid flooded areas if possible. In addition, such computation allows the municipality to correctly calculate the areas where to place the walkways that allow the passage of users in the flooded areas, with significant cost savings and great efficiency of the walkway placement operations.

2. RAMSES TECHNICAL DETAILS

2.1 Terrestrial laser scanner survey

Insula (Insula, 2024) estimated that the only technology available at the time that could enable an elevation 3D model of the city of Venice, with altimetric accuracy of 1 cm and a point density on the order of about 25 points per square meter, was the laser scanner one. In 2005, registering and geo-referencing point clouds acquired with static scanners necessitated the use of targets. It has been determined that to produce a 1 cm DTM of Venice, an altimetrically accurate network with an accuracy of less than 1 cm is insufficient; for geo-referencing of scans, at least 2 cm planimetrically known targets are also required. The laser scanner survey was conducted using a Riegl LMS-Z420i (Riegl website, 2024) laser scanner in conjunction with a Nikon Reflex camera. The picture acquisition enabled the capture of a practical, although of standard quality, RGB digital archive of the town, including both the pavement and the facades of the buildings. The camera focal length did not permit the full colorisation of the point cloud, having a different field of view (FOV). A part of the point cloud could not be colourised in several geometrical configurations, namely when the scanned surfaces were too close to the laser scanner. The Riegl device was chosen by the Innova company, which won the tender, for safety reasons. It was the only Class 1 TLS available in the market between 2005 and 2009, and for this reason, it was usable in a town always crowded with inhabitants and tourists.

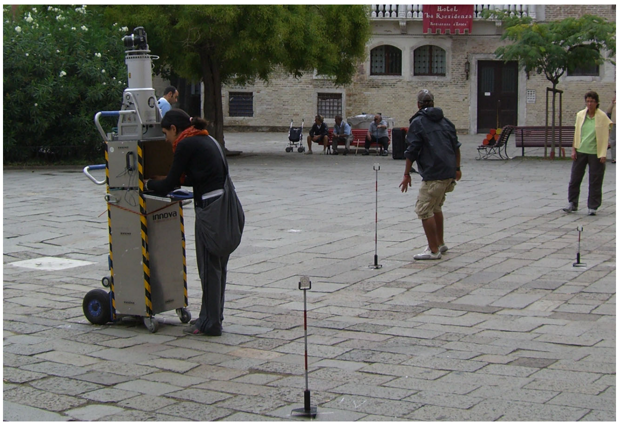

Figure 2: The picture shows the Riegl laser scanner mounted on a trolley to speed up the mapping activities.

In order to guarantee precise measurements of the urban flooring, the inclination between the TLS measuring laser radius and the floor needed not to fall below an approximate minimum of 30°. This constraint ensures that the spot of the measuring laser has contained dimensions and that it does not become too rough on the floor. Obviously, this restriction has dramatically affected the number of scanning points, as the height from the ground of the laser scanner sensor. By enforcing the 30° restriction, it was not possible to measure the flooring from greater than a few tens of meters away; thus, the instrument's measurement range of one thousand meters was significantly reduced.

2.2 Scans georeferencing

Insula and the team of technical consultants defined that it was mandatory that for each scan, at least 6 targets must be scanned, of which at least three in common with the previous scan and at least three with the following scan, namely the 2 nearest ones. To verify that each scan does not have geometric deviations from the 2 scans mentioned before, the creation of a single point cloud file (in ASCII format, x, y, z, reflectance, - R,G,B if available-) comprising the three geo-referenced scans (containing all the points acquired in the individual scans) had to be provided. So, each "triplet" was geo-referenced independently of the other triplets. The data alignment was managed using RiscanPro (Riegl, 2024b). The data testing was done using the software JRC 3D Reconstructor (Gexcel, 2024a).

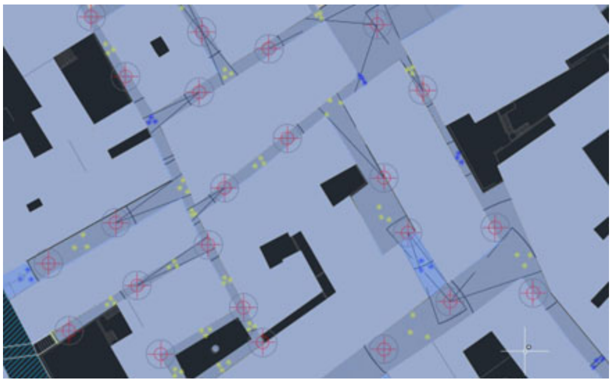

Figure 3: Example of the scanning structure: In red are the scanning positions, and in Yellow, the target positions.

The targets were made with a small panel of retro-reflective material, with a marked center measurable with the total station, installed on a moving pole to be easily measured and moved after the mapping procedure. Every target was positioned at a different height from the ground (figure 4) to strengthen the alignment process.

Figure 4: A scanning phase with reflecting targets

2.3 Topographic network

In order to compute the coordinates of the targets, Insula realised a topographic network that could ensure the mentioned level of accuracy (Tecap Studio srl carried on fieldwork). A global GPS network was established in Venice, composed by 65 vertexes interconnected with 190 baselines. The measurements were conducted in static mode, and two temporary GPS stations were erected on two IGM95 points (figure 5) to serve as always active reference points during the acquisition phases. The GPS network has been adjusted with The least squares adjustment of the GPS network have used as constrains all the IGM95 (Surace, 1997) and GPS2000 vertices, of known coordinates available in Venice. The network structure was organised into 4 rings with a closed traverse-like geometry. Each GPS vertex of such a closed traverse structure was connected to the previous and next vertices and the two fixed stations. In this way, each vertex was connected to the network with at least four baselines (figure 6).

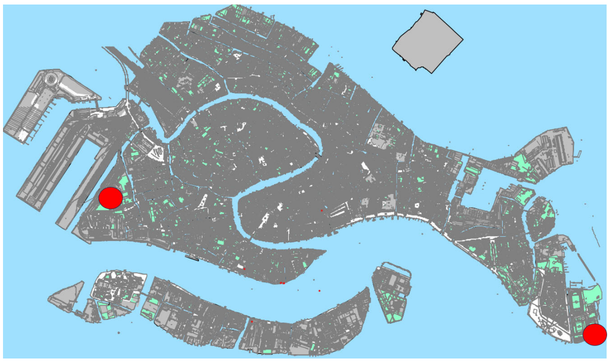

Figure 5: During the acquisition phases, two points always remained on and were used as master stations.

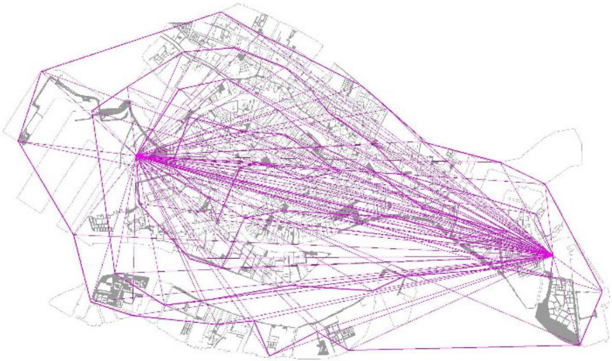

Figure 6: The GPS network efficient structure.

Figure 7: The first-order topographic network

This structure was rigid, and the movements of the surveyors on the field were quite efficient. Selecting the appropriate site for placing the vertices was a highly intricate task due to the layout of the streets of Venice, which limits the visibility of the sky and creates the well-documented Urban Canyon conditions. The network provided the vertexes coordinates both on the WGS84-ETRF89 frame and Gauss Boaga, the historical Italian Cartographic reference systems.

A modified cartographic projection was used to reduce the distortions in the map. An ad hoc Gauss projection with a central meridian that is not contracted was created. The central meridian was chosen to pass through the centre of an IGM95 vertex located at the longitude of 12°.20' 16,2263" in San Marco Square.

Figure 8: The complex network realised in Venice. In blue, the GPS vertexes. In red and green, the vertexes of the first and second-order networks are measured by total station.

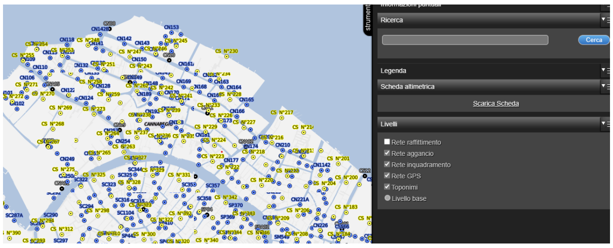

Figure 9: The topographic coordinates web GIS (http://maps.Ramses.it/Ramses/ - RAMSES, 2024)

This point is almost at the centre of Venice. A False East of 15,000 m and a False North of 5,008,169.250 m have been applied to make the local coordinates easily recognisable. Due to the minor deviation of Venice's elevation from the mean sea level, no adjustments have been made to the size of the projection ellipsoid, as used when this kind of solution is applied to reduce the projection deformation.

Thus, to measure the targets' coordinates, a traditional topographic network was established throughout the city and measured using a total station.

A first-order topographic network of 757 points was built using GPS vertices as constraints (Figure 7).

Therefore, a second dense network was realized, consisting of 4,015 points connected by closed traverse structures (green vertices in Figure 8). Finally, a highly accurate topographic levelling network was established to determine the elevations of

the points of both the first and second-order networks. 1183 new only-altimetric reference points have been created.
A web GIS was developed, where all the topographic points of the network are visible (Figure 9).

2.4 The scanning measurements

The laser scanner acquisitions were performed using maximum instrument FOV and photographic acquisition. All targets were measured from the points of the network of the first and second order. The survey was to be carried out to ensure the positioning of the artificial targets with a relative planimetric and altimetric accuracy, with respect to the station point, better respectively than ± 5 mm and ± 2.5 mm. Globally, 22.000 scans have been acquired.

2.5 Results and deliverables of the survey

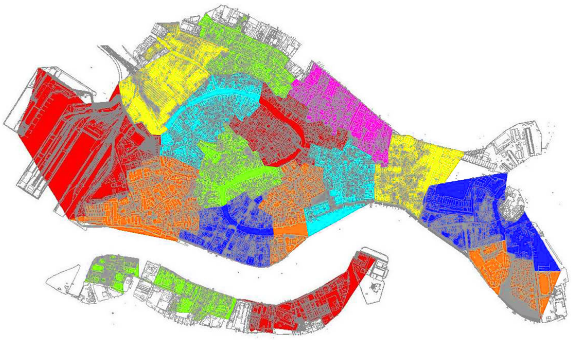

Figure 10: Venice has been divided into 16 sectors.

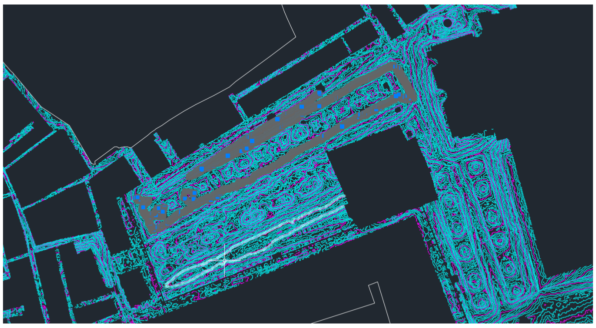

Figure 11: San Marco square described with 1 cm spaced contour lines

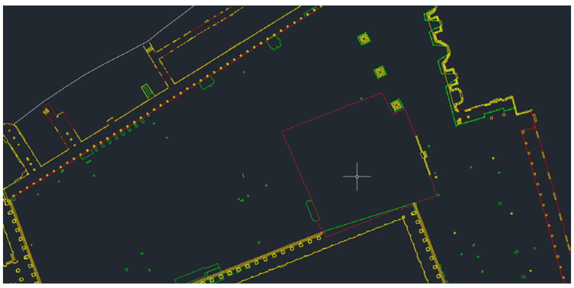

Figure 12: A CAD representation was extracted using the point cloud model and images. Images have helped recognize the items to be represented.

The point cloud model of Venice enabled an accurate reconstruction of the planimetric structure of the historical centre's pavement, represented by contour lines that are uniformly one centimetre spaced (figure 11). During the post-processing phase, the doorsteps of all the buildings were reconstructed, and the detection of all drillings in the walls of the building's façade to a height of 120 cm from the ground was reported and mapped in a CAD drawing. To better organise the entire job, Venice has been divided into 16 sectors (Figure 10).
The discontinuities in the flooring, such as ramps, stairs, access points to bridges, and various urban elements across the city, have been accurately documented (Figure 12). The actual locations of all the road manholes on the city pavement have been accurately detected from the point cloud model and images. After being catalogued, the individual items have been connected to a database that provides detailed descriptions of their attributes and key information. Approximately 80,000 items have been recorded, including manholes, sewer grates, gutters and sluice gates within Venice. The precise knowledge of the elevations of the pavement made it possible to predict the extent of the area subject to flooding and all doorstep elevations and to optimise the arrangement of footbridges to ensure the safe passing of men and goods. Using this information, every Venetian could know the elevation of his home doorstep so he could take precautions when high tides are expected. By connecting via the internet, citizens and tourists can know in advance the dry or usable walking routes inside the town. Furthermore, using a 360-degree FOV acquisition with colour permitted the mapping of the city's façades, generating an essential digital repository of Venice's condition at the mapping date.

2.6 Preservation of 3D data - Data repository

The scans were captured in RIEGL's proprietary format and a structured ASCII format, while they were not still in an open format like E57. It was done to guarantee future accessibility of the images without depending on proprietary applications. The format specifications are detailed in Table 1, which describes the text format used for saving scans.

Number of rows	500								
Number of columns	500						If available color data		
	Rows	Columns	X	Y	Z	Reflectance	Red	Green	Blu
ASCII Data structure	1	1	1.500	2.100	1.500	16	1	5	7
	1	2	3.100	1.300	3.45	200	20	255	2

Table 1: The scan data format for the ASCII files

In addition, each scan was accompanied by its roto-translation matrix, which could be roto-translated in the local reference frame of the RAMSES project.

3. IMMS-BASED POINT CLOUD MODEL UPDATE

Once the surveying and data return operations were completed, the not-easily-solved problem of how to keep the three-dimensional model up-to-date immediately arose. Venice is a lived-in city; therefore, continuous work and daily life can cause geometric changes in the elevations of the city pavement. Unfortunately, the only solution to keep the three-dimensional model up-to-date should have been performing static laser scanner scans to update the point cloud after the work. This solution immediately turned out to be impractical due to the cost and organizational complexity of such an operation. It is for this reason that more than 10 years after the conclusion of the project, the authors wish to test if a current technology, such as IMMS SLAM, could be used to carry out, with sustainable costs and timing and with the accuracies achieved by the Ramses project, such updating activity. Experiences have already been carried out in Venice, testing MMS technology for city mapping and moving along the water canals or the town, but not using the Ramses data set as a reference. (Guerra et al., 2011), (Martino et al., 2023), (Studnicka et al., 2011a), (Studnicka et al., 2011b), (Tanduo et al., 2022).

3.1 The Indoor Mobile Mapping Technology

The implementation of LiDAR devices capable of surveying both indoor and outdoor areas (Ceriani et al., 2015) (Comai et al., 2020) (Durrant-Whyte et al., 2006) (Otero, 2020) while in motion, rather than remaining stationary during the data collection process as the tripod based laser scanners require, is being highly significant in the surveying community. This technique enables the surveyor to perform 3D mapping procedures using a portable device carried by hand or put on a backpack. The surveyor only needs to go around the location that needs to be surveyed. IMMS seems to be the most advantageous technology for ground-based 3D mapping due to its ability to simplify field survey operations and significantly improve productivity while providing a comprehensive 3D point cloud model. The productivity improvement maintaining the same accuracy reached of the Ramses seems to fit the update needs of the Venice 3D model. IMMS devices utilise the SLAM algorithm, which stands for "Simultaneous Localisation and Mapping", initially implemented in computer vision, enabling an instrument to detect its position and simultaneously create a map of the area around it. This is especially advantageous in scenarios where the mobile device navigates through unfamiliar or uncharted surroundings, lacking the assistance of any positional sensor such as GNSS, as it occurs in the Urban Canyons of Venice. The particular configuration of the city, with its routes characterised by very narrow streets, requires the use of mobile mapping instrumentation based on the SLAM algorithm, where the trajectory estimation does not require the use of GNSS. Lidar-based SLAM systems have consistently shown some limitations in measurement accuracy, but in city mapping applications, such as the one we are facing in the Venice project, it seems the SLAM device has very close to or equal to the required accuracies. The aim is to compare and verify the possibility of using a recent mobile mapping survey instrument to carry out a survey that would be similar in accuracy to the one carried out with laser scanner instrumentation by the Municipality of Venice. The accuracy of using an IMMS device depends on numerous factors, such as the lack of GNSS positioning data, the design of the survey trajectory, the 3D geometrical characteristics of the mapped environment, and how the surveyor moved during the mapping moments. If the post-processing software allows, it's also essential to choose the proper SLAM algorithm parameters during the post-processing procedure. These factors can change how accurate and repeatable the method is. Adding the measurement of the right amount of Ground Control Points (GCPs) and/or Ground Control Scans (GCSs) to the SLAM post-processing process is an effective way to deal with this problem.

3.2 Use of GCPs with Mobile Mapping Systems

Several investigations have been carried out for the analysis of the measurement accuracies of SLAM systems (Maset, 2021) (Maset, 2022), and it is well established that to maintain centimeter accuracies for routes in the outdoors and particularly in the urban environment (Marotta et al., 2022a) it is necessary to use an adequate number of GCPs.

On the other hand, it is evident that if one wishes to update portions of an urban area regularly, it is not possible to think that IMMS surveying activities of dense portions of urban territory rely on the presence of a dense and affordable network of vertices of known coordinates on the ground. It is, therefore, necessary to verify, in a particular environment such as the city of Venice, where GNSS positioning is frequently problematic, whether there is an alternative way for accurate geo-referencing of IMMS deliverables and reducing the drift. In this direction, a technology has recently been introduced which makes it possible to employ the point cloud generation process with the SLAM algorithm by using point clouds or portions of point clouds geo-referenced as constraints (Marotta et al., 2022b).

3.3 Heron IMMS: geo-referencing methods and control scans

The test was conducted using the Heron MS Twin Color mobile mapping system (Gexcel, 2024a) developed by the Italian Company Gexcel in collaboration with researchers from the Joint Research Centre of the European Commission at Ispra (Italy). It has two Hesai XT32 (32 lines multibeam LiDAR sensors) and an 8K MG1 resolution RGB camera in the capture head. The process for getting colour is achieved through a pair of approaches: the operator must decide whether to configure the system in video mode (streaming mode) or single shot mode, where the surveyor acquires high-resolution images on demand. The video mode is employed to acquire 5K-resolution 360° spherical images, which enrich the point cloud model with colour. The operator exercises complete control over the system via a PAD device, and the mapping procedure is carried out at an average walking speed while traversing the survey area. The procedure to connect the trajectory of the instrument to the control points can be executed by placing the capture head on an extensible pole. The distinctive feature of the device is that it can put constraints into the SLAM algorithm using three distinct methods.

a) The first involves finding targets in the cloud generated inside the SLAM post-processing software Heron Desktop (Gexcel, 2024c). If the coordinates of such targets are known, the point can be used as a constraint. This operation is, therefore, performed in post-processing, and it is only possible if the target or known coordinate is clearly visible in the point cloud.

b) The second option involves the measurement of known coordinate points present at the measurement site by placing the capture head support pole directly on the point during measurement operations.

c) The third is the one that has attracted our most significant interest and whose performance we intend to test against procedures (a) and (b). It consists on using the point clouds of some georeferenced TLS scans as constrains inside the SLAM post processing procedure (Vassena, 2022). This is possible because it is available the point cloud model of the entire historic center of Venice, and all geo-referenced TLS scans acquired in the Ramses project are available. Therefore, if geo-referencing approach (b) would bring similar results to procedures (a) and (b), this would mean that it is possible to update portions of the 3D model of the city of Venice without having the use of control points but simply by extracting some historical static scans from the archives.

3.4 La location del test site at the Salute Basilica in Dorsoduro

A portion of the city of Venice close to the Basilica della Salute in the Dorsoduro "Sestriere", which has already been used as a place to test new technologies, was chosen to run the present and future tests. For the current test, path number 4 has been chosen (figure 13).

3.5 Retrieval of TLS data from the RAMSES project.

To access the raw scans from the Ramses project, the research team lacked current software licenses for the RIEGL manufacturer’s RiscanPro® software. As a result, they developed a basic software program that could read the TXT files of the TLS scans and the TXT files of the roto translation POS matrices. They then imported this data into the Reconstructor® (Gexcel, 2024d) point cloud post-processing software to run the analysis. Therefore, getting the three-dimensional point clouds of the initial geo-referenced scans was feasible inside an up-to-date software platform.
This is an a-posteriori example of how open formats ensure future compatibility and ease of access.

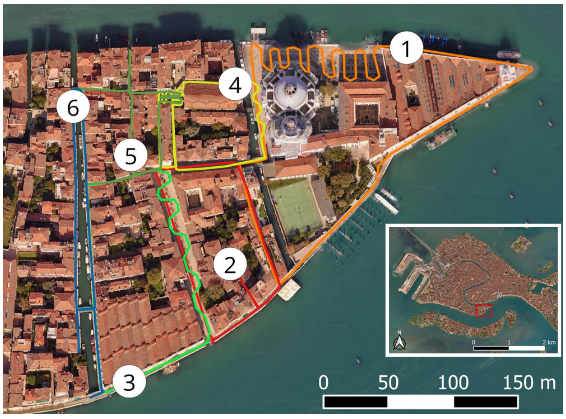

Figure 13: Location of the test site (Image from GoogleMaps®)

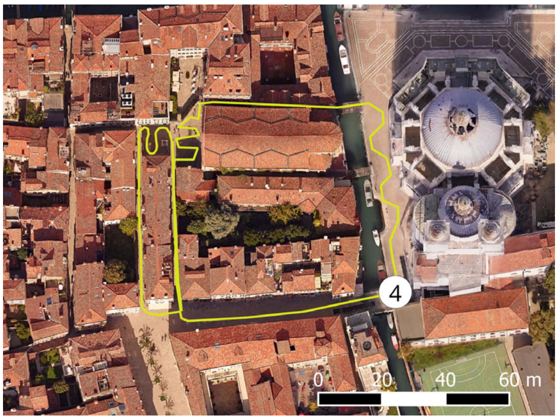

Figure 14: Path #4 is where field tests were conducted. (Image from GoogleMaps®)

3.6 Data acquisition on the field with the IMMS device.

Measurements were acquired at the beginning of January 2024 along path #4. Seven vertices along the path were still present on the town's pavement.The survey was performed twice in two different modalities. Firstly, the images were taken in the “single shot mode”, standing for some seconds and shooting the high-resolution panorama. During the second acquisition, the camera was set in video mode, i.e., streaming mode. The detection was performed once at the 7 vertices of known coordinates along the path by positioning the capture head support pole on the known coordinate point (Figures 16). When set in streaming mode, the operator moved along path #4, without stopping, and trying to ensure that the point cloud capture near the GCPs was captured at the highest density. By thoroughly calibrating the 3D point cloud model with the spherical image, it is possible to map high-resolution images onto the 3D model.
Single-shot acquisition with ground point measurement (pole tags) took 17 minutes, while the acquisition in streaming mode required 8 minutes, with a survey trajectory length of 599 meters and 543 meters, respectively.


Figure 15: Mobile mapping inside an Urban Canyon in Venice


Figure 16: Points measurement by using the capture head of the IMMS installed on a pole (left image) and streaming mode (right image)

3.7 Data elaboration.

The data processing was performed on the Heron Desktop platform.
a) First, a data elaboration using 7 points of known coordinates present along the #4 route and directly measured on the field with the “pole tag” approach has been used as constraints. One control point was discharged due to a more than 20 cm positioning error. b) A second data processing was performed, picking the 6 control points directly from the point cloud. c) The last data elaboration was processed using the Heron Desktop software, using 4 geo-referenced scans as constraints (Figure 18). Figure 19 shows the altimetric differences of the city

pavement between elaborations a), b), and c) compared with the results obtained in 2009 by the Ramses project.

Figure 17: GCPs position. The red one is the GCP excluded. The two IMMS mapping trajectories are also visible.

3.8 Results and model comparison

The first step in processing the measurements was to extract the TLS images and then apply the relevant roto translation matrix. Four scans have been used as constraints in type (c) processing. At this stage, it became feasible to compare the three-dimensional point cloud model obtained in the Ramses project with the point cloud model obtained by mobile mapping and processed using the different constraint approaches (a), (b), and (c).

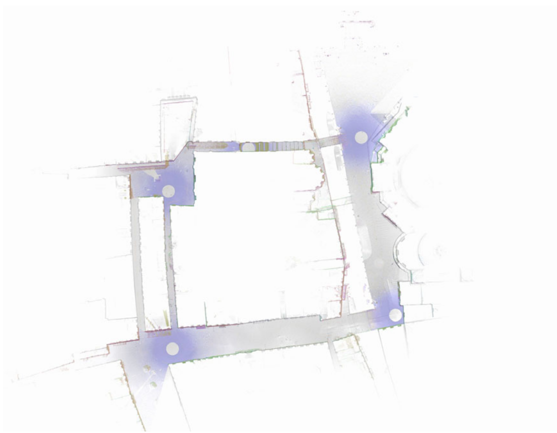

Figure 18: Four scans from the original Ramses project have been chosen to become constraints Scans (Control Scans) in the SLAM elaboration.

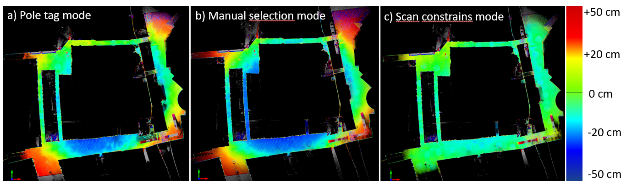

Figure 19: Point cloud models comparison

The analysis of the results indicates no significant differences between the strategy of directly measuring control points in the field (Pole tags) and picking them from the pointcloud. Using Control Scans reveals a remarkable correspondence between the Ramses model and SLAM detection.

CONCLUSIONS

The 3D model Insula created provides unique documentation and a historical repository of the city of Venice.
This paper first aimed to elucidate the survey procedures, which remain pertinent in numerous aspects to this day. The results of this first test show the efficiency of using geo-referenced (control scans) scans to constrain the SLAM algorithm. This technique proves to be highly effective for minimizing the drift errors often observed in IMMS systems. Figure 20 shows that the differences are on the order of 2-3 cm. If well-coordinated, the proposed method could enable an affordable updating of the city's three-dimensional model acquired in the Ramses project, even if not with the 1 cm accuracy reached by the Ramses project.

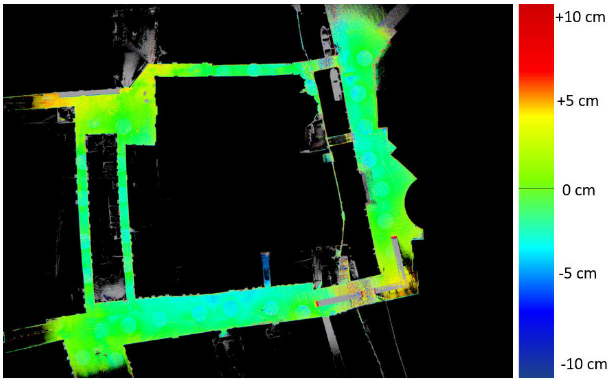

Figure 20: Comparison between the model acquired with Heron (using control scans) and the Ramses point cloud model.

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