Applied Geomatics (2024) 16:293–312
https://doi.org/10.1007/s12518-024-00555-w

ORIGINAL PAPER

Mobile mapping system for historic built heritage and GIS integration: a challenging case study

Daniele Treccani[1] · **Andrea Adami**[1] · **Valerio Brunelli**[2] · **Luigi Fregonese**[1]

Received: 28 September 2023 / Accepted: 6 February 2024 / Published online: 15 February 2024

Abstract

To manage the historic built heritage, it is of fundamental importance to fully understand the urban area under study, so that all its characteristics and critical issues related to historical conformation, stratification, and transformations can be better understood and described. Geometric surveying allows a deeper investigation of these characteristics through analytical investigation in support of urban planning theories as well. To date, geomatics provides various tools and techniques to meet the above-mentioned needs, and mobile mapping system (MMS) is a technology that can survey large areas in a short time, with good results in terms of density, accuracy, and coverage of the data. In this context, the article aims to verify whether this approach can also be useful in the complex and stratified reality of the historic urban context. The case analyzed—the historical center of Sabbioneta—presents some criticalities found in many urban centers of historical layout. Examples are narrow streets inserted in an urban context with multi-story buildings and consequent difficulty in receiving the GNSS signal and difficulty in following general MMS survey guidelines (trajectories with closed loops, wide radius curves). The analysis presented, relating to a survey carried out with Leica Pegasus:Two instrumentation, in addition to describing the strategies used to properly develop the survey, aims to analyze the resulting datum by discussing its possibilities for use in urban modeling, for cartographic or three-dimensional information modeling purposes. Particular attention is paid to assessing whether the quality of the data (accuracy, density) is suitable for the urban scale. Finally, an analysis of the data obtained from MMS was made with the geographic-topographic database (DBGT), in a GIS (Geographic Information System) environment, to check the possibilities of use and integration between the two models.

Keywords MMS · Point cloud · Built heritage · Urban analysis · GIS · DBGT

Introduction

Thorough knowledge of historic built heritage is vital to proper management, regardless of the asset's size. Whether it is a modest-sized building, a medium-sized complex of buildings, an archaeological site, or an extensive historic city or site, Geomatics technology can provide support by offering knowledge of the asset geometry (Chiabrando et al. 2019; Farella et al. 2016; Nieto-Julian et al. 2022; Vacca and Dessi 2022). The appropriate techniques and tools must be chosen based on the object's scale and the goals of the geometric survey, including the possibility of surveying by merging data from various instruments with different resolutions (Guidi et al. 2009; Murtiyoso et al. 2018).

Focusing on historic cities and heritage sites, conducting a geometric survey of the cultural asset of interest becomes a fundamental element to enable a series of interventions related to its management, maintenance, and use.

✉ Daniele Treccani
daniele.treccani@polimi.it

Andrea Adami
andrea.adami@polimi.it

Valerio Brunelli
luigi.fregonese@polimi.it

Luigi Fregonese
valerio.brunelli@leica-geosystems.com

[1] Department of Architecture, Built Environment and Construction Engineering, Politecnico di Milano, UNESCO Research Lab, Mantua Campus, Piazza C. d'Arco, 3, 46100 Mantova, Italy

[2] Leica Geosystems Italia, via Codognino 10 –, Cornegliano Laudense, LO, Italy

Additionally, considering the European Community's strong emphasis on developing the smart city concept, digitizing the built heritage represents the first step in that direction (Javed et al. 2022; JungHoon 2022; Mortaheb and Jankowski 2022). The geometric survey serves as a starting point for developing three-dimensional digital models and a digital twin of the city (Wang et al. 2023). It can also be considered a three-dimensional model into which all useful information for end-users is channeled (Wegen et al. 2022).

For the purpose of surveying a large urban area, considering the area to be acquired, the accuracy, and the urban scale of representation, one of the appropriate tools is a mobile mapping system (MMS). A MMS is a data acquisition system that can move through an environment while gathering data. Typically, it involves mounting one or more laser scanners and cameras on a moving platform, in combination with direct positioning and orientation sensors (Ma et al. 2018).

Due to the flexibility of the survey system, MMSs can be considered an excellent tool for rapidly and efficiently surveying large cultural heritage sites and performing urban analysis. However, it is important to note that reliable data can only be obtained if the survey is conducted according to certain arrangements.

The urban patterns of historic sites can be challenging for the execution of MMS surveys; in fact, the presence of very narrow roads with tall buildings facing them may result in interruption or reduction of signal reception of the on-board GNSS receiver with consequent problems in trajectory reconstruction. In addition, a checkerboard pattern with right-angle curves and sudden changes in direction requires that the survey is planned carefully so that the resulting datum has the greatest coverage of the surveyed areas and adequate accuracy.

The purpose of the paper is to describe the execution of a MMS survey in historical sites coping with the aforementioned conditions, providing practical suggestions and discussing the suitability of the resulting data for subsequent urban modeling and analysis. The paper describes the use of an MMS for the geometric survey of Sabbioneta, a historic city located in northern Italy and a UNESCO World Heritage List site. The Leica Pegasus:Two MMS was used for the survey, and the article provides a detailed account of the survey's conduct, including precautions taken. The resulting data was analyzed in detail.

Furthermore, this paper explores the possibility of integrating data from different systems including cartographic data representing the urban territory, managed by national entities like the geographic-topographic database (DBGT), which for the analyzed case study is managed by region Lombardy (Belotti et al. 2021). The goal is to explore the possibility of data exchange and integration between cartography and the point cloud, exploiting the potential of the two systems. In particular, the map databases contain a geometric description of the territories and associated attributes, while the point cloud contains a 3D and more detailed representation of the territory. However, it should be noted that the data in different databases is not always directly combinable, and it is often necessary to identify methodologies to perform a fusion of the data (Pasquinelli et al. 2019).

The article is organized as follows. The "State of the art" section presents an overview of MMS and their usage in historic urban areas. The "Materials and method" section describes the case study, the survey instrument, the survey methodology, and analysis. The "Results" section provides a detailed presentation of the survey results and subsequent analysis. The "Discussion" section presents discussions based on the results obtained. Finally, the "Conclusions" section presents conclusions and future work.

State of the art

MMS is a term that refers to integrated systems composed of mapping sensors (e.g., light detection and ranging (LiDAR), high-resolution cameras) mounted on a moving platform whose localization is continuously measured while collecting geospatial data (Al-Bayari 2019). The typical combination of sensors used includes one or more 2D or 3D laser scanners to collect metric data, advanced digital cameras to provide additional information to the dataset, a GNSS (Global Navigation Satellite System) receiver that provides accurate positioning of the vehicle during the survey, and an inertial measurement unit (IMU) coupled with an accurate odometer (ODO) (Wang et al. 2019). The GNSS receiver, the IMU, and the ODO (which is optional) compose the positioning system. Using ODO data helps locate the vehicle when GNSS signals are weak or lost. The movement must be recorded continuously to track the location and orientation of the onboard instruments. The accuracy of the data acquired by an MMS depends on the acquisition system precision but is also primarily reliant on the performance of the positioning system on board, which provides the trajectory and orientation information (Javanmardi et al. 2017).

One possible classification of MMSs can refer to the type of mobile platform on which the measurement sensors are placed. Thus, handheld, backpack, trolley, and vehicle-based instruments can be distinguished (Elhashash et al. 2022). Regarding handheld and backpack instrumentation, it is held directly in the hand, in the former case, or on the shoulders, as with a backpack, in the latter case, by the user walking in the survey area. In the case of trolley-based instrumentation, it is placed on a trolley-like platform with wheels that is pushed by the user into the environment to be surveyed. The vehicle-based instrumentation, on the other hand, is placed on top of a moving vehicle, whether it is a car, a boat, or a locomotive on rails. The cited platforms are designed for specific working conditions, some of them are capable of working only outdoors, others can work indoors without the use of GNSS receivers to locate the platform's position, and others can work both indoors and outdoors.

The continuous collection of point clouds with high point density allows the capture of detailed road features such as curbs and surface conditions (Wang et al. 2019). Compared with terrestrial laser scanning (TLS), airborne laser scanning (ALS), and digital satellite imaging technologies, MMS systems represent a more flexible solution and can collect highly dense point cloud data with cost-saving and time-efficiency measurements (Ma et al. 2018). Various applications related to urban management use MMSs as the main urban remote sensing platform. Such applications include 3D map reconstruction for intelligent vehicle navigation and control, 3D city modeling, city visualizations, road asset inventories, railway modeling, vegetation detection, and urban forest inventories (Javanmardi et al. 2017). In addition, the use of data analysis and processing techniques, including machine learning approaches, allowed the classification and extraction of objects on the surveyed data, whether they were related to the road surface, like cracks or road markings (Soilán et al. 2019; Che et al. 2019), or related to typical elements of urban areas such as vegetation, buildings, manholes, etc. (Di Stefano et al. 2023), or classification of building elements when the MMS is used indoor (Franzini et al. 2023).

MMS instrumentation has great flexibility of use, and major applications may include road asset management and condition assessment, using vehicle-mounted MMS, proving to be more efficient than manual inspections, and often leveraging the use of machine learning; building information modelling (BIM) applications, often using portable MMS, with maintenance purposes and for better information management; emergency and disaster response, to facilitate decision-making process; vegetation mapping and detection, to provide accurate measurements automatically; and digital heritage conservation, exploiting the flexibility of portable MMS, for virtual tourism purposes and digital recording of cultural sites (Elhashash et al. 2022).

Focusing on cultural heritage (CH) and built environment, it is possible to find in the literature several works dealing with surveying assets that are more or less complex, with different scales of survey, and with different purposes, mostly using as a method of validation of the work the comparison with scans made with TLS, considered a reliable basis of comparison. Comparison methods mostly include Clout to Cloud (C2C) and Cloud to Mesh (C2M) distance calculation techniques, including visual analysis of the data by making sections and verifying the profile.

Works can be found that are primarily concerned with providing information on the accuracy and reliability of some specific MMS tools for their use with CHs as well, as in the case of Sammartano and Spanò (2018) that using a handheld MMS developed a set of test datasets for the documentation of both landscape and architectural complexes (including CH domain), used to validate the accuracy of the handheld system by comparing the resulting point clouds with data acquired with more precise systems. The study also discusses the possible drawing scale of deliverables developed using point clouds from the instrument and provides some operative suggestions for the survey conduction. With a similar purpose, Tanduo et al. (2022) tested three different MMS systems: a backpack solution, a handheld solution, and a MMS mounted on a boat. They tested the three instruments in Venice and compared the resulting point clouds with TLS data supported by topographic measurements. The data validation was conducted by using C2C and C2M distance methods, analyzing the control point residuals, and performing local analysis on horizontal profiles.

In addition, several works can be found in the literature in which authors have described the conduct of surveying a cultural asset using MMS systems and dealing with objects of different sizes and complexity. An example is the work of Tanduo et al. (2023) that documented the underground structure of Castello del Valentino (Torino, Italy) using a handheld MMS; results were validated by comparing with some TLS range scans used as a ground reference. The authors also discussed the data by analyzing some features like density and roughness. On the other hand, a first case dealing with bigger survey areas is the work of Rodriguez-Gonzalvez et al. (2017) which surveyed the huge area of the Medieval Wall of Avila (Spain) using a vehicle-mounted MMS. The MMS results were compared with a set of TLS range scans, highlighting errors affecting the architectural structures. They also proposed a point cloud optimization method to be applied to the MMS point cloud. Another case involving a large survey area is that presented by Brumana et al. (2023) who performed a multi-sensor survey of the Appian way (Italy) using a handheld MMS to give a continuous frame and by integrating with TLS and photogrammetry when necessary. The choice of a handheld MMS was made due to its high productivity and its flexibility with respect to vehicle-mounted ones. To prevent drift effects, control points were positioned in the survey area, and their coordinates were measured by a GNSS receiver in RTK mode. Another work done on an urban area is that presented by Martino et al. (2023), where authors used a handheld MMS for urban CH documentation. They set out three tests in Venice historic center and evaluated the instrument's results considering time, accuracy, and point resolution, also comparing it with TLS range scan and photogrammetric point clouds.

Materials and method

Considering what has been presented, it seems interesting to describe the conduct of a survey with a vehicle-mounted MMS of a historic urban area, which can be challenging when facing its peculiar characteristics (e.g., urban canyons, chessboard urban layout). In such a case study, it becomes interesting to describe the practical expedients implemented to adapt to the peculiarities of the urban environment, while also providing a visual and geometric analysis of the resulting data. In this way, it is possible to determine the possible scales of use and fields of application of the survey carried out.

Case study: Sabbioneta, an example of peculiar historic urban scenario

The case study selected for the mapping activity with the MMS is the historic city of Sabbioneta (Fig. 1). Located in northern Italy, Sabbioneta was founded in the second half of the sixteenth century by Duke Vespasiano Gonzaga, based on a pre-existing medieval village. The reconstruction of the city followed the precepts of the *ideal city* theorized in the Italian Renaissance. The town was enclosed in a hexagonal defensive wall with wedge-shaped corner bastions. This defensive system appeared rigorous in its geometry, but irregular, given the presence of the pre-existing medieval fortress. Inside the walls, the city was structured in a pattern reminiscent of the Roman castrum with some arrangements derived from *ideal city* principles.

The pattern of the city is formed by cardi and decumani, thus forming a set of regular blocks whose shape and structure have remained almost unchanged over time. The streets vary in width between 5 and 14 m, often with abrupt changes corresponding to specific areas or notable buildings in the city. The buildings are of modest height, tending to be two stories above ground, they stand close to the street, with which they maintain a continuous relationship. As a defensive choice, but also to realize real urban theaters, the checkerboard schema was implemented in a non-rigorous way. The result was a more complex street layout, resulting in peculiar forms of street intersections. There are also exceptions to the regularity: where the chessboard pattern meets the hexagonal fortified walls; the off-center position of the squares; the irregularity of the size of the streets; and the conformation of the crossroads (Lorenzi 2020).

The mobile mapping system used: multi-sensor platform Leica Pegasus:Two

The instrument used to perform the survey was the MMS Leica Pegasus:Two. Figure 2 shows the instrument during the survey of Sabbioneta. The instrument is a multi-sensor platform that mounts one high-end 2D laser scanner (profiler), eight cameras, IMU, and GNSS receiver. The laser scanner provides relative position and reflectance of measured points, while the cameras offer a 360° coverage and allow to complement the laser data with RGB color attributes. The instrument mounts also a light sensor to better control the images' exposure. Even if georeferenced images

Fig. 1 Several photographs showing Sabbioneta, the historic city used as a case study in this article. The pictures show some of the town's streets, characterized by various widths, and buildings leaning against the street; the fortified walls and a square can also be seen

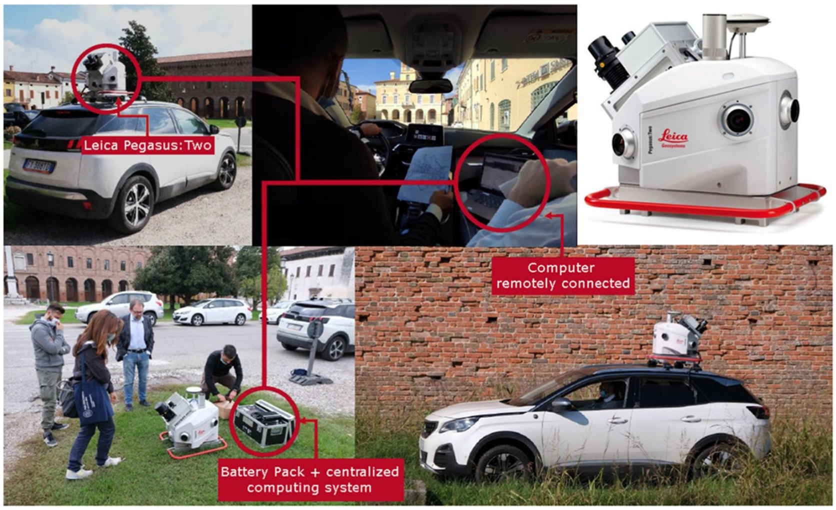


Fig. 2 Use of Leica Pegasus:Two in the field. The instrument was placed on top of a car throughout the survey. The system was controlled remotely from a PC placed on board, while the battery and centralized computing unit were placed inside the car.

could be an output of the instrument, the expected output of this survey is a point cloud of the urban area of the city.

The IMU has a declared frequency of 200 Hz so that accidental bumps (e.g., due to road irregular surface) could be detected and registered by the system. Then, the ability to measure and compensate for such bumps largely depends on the employed processing and the presence or absence of GNSS signal data during the bump. The GNSS subsystem on board is made of a triple-band sensor, capable of connecting to multiple constellations: GPS, GLONASS, Galileo, and BeiDou. The combination of IMU and GNSS allows a positional accuracy after 10 s of signal outage of 0.020-m RMS horizontal and vertical, 0.008° RMS pitch/roll, and 0.013° RMS heading. An optional ODO can be placed to help with trajectory.

The laser scanner mounted on the instrument can be either a Z+F 9012 profiler or a Leica P20. The Leica Pegasus:Two used for this test mounted a Z+F 9012 profiler, which has a field of view of 360°, an acquisition range from 0.3 to 119 m, a maximum scan rate of 1.016 million points per second (200 profiles), and is capable of acquiring one profile every 5 cm if the speed is of 36 km/h. The declared typical accuracy (Leica 2023) of Leica Pegasus:Two is 0.020-m RMS horizontally and 0.015-m RMS vertically (in open-sky conditions). The density of points on the surveyed surfaces depends on the incidence angle of the laser beam concerning the surface, the laser scan rate, the number of points collected per second, and the speed of the vehicle on which the instrument is mounted.

The instrument sensors (placed on top of the car in Fig. 2) are controlled by a centralized computing system, which during the survey is placed inside the vehicle. The centralized computing system contains also the battery, whose operational time is 9 h for the profiler version and 13 h for the scanner version. Data acquired on site are on average (for a vehicle speed of 40 km/h) 1.1 GB/km, which becomes 1.5 GB/km after processing. Data are stored on the internal drive. The data acquiring time and the post-processing time (without colorizing the point cloud) have a proportion of 1:1, which increases up to 1:5 when images are used to colorize the point cloud.

The instrument is designed to be placed on a variety of vehicles, boats, trains, and cars. For the test presented in this paper, Leica Pegasus:Two was placed on top of a car, the centralized computing system was placed inside the car, and the survey was controlled by a PC connected to the computing system. A summary of the features of the instrument used during the survey is recalled in Table 1.

Precautions for planning the MMS survey of Sabbioneta

To limit the size of the final file, reduce post-processing time, and for the optimization of the final data, it is advisable to carefully plan the execution of the survey. The peculiarities of the case study selected make it a challenging test area, and a properly designed plan of the acquisition routes is fundamental. Such peculiarities are related to the street layout and the building's characteristics. In particular, the checkerboard pattern of the city under study is composed of many road intersections and 90° curves, and the building's height combined with the narrow width of the roads make several areas of the city an urban canyon (very narrow streets with buildings standing on both sides), where GNSS signal could be weak or loss due to poor visibility or multipath effects. Those characteristics make the case study a challenging area because trajectory estimation errors might occur when performing car maneuvers in a challenging GNSS area, due to multiple varying acceleration signals from the IMU which are however not well supported by the GNSS position.

The survey of the city was split into several survey missions (named "Tracks" by the acquisition system), which

Table 1 Characteristics Leica Pegasus:Two, the MMS used in this study for the survey of Sabbioneta. Features were retrieved from the instrument datasheet (Leica 2023).

Instrument feature	Value
Number of cameras	8
Pixel size	5.5 × 5.5 microns
Camera coverage	360° x 270° excluding rear down-facing camera
Scanner	Z+F 9012 profiler
Rotation speed	200 Hz
Coverage	One profile every 5 cm at a speed of 36 km/h
Acquisition range	From 0.3 to 119 m
Field of view	360°
Scan rate	1.016 million points per second
GNSS sensor band	L-Band, SBAS, and QZSS
Supported constellations	GPS, GLONASS, Gaileo, and BeiDou
IMU frequency	200 Hz
Position accuracy after 10 seconds of outage duration	0.020-m RMS horizontal, 0.020-m RMS vertical, 0.008° RMS pitch/roll, 0.013° RMS heading
Operating time	9 hrs, profiler version; 13 h, scanner version
Weight	51 kg (without case), 86 kg (with case)
Size	60 × 76 × 68 cm, profiler version
Typical accuracy (without control points in open sky), horizontal	0.020-m RMS
Typical accuracy (without control points in open sky), vertical	0.015-m RMS
Data produced per project	43 GB/h or 1.1 GB/km
Data produced after processing	60 GB/h or 1.5 GB/km
Post-processing time	1 hr of data collection equals 1 hr of post-processing without colorizing, and 5 hrs of post-processing with colorizing

were planned considering the following conditions that come from practice:

- A sufficient number of satellites must remain visible during the progress of the survey to continuously support the precise localization of the vehicle, so the conditions that are beneficial for a survey with GNSS are also beneficial for a survey with the MMS instrument; in particular, the time of day must be carefully chosen, and it must also be considered that urban canyons limit the acquisition signal.
- The survey route should be planned by reducing as much as possible abrupt maneuvers and avoiding forward and reverse car directions on the same mission.
- Since the combination of sharp-edged road curves (e.g., 90° or almost) and GNSS occultation due to high buildings can result in trajectory estimation errors, it is advisable to plan the route by reducing the number of necessary turns or to turn only in areas with good GNSS visibility; so it was decided to pass through crossroads by continuing straight ahead whenever possible, as shown in Fig. 3.
- To better handle the resulting data and to better manage the processing time, it is preferable to carry out several missions for short stretches rather than a single mission for long stretches of road.
- Acquiring the same area two or more times is helpful for the data processing phase (better if the path is in closed rings), specifically during the multi-pass adjustment of the trajectory (see "Data processing" subsection for further explanations).
- To get a homogeneous result in the final point cloud, the car should be located as much as possible in the middle of the road, thus having symmetry of acquisition volumes with respect to the left and right sides of the road.
- To aid in the trajectory reconstruction phase, it may be useful to identify significant architectural points (e.g., manhole corners) whose coordinates can be measured by other systems (e.g., a GNSS receiver) and which can be used as control points; it is appropriate to plan the survey by making sure that these points are measured by the instrument and that they are not hidden or obstructed (e.g., by parked cars).

The survey of Sabbioneta was carefully planned to take into consideration the aforementioned precautions and based on the urban layout of the city. The missions were planned to avoid running into critical situations as best as possible. However, considering the pattern of the city, it was not always possible to follow all the precautions; for example, in many areas of the city, there are actual urban canyons, and

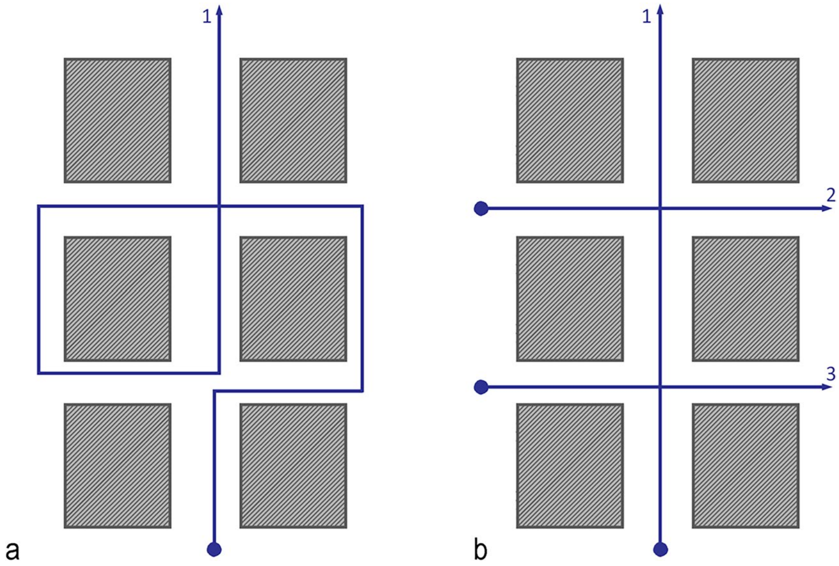


Fig. 3 Scheme showing the ideal survey of several blocks (the grey rectangles) and street intersections as from Leica Geosystems suggestions. **a** Not an ideal survey course, as it involves several sudden changes of direction and surveying the same areas within the same mission. **b** Ideal survey path, several missions (1, 2, 3) were planned to keep the path straight and avoid surveying the same area several times in the same mission

given the presence of many intersections and 90° curves, it was not always possible to avoid them. In conjunction with the survey using the MMS, the coordinates of notable points along the survey route were also measured. Those points were chosen such that they could be visible from the MMS and were chosen in manhole corners, sidewalk joints (e.g., between curb and sidewalk), and easily visible features on the road surface (e.g., road markings). The coordinates of those points were measured with a multiband GNSS receiver: Emlid Reach RS2. It was used in RTK mode, connected to the satellite positioning service of the Lombardy region (SPIN3 GNSS), to reach centimeter accuracy.

Survey data processing with Leica Pegasus Manager software

Data measured during the survey by the different sensors were stored in the centralized computing system and needed post-processing in order to visualize and use the point cloud and the geo-referenced imagery. For the generation of the final point cloud, it was necessary to process all the different data together. The raw data were merged based on the survey trajectory, which became the backbone and a fundamental element. Specific software was used to process the raw data: Leica Pegasus Manager.

This software is subdivided into several modules that allow for performing several tasks. This software also has a module related to survey planning (mission planning module), which takes into account the survey area, building height, and hypothetical GNSS signal strength, and a module that allows automatic extraction of information from the resulting point cloud (feature extraction module). In this study, the survey plan was developed with technical staff already experienced in such acquisitions, while feature extraction was considered unsuitable for the historical context and not used. Instead, modules allowing data processing (processing module), trajectory correction (basic and advanced trajectory adjustment modules), and data visualization (visualization module) were used. Data processing was conducted by Leica Geosystem Italy.

The first and most important step in the process was estimating the trajectory. Initially, raw data from Pegasus:Two were used to make a rough calculation of the trajectory. A statistical computation was then performed on the IMU and GNSS data, following the kinematic registration chain from the beginning to the end and from the end to the beginning. Various thresholds and parameters could be set to weight IMU and GNSS data based on survey conditions.

Once the trajectory was defined, scans and images were imported and connected to the trajectory based on the acquisition time. Each point acquired by the laser scanner had a timestamp attribute indicating when it was surveyed, as do the images and GNSS points of the trajectory. This allows points to be mounted on the trajectory, and photos to be oriented and used to add color information to the points.

At this stage, a unique point cloud is generated for each mission. The point cloud is filtered using a range filter to remove points that are too far away. On the points RGB colorization, masks can also be applied to all photos to remove repetitive elements; in this work, the back of the car was masked away as it appeared in all photos.

The result of this procedure was not the final point cloud, a check of the data was necessary. By exploiting the Pegasus Manager visualizer module, it was possible to inspect portions of the dataset of each mission, check the linked images and exclude the ones with bad light exposure or other errors, make slices, and look for possible misalignments. After this initial trajectory and point cloud computation, the approach to data processing consisted of a continuous iteration with successive refinements by repeating the advanced processing and data verification operations. At any iteration, the trajectory and point cloud were recomputed based on the refinement parameters computed in the previous step. After any iteration, the result could be exported in a meaningful format (if deemed of sufficient quality), or it could be processed again with the advanced trajectory adjustment module (if there were too many errors in trajectory reconstruction).

The advanced processing of the dataset implemented throughout the iterative process could be carried out by relying on three methods: time adjustment, multi-pass, and target-based. Time adjustment redistributed the errors along the trajectory by relying on the survey timeline. Multi-pass computed automatically homologous points on the survey and adjusted the trajectory accordingly. Target-based recomputed the trajectory by using user-defined control points as constraints. A combination of the three methods was used to adjust the trajectory. Specifically, a set of architectural points coordinates were measured for the target-based adjustment.

The final data could be exported in a variety of formats (e.g., *.las*, *.lcs*, *.e57*, *.rcp*), including a proprietary Leica format, a *.imp* file, i.e., a database that could be interfaced with by Leica Cyclone software. In the latter case, the export options allowed each mission to be exported by splitting and reconfiguring it as a set of successive range scans along the trajectory. The user could set the distance between each range scan.

Analysis of the resulting point cloud

The resulting data from the survey was analyzed in order to determine its usability for urban analysis purposes, such as for the study of the morphology of the built heritage, the analysis of pedestrian routes within the historic city, evaluations of road and sidewalk accessibility, and maintenance, and the creation of a digital urban city modeling.

A three-level analysis was implemented (Fig. 4). Firstly, the software Leica Pegasus Viewer was used to assess the quality of the data, exploiting an internal feature of the software. Secondly, the point cloud was analyzed by exploiting the data exported in Leica Cyclone Database format to assess possible misalignments and checkpoint coordinates. Lastly, a visual inspection of the point cloud was performed, by navigating the dataset.

Leica Pegasus Viewer is a free software used to visualize and navigate the data from any Leica Pegasus MMS (e.g., Pegasus:Two, Pegasus backpack). It displays each mission of the survey and allows the user to interact with associated points, images, and trajectories. By exploiting its features, it was possible to visualize the point cloud with a colored scalar field, according to the “quality” of each point. The “quality” parameter is a feature computed internally by the software, and it depends on factors related to the trajectory calculation. Although the software and its user manual do not provide an analytical explanation of how the quality parameter is calculated, it can still be useful for an initial observation related to trajectory reconstruction and the confidence of the resulting point cloud. A colored map was generated based on the “quality” values, and the areas of lower and higher qualities were discussed, comparing them with the characteristics of the city.

The Leica Cyclone database exported at the end of data processing was analyzed focusing on two aspects: looking for possible misalignments between different missions that surveyed common areas and evaluating the coordinate errors of 32 checkpoints distributed along the route. For the assessment of misalignments, areas of the city surveyed several times by different missions, or areas measured several times by the same mission, were chosen, and misalignments were measured. For the verification of check-points, notable points were identified along the survey trajectories, their coordinates were measured using a GNSS receiver and compared with coordinates retrieved on the Cyclone database.

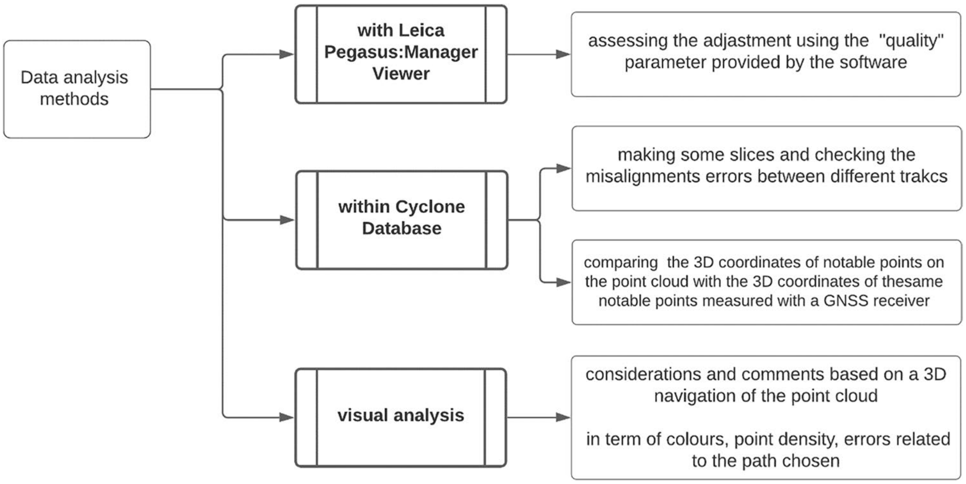


Fig. 4 Diagram showing the analysis of the survey data, which took place at different levels: using the Leica Pegasus Viewer and the “quality” parameter, making slices to search for misalignments, comparing the measurements of certain checkpoints, and observing the point cloud

To make the comparison, point clouds of every mission were co-registered with GNSS-measured points and the errors on checkpoints were checked.

The last check consisted of a visual assessment of the point cloud. The dataset was navigated and observed, with particular attention to inhomogeneities in the density of points on different surfaces, areas not surveyed because of obstacles or because of particular survey configurations, the coloration of the point cloud, and the overall quality of the resulting data.

MMS and GIS data integration analysis for cartographic production

Having obtained the point cloud, some tests were carried out to verify its integration with existing map databases. The goal is to verify their 2D and 3D integrations, as well as MMS data usability for drafting and updating existing cartography. The comparison was made with the DBGT of the Lombardy region (in which the case study is located).

The resulting georeferenced point cloud has coordinates in a cartographic reference system (WGS84/UTM zone 32N, EPSG:32632), while the datum of the cartographic data is in the RDN2008/UTM zone 32N (EPSG:6707). It is possible to integrate such data into a GIS environment and thus develop reasoning about the possibilities given by the combined use of different datasets. ESRI ArcGIS Pro was used to reach the purpose. By using the *Local Scene*, it was possible to overlay the layers of the DBGT on the point cloud and thus be able to exploit the potential of these datasets together. To determine the possible uses of this approach. Based on browsing and visual analysis of the overlay, considerations were then drawn about their use, pointing out possible strengths and weaknesses arising from this approach.

Results

The 3D point cloud database of Sabbioneta

The historic city of Sabbioneta has an area extent of 0.4 km^2; its road network consists of various types of streets: one-way, two-way, alleys, and dead-end streets. The city also has two squares, green areas, fortified walls (some portions of which are missing to date), fortified city doors, and a moat that passes close to the walls. The survey included both the city squares, a portion of the fortified walls, and both the main doors of the city.

The survey was planned considering all the precautions and covering almost the whole city. A total of 10 acquisition missions were planned and executed (Fig. 5). Leica Pegasus:Two was mounted on top of a car, the driving speed was, on average, 30 km/h, and the complete survey was conducted in almost 1 h: 20 min for the calibration of IMU and GNSS sensors and 40 min for the 10 missions. The acquisition missions were of different lengths for a total acquisition path of 7.7 km, and a global point cloud of 1.2 billion points (Table 2).

Data processing was performed by Leica technicians by following the presented methodology. A combination of

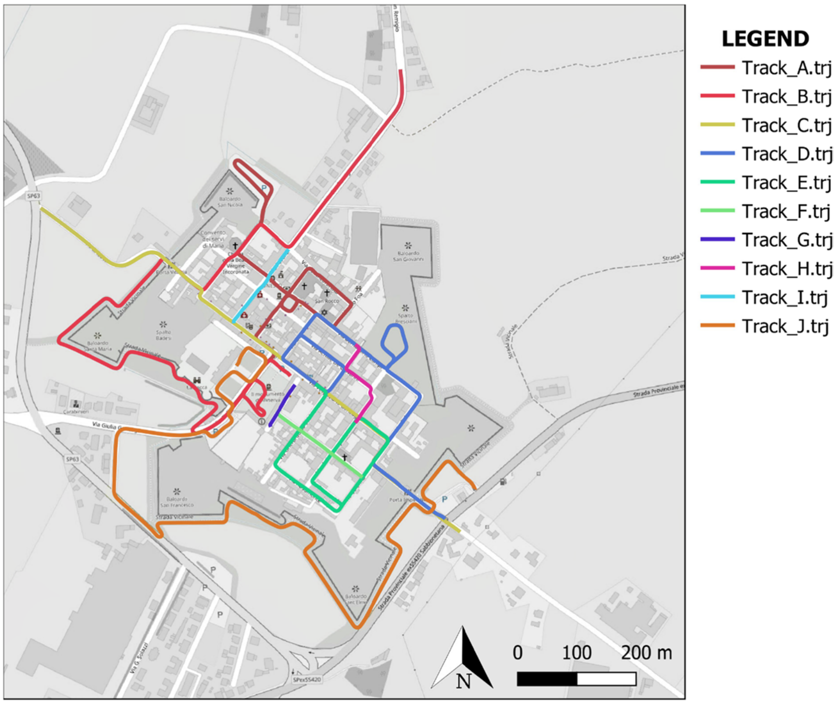


Fig. 5 Map of Sabbioneta showing the path of each acquisition mission carried out during the survey of the city

Table 2 Description of the acquisition missions carried out during the survey of Sabbioneta. For each mission (Track) the length of the survey route and the number of points in the point cloud are reported. The total is reported in the last line.

Name of the track	Length (m)	No. of points in the p.c.
Track A	1070.10	163,978,878
Track B	1684.40	246,213,213
Track C	975.03	121,343,926
Track D	1028.40	167,054,560
Track E	707.48	110,907,544
Track F	181.82	35,589,428
Track G	77.85	23,610,095
Track H	165.93	43,903,368
Track I	151.22	32,262,130
Track J	1671.90	264,605,024
Total	7714.13	1,209,468,166

the multi-pass and target-based techniques, as previously described, was used in the iterative phase of trajectory adjustment. During processing, two-stage point clouds were generated: one for each mission and one formed by merging all the missions. A range filter was applied to the laser scanner measures, and points with a distance greater than 50 m from the scanner were removed. This value was selected by taking into consideration that the surveyed area was mostly composed of urban canyons with buildings at short distances with an average height of 10 m, and where open spaces were mostly absent.

The resulting data was exported to different formats. First, a Leica Cyclone database containing both the 10-point clouds of each mission individually and a version with everything merged into a single-point cloud. The point clouds in the cyclone database were presented as a set of range scans placed at fixed distances along the trajectory. This distance was chosen to be 50 m. Secondly, the point cloud containing all the missions together was also exported in the open source *.e57* format.

The point clouds were reported with the color attribute derived from the photographs taken by the instrument during the acquisition. They also presented the intensity attribute, derived from the laser scanner measurement. The raw data extracted from the instrument at the end of the survey consisted of 75 GB, the Leica Cyclone database at the end of processing occupied a storage space of 168 GB, and the file in *.e57* format weighed 35 GB.

Analysis of the resulting point cloud

A three-level analysis was implemented. The first tool exploited was Leica Pegasus Viewer, which was used to colorize the point cloud according to the “quality” attribute. The “quality” values for the Sabbioneta dataset ranged from 0 to 6 (an adimensional value set by the software), so it was decided to divide that range into three equal steps and assign a meaningful color to points. Red was used for the lower quality points, yellow for the medium quality, and green for the higher quality points. Figure 6 shows the point cloud seen from the top, with points colorized using this scheme, and placed next to an orthophoto of the same area. Areas with lower quality (red points) were located in the inner parts of the city (thus in the network of checkerboard streets), in a small portion of the outer street near one of the fortified bastions, and in an avenue connecting the outside to the city. The city’s squares presented medium quality, while the streets located on the flanks of the fortified walls and the area of the large park built in one of the ramparts presented high quality.

Concerning the verification of checkpoints, related to the second level of analysis, the GNSS survey was performed by using a multiband GNSS receiver (Emlid Reach RS2), used in real-time kinematic (RTK) mode connected to the SPIN3 GNSS satellite positioning service of the Lombardy, Piedmont, and Valle d’Aosta regions, providing centimeter accuracy. The surveyed points were architectural points identified on the road surface (manhole edges, notable points on road markings), taking care that they were visible in the point clouds of the survey. Then, the same points were identified on the point cloud obtained from the merging of all missions, and the coordinates of those checkpoints were compared. The checkpoint errors were identified by checking the differences between the coordinates retrieved from the two systems. The points used are shown in the map in Fig. 7, where the points have been colored with a color scale similar to the one used in previous analyses: red points correspond to an error ≥ 0.160 m, yellow points in the range between 0.050 and 0.160 m, and green points having an error ≤ 0.050 m. Those errors are shown in Table 3, from which it can be seen that 66% of the points had an error lower than 0.10 m, 24% of points had an error between 0.10 m and 0.16 m, and only 10% of points had an error higher than 0.16 m.

Still related to the second level of analysis, a check for misalignments between scans made during different survey missions, made by doing sections on the point cloud, was performed. It was intended for a visual check of the various scans of different survey missions. The position of check-points and sections were not related. The check-points were spread all around the surveyed city, while the misalignments were checked at some specific locations where misalignments are most likely to occur. Such locations could be found in the merged dataset in areas surveyed by multiple missions, or in the point clouds of individual missions where the mission trajectory self-intersects. For this purpose, vertical and horizontal sections were made, finding an average misalignment of 0.05 meters, with peaks up to 0.20 meters. In general, the largest misalignments occurred

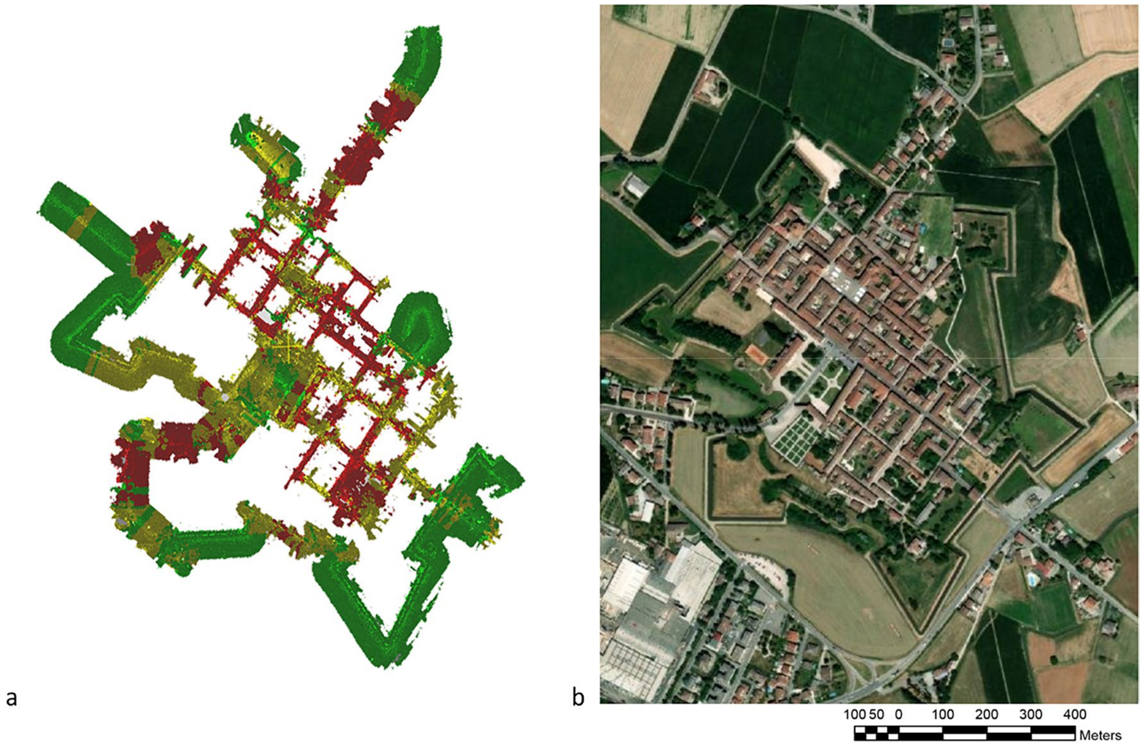


Fig. 6 Analysis of the survey data using the "quality" parameter of the Leica Pegasus Viewer software. **a** Top view of the point cloud, colored according to the "quality" parameter. Red was used for the lower quality points, yellow for the medium quality, and green for the higher quality points. **b** Top view of the city of Sabbioneta. By observing and comparing the two images, the areas with lower "quality" can be contextualized

in areas identified as "low quality" by the quality parameter discussed in the previous paragraph, thus emphasizing their lower quality compared to the other areas. Figure 8 shows three examples of sections, two vertical and one horizontal, while the positions of those three sections are depicted in Fig. 7 together with the position of check-points. In particular, Fig. 8a represents the case of a section made on a mission where the path passed two times on the same area (with errors of 0.15 m), while Figs. 8b and 8c represent two vertical and horizontal sections made on the cloud generated by joining all missions (error of 0.03 m for the vertical section and 0.05 m for the horizontal section).

The latest analysis was performed by navigating the point cloud. The first observation made was regarding the density of points. The point density is dependent on the vehicle speed during data acquisition, the number of points scanned by the scanner for every profile, and the distance of the scanned object from the instrument. The MMS used for this case study mounted a profilometer able to acquire 1.016 million points for every profile, for 200 profiles every second (which means 0.005 s for one profile). From the vehicle speed (in our case an average of 40 km/h) and the time spent by the profilometer to scan one profile, it is possible to determine the theoretical space between two consecutive profiles (which is independent of the distance of the scanned object) exploiting the well-known equation to retrieve space for uniform motion. In our case, the expected spacing is 0.055 m. Then, the density of points is also related to the spacing between points on the same profile. This spacing is dependent on the distance of scanned objects from the scanner. Since the profilometer acquires 1.016 million points on 200 profiles, it follows that one profile acquires 5080 points. So, for a circumference of 10 m (i.e., for objects at a distance of 10 m), we can compute a theoretical space between points of 0.012 m. So, considering a grid of points in the just mentioned situation (40 km/h of speed at a distance of 10 m), spaced of 0.055 m and 0.012 m, a density of 1515 points per square meter could be expected.

It was noted that ground surfaces tended to exhibit a higher density of points than the upper surfaces of building facades, especially when they were positioned high up and farther away from the instrument position (Fig. 9). This can be attributed to the position of the MMS, which is about 1.5 m above the ground as it is mounted on top of a car, and is closer to the road surface. As said, both the vehicle speed and the scanner position respect the scanned object influence the point density. Plus, it could be noted that the high parts of the buildings suffered from a lack of data due to

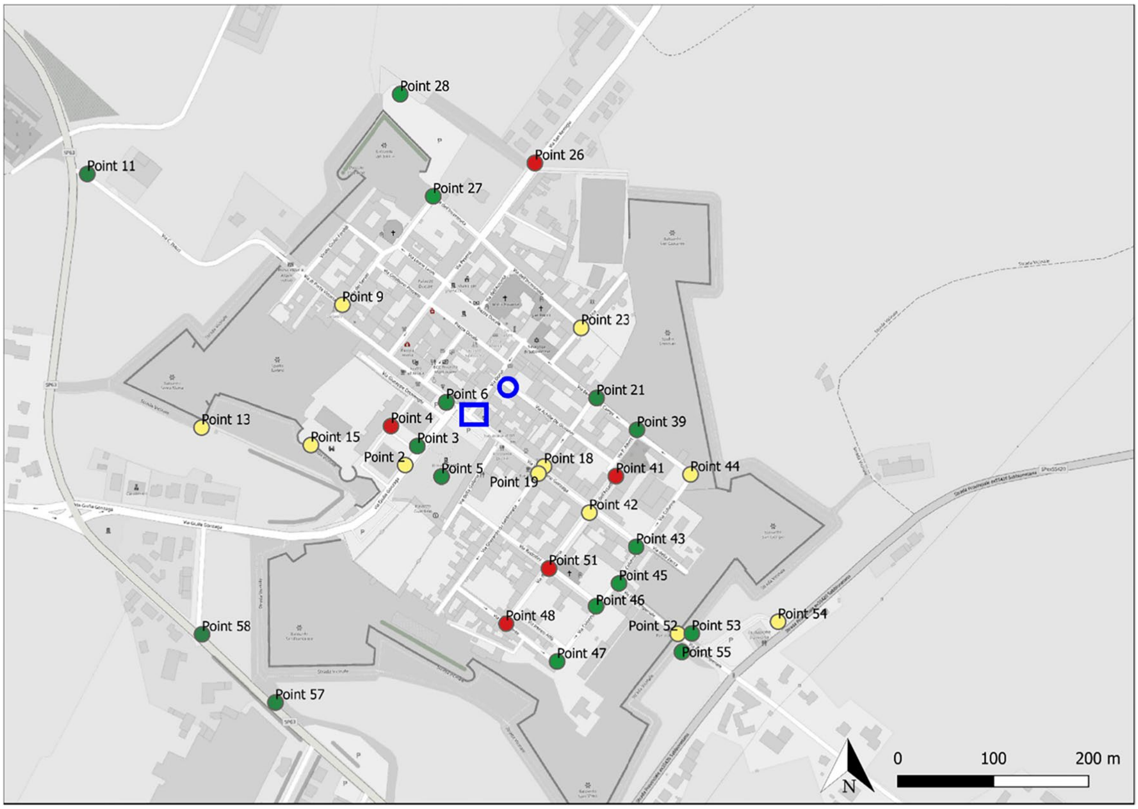


Fig. 7 Second level of analysis of the survey data firstly by checking for misalignments using sections on the dataset, and secondly by comparing the coordinates of the point cloud with those of check-points measured using a GNSS static receiver (Emlid Reach RS2). The map of Sabbioneta shows the measured check-points, colored according to their error. Red points correspond to an error ≥ 0.160 m, yellow points in the range between 0.050 and 0.160 m, and green points have an error ≤ 0.050 m. Furthermore, the Blue circle shows the position of the section shown in Fig. 8a, while the Blue rectangle shows the position of the section shown in Figs. 8b and 8c

the projecting surfaces (sills, cornices, etc.) which created shadows on the façades to map.

Exploiting CloudCompare software (CloudCompare 2022), it was possible to compute the neighborhood-related geometric feature "Surface Density" (CloudCompare 2023), which can help estimate the density of points on the ground and the upper part of a building's facade. The "Surface Density" is computed by the software as the number of points inside a sphere of a given radius centered on the point of which the feature is computed (named neighboring points), divided by the area of the circle of the same given radius. Given that definition, the "Surface Density" could be interpreted as the average number of points per square meter. Then, two roads of the city, with different widths, were selected (Fig. 10) and their point density was computed. The first road (Fig. 10a) had a width of 5.5 m, while the second road (Fig. 10b) had a width of 9.5 m. The point density of both roads had a very similar distribution. The "Surface Density" on the ground surfaces was, on average, 10,000 points per square meter, corresponding to a spacing between points of about 1 cm. The "Surface Density" of the upper part of the building facades, retrieved at 12 m from the ground, was, on average, 200 points per square meter, corresponding to a spacing between points of about 10 cm. The variability of the density along the height of buildings' façade could be crucial for some urban studies related to the analysis of buildings' facades.

A second observation was made regarding road intersections and curves, particularly when the acquisition trajectory made sharp turns. In such areas, and in the presence of buildings close to the road, a lack of data was regularly observed on the facades of those buildings (Fig. 11). The absence of surveyed data could be attributed to a combination of sharp bends and laser scanner position. In the MMS used, the laser scanner is mounted on a tilted position, such that the rotation axis, and so the scan lines, are inclined and not vertical. Combining this inclined scanning position with a rapid turn of the vehicle (due to the sharp bend), the result is the presence of two shadow cones (and thus unsurveyed areas) located in opposite positions: one at the top and one at the bottom of the building facade, depending on the driving direction.

A final observation was made regarding the coloring of the point cloud based on the images acquired from the 360°

cameras. Apart from some image projection errors on the point cloud (Fig. 12b), it was noted that the reconstruction of the panoramic images, generated by stitching eight shots and using an average exposure, was affected by over- and under-exposure problems in some areas (Fig. 12a). This issue occurred in the images when moving from a dark to a bright area (or vice versa). But then the system adapts to the new illumination and the images appear correctly exposed.

Table 3 Analysis of the survey data by comparing the coordinates of the point cloud with those of checkpoints measured using a GNSS receiver. The table shows the deviations between the coordinates of the measured checkpoints and those identified on the point cloud

Point	Error	Error vector (x, y, z)
51	0.221 m	(0.059, 0.199, 0.077) m
48	0.210 m	(0.050, 0.196, 0.055) m
26	0.160 m	(0.052, 0.029, 0.148) m
41	0.155 m	(0.072, 0.113, 0.079) m
42	0.153 m	(0.049, 0.123, 0.076) m
4	0.149 m	(0.059, −0.088, 0.104) m
54	0.130 m	(−0.023, −0.128, 0.002) m
44	0.125 m	(−0.062, −0.108, 0.010) m
15	0.111 m	(−0.007, −0.014, −0.110) m
52	0.108 m	(−0.064, 0.042, 0.076) m
19	0.108 m	(0.062, 0.056, 0.067) m
23	0.089 m	(−0.052, −0.072, −0.007) m
9	0.087 m	(−0.024, −0.027, 0.079) m
45	0.085 m	(−0.036, −0.039, 0.066) m
13	0.084 m	(−0.003, −0.084, 0.005) m
55	0.074 m	(−0.046, −0.058, 0.009) m
2	0.074 m	(−0.015, −0.060, −0.040) m
18	0.069 m	(0.025, 0.046, 0.045) m
28	0.066 m	(0.005, −0.065, 0.008) m
47	0.063 m	(−0.010, −0.061, 0.013) m
57	0.058 m	(−0.040, −0.037, 0.018) m
21	0.058 m	(0.013, 0.009, 0.056) m
3	0.057 m	(0.026, −0.050, −0.003) m
39	0.055 m	(−0.031, −0.029, 0.035) m
46	0.055 m	(0.018, −0.048, −0.020) m
27	0.048 m	(−0.008, −0.046, 0.011) m
6	0.043 m	(−0.004, −0.041, −0.012) m
53	0.041 m	(−0.032, −0.025, 0.006) m
11	0.037 m	(−0.009, −0.036, −0.002) m
58	0.033 m	(−0.011, 0.000, 0.031) m
5	0.023 m	(0.011, 0.002, 0.020) m
43	0.017 m	(−0.004, −0.014, 0.009) m

MMS and GIS data integration analysis for cartographic production

The Geoportal (WebGIS) of the Lombardy Region (https://www.geoportale.regione.lombardia.it/) is an integral part of the Italian national infrastructure for spatial information and environmental monitoring, the transposition regulation of the INSPIRE Directive. This Directive (https://knowledge-base.inspire.ec.europa.eu/index_en) requires that standard Implementing Rules (IR) are adopted in several specific areas, to ensure that the Spatial Data Infrastructures of the European Member States are compatible and usable in a community and transboundary context, the INSPIRE Directive

According to the Directive adopted by the Lombardy Region, the Geoportal is based on the DBGT, the geographic and topographic reference basis for its geographic information system. Following the production specifications and regulations, the DBGT was produced using an aerophotogrammetric methodology (direct numerical restitution of aerial photographs) mainly at a scale of 1:1000 and 1:2000 for the urbanized area, at a scale of 1:5000 for the extra-urban area and at a scale of 1:10,000 for mountainous areas or areas completely devoid of urbanization. The geodetic reference system used is the official Italian reference system, i.e., the realization ETRF2000, at the time 2008.0, of the European Geodetic Reference System ETRS89. The production is carried out in the derived UTM Fuso 32 cartographic system. The altimetric reference is the surface of the WGS84

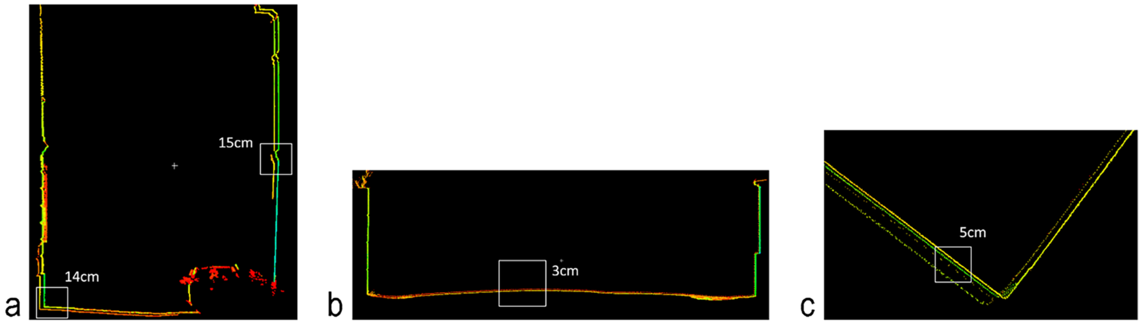


Fig. 8 Analysis of the survey data by carrying out several sections and checking for misalignments. **a** and **b** Vertical sections in two areas of the city with different street widths. **c** Horizontal section in an area surveyed a large number of times throughout the survey. The positions of these three sections within the city are reported in Fig. 7

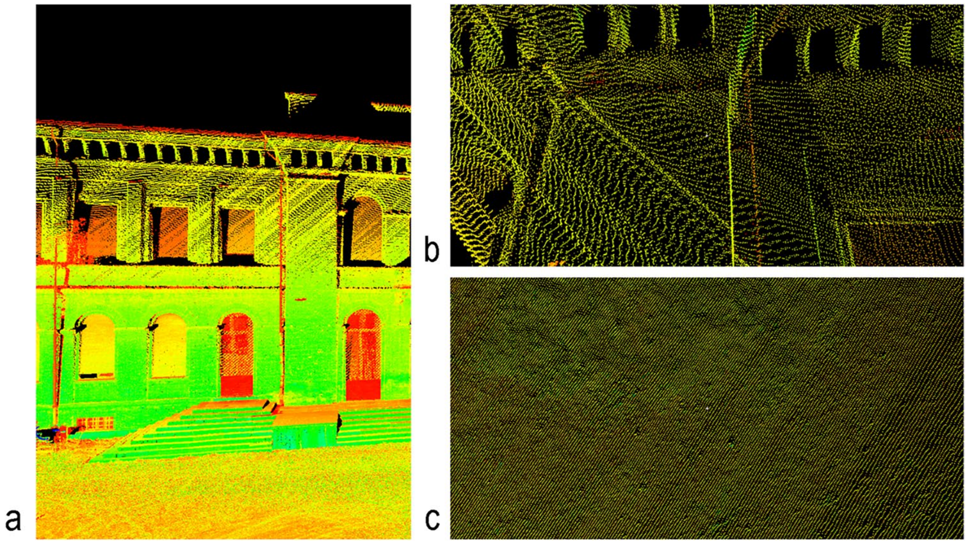


Fig. 9 Analysis of the survey data by observing the point cloud. It was noted how the number of points was different on the ground surfaces (closer to the instrument) and at the top of the building facades (further away from the instrument). **a** A portion of the point cloud, showing a building. **b** Magnification of the upper area of the façade. **c** Magnification of an area on the ground in front of the building

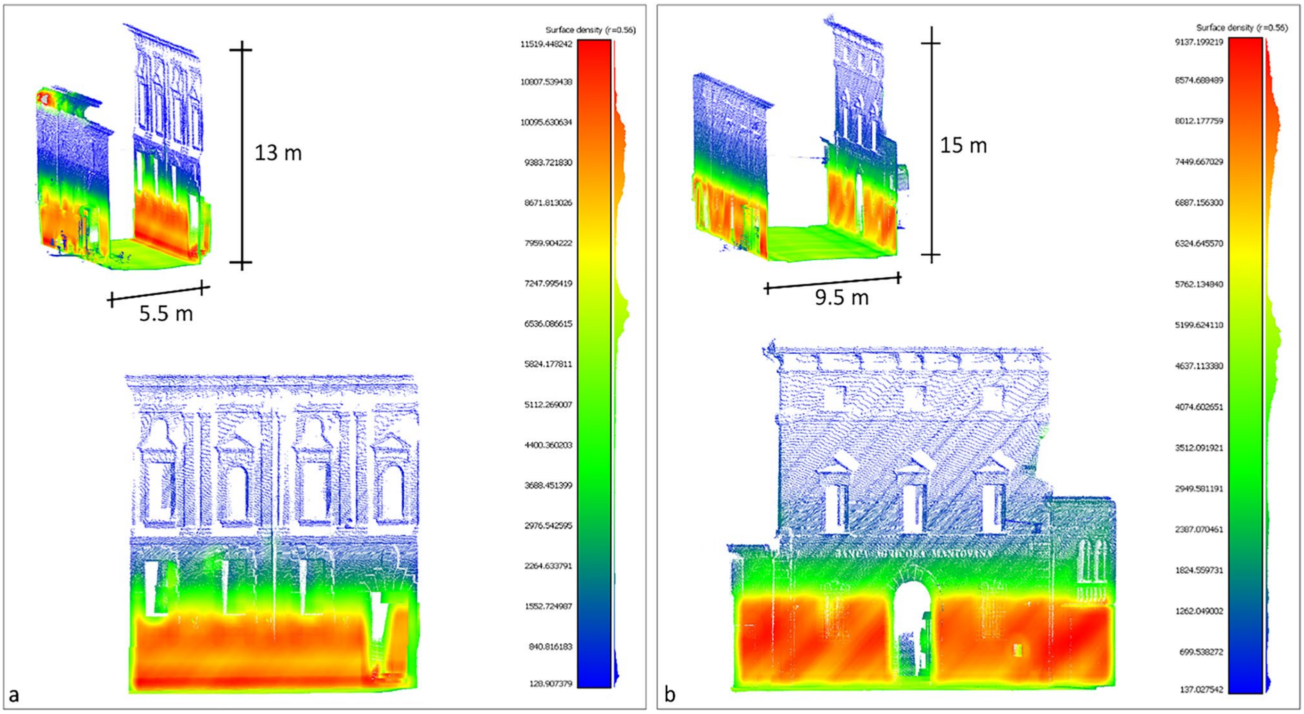


Fig. 10 Example of the calculation of the "Surface Density" feature in two areas of the city. **a** A portion of the street with an average width of 5.5 m. **b** A portion of the street with an average width of 9.5 m. The density of points on both roads had a very similar distribution. The values on the images are expressed in points per square meter

ellipsoid and the national altimetric reference national elevation reference.

The DBGT specifications provide also a field survey phase at the end of the restitution phase of acquired data to integrate the data already collected and processed. In particular, the Directive provides for (a) metric data integration, (b) informative recognition, and (c) collection of place names and other data for constructing the DBGT.

This phase is undoubtedly time-consuming as it requires direct observation of the territory through an exploration generally done by walking. Using the data MMS, correctly acquired, georeferenced, and validated, as in the case of Sabbioneta described here, makes the field survey phase much faster, especially concerning the phase of metric data integration. As foreseen in the specification, the metric data integration shall cover:

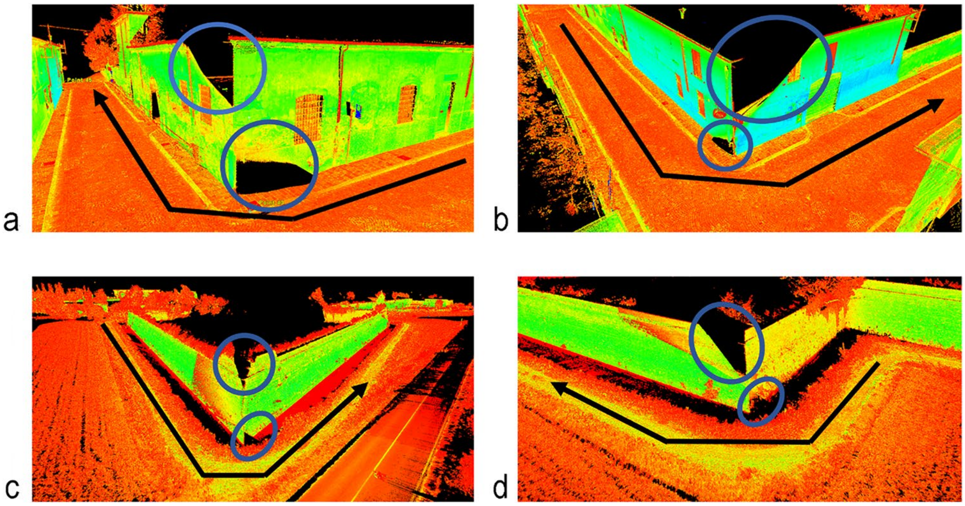
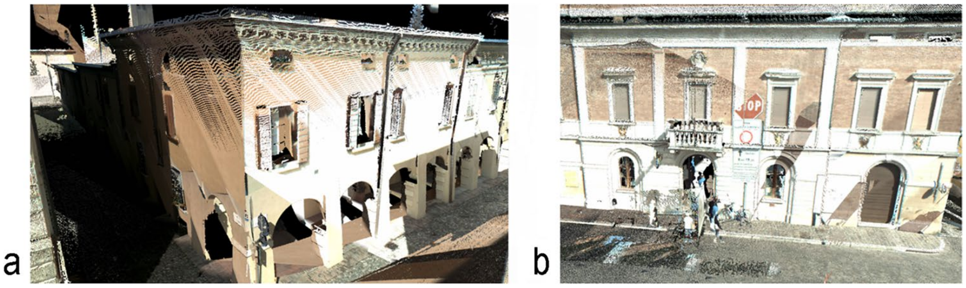


Fig. 11 Analysis of the survey data by observing the point cloud. It was observed that at very sharp bends, in portions of the road with buildings leaning against the road, shadow cones are created and the data was lacking. This was due to a combination of the position of the scanner in the MMS and hard curves that resulted in sudden changes in direction. The black arrow indicates the direction of travel of the car on which the MMS was positioned. **a**, **b** This phenomenon happened inside the built environment. **c**, **d** The same situation happened also outside the city while passing near the fortified walls

Fig. 12 Analysis of the survey data by observing the point cloud. Two snapshots of the point cloud colored with the images. **a** The over- and underexposure of the images resulted in bad coloring of the points. **b** An example of projection error, a "stop" signal was projected onto a facade



- The details not clearly acquired in image acquisition
- The details masked by vegetation
- The loggias, the porches, and any passage or opening in general, covered and open to the public
- Other details indicated by the restitution operators because they are not sufficiently clear
- The shelling

Data acquired via MMS, thanks to their specific acquisition point (human height), their numerousness, and coverage, constitute a source for numerous observations that can move part of the work from the field survey towards a data restitution activity.

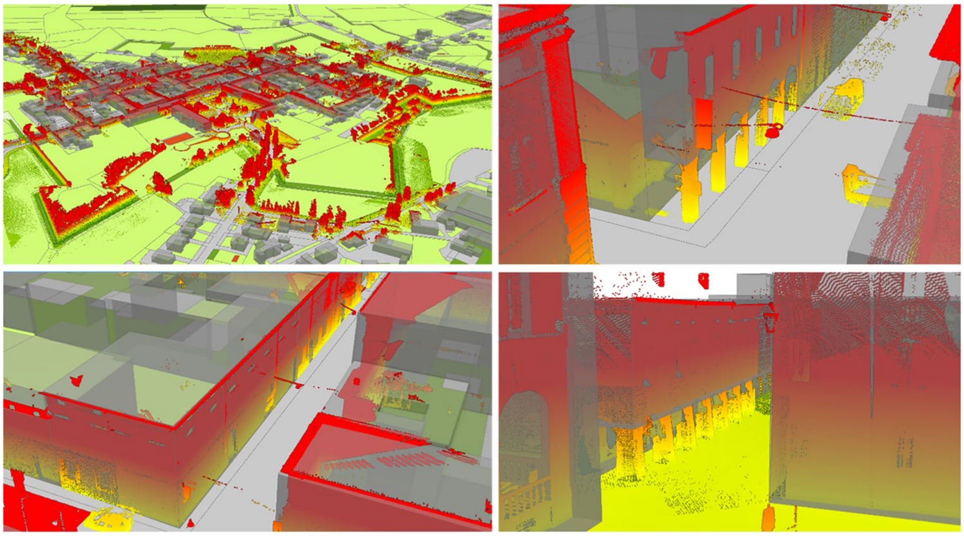
Aware of all this, we tried to apply the same process to the DBGT of Sabbioneta, made in 2019 according to the directives of the Lombardy Region. In particular, focusing attention on Piazza Ducale, the elements of the DBGT were tested, in some cases validating the metric content, in others modifying some elements until the integration with new objects that had been omitted because they were not visible.

Note that this test was carried out manually, extracting slices from the cloud of points and checking them with the DBGT, but these operations can also be automated according to the elements to be recognized and modeled.

To test the possibility of metric data integration, the MMS point cloud has been decimated to an average resolution of 1 cm, largely suitable for the scale of representation 1:1000. This reduced point cloud has been imported into ESRI ArcGIS Pro using the same reference coordinate system of the DBGT (Fig. 13), as downloaded from the Geoportale ("WebGIS"). To better manage the entire project, the point cloud has been converted in a pyramid format and then it has been segmented, according to elevation, into some classes related to the most useful height of buildings of the whole Sabbioneta. In this way, the point cloud is a powerful tool, especially in combination with the 3D data, built automatically in ArcGIS Pro.

From the comparison between the DBGT and the point cloud, it appears that many parts of the square are correctly modeled, obviously taking into account the 1:1000

Fig. 13 Different views (on ESRI ArcGIS Pro) of the point cloud over imposed with building data from the DBGT of Lombardy Region. The points have been re-colored according to their height



scale constrictions of the DBGT. This is evident, for example, in the arcades/portico on the ground floor where the line of the volumetric units on the ground floor, which defines the arcades, is correctly positioned and drawn, as visible in Fig. 13.

However, the same cannot be said of the Palazzo Ducale. The situation is much more complex since, in the published database, there is only one polygon in place of the staircase, defined as "Area Attrezzata al Suolo" ("ground equipped area"). However, not much information is known about this staircase: it constitutes the entrance to a public building, the Museum of Palazzo Ducale, and also involves the crossing of a portico positioned at a height aboveground level. Complex situations of this kind require great attention both in the interpretation of production specifications (e.g., defining which is the most correct class to contain the staircase) and the need to represent public spaces, accessible to the general public. Regardless of all this, the MMS proves to be, in these complex situations above all, a tool with great possibilities that allows to delve into details (see Fig. 14) otherwise difficult to grasp from different kinds of datasets (e.g., aerial datasets).

Another issue, which can be revealed by the integration of GIS data and MMS point cloud, is dealing with the profile of the building. In some cases, in fact, the perimeter of the building is built clearly from the roof profile, without considering the roof overhang.

Discussion

The survey of almost the entire city was carried out in quite a short time, especially considering the large amount of surveyed areas and the amount of data collected. The planning of the survey and its execution faced from the very beginning the historical pattern of the studied city. Indeed, the presence of many intersections and the presence of actual urban canyons made the execution of the survey more difficult. The latter created difficulties in the signal input of the GNSS receivers on board the instrument. During the data processing, it became very evident that the advanced

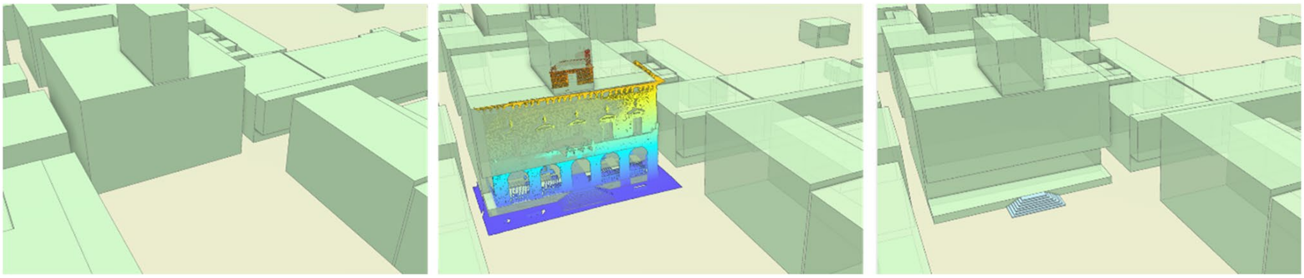


Fig. 14 Different views (from ESRI ArcGIS Pro) of the Palazzo Ducale in Sabbioneta: 3D buildings from DBGT (left); buildings superimposed with the point cloud data (middle); the building of Palazzo Ducale with the staircase and portico manually generated using MMS point cloud as reference (right)

trajectory refinement phase was crucial. As mentioned above, this phase could be repeated iteratively; however, due to computational constraints, the number of iterations and quality of the final result must be balanced with survey requirements, available time, and costs. Thus, it is crucial to carefully plan mission paths and trajectories.

From this experience, it becomes evident that certain adjustments have turned out to be essential to control the error and to be able to process the data with a discrete quality. In particular, the survey design guidelines indicated in the section "Precautions for planning the MMS survey of Sabbioneta" proved to be useful. Considering the presence of urban canyons and therefore foreseeing the decay of the GNSS signal and the consequent difficulty in reconstructing the trajectory, it was useful to have measured the coordinates of some notable points used as control points for the target-based processing procedure, which was implemented together with the multi-pass procedure. Furthermore, to ensure a good survey coverage and minimize right-angle curves, several survey missions intersecting each other were planned and implemented, so that the combination of all of them would provide a complete survey of the city, but individually would tend to minimize such cases.

Regarding the analysis of the measurements made, it could be observed that there was good consistency in the analysis results. For instance, it could be noted that the areas identified with lower quality by the Leica Pegasus Viewer software were the same ones in which the misalignment errors were greater and were the same ones in which the check-points had larger errors.

Particularly, looking at the color-scaled point cloud with the quality information obtained from Pegasus Viewer and looking at Fig. 6b, it was possible to observe an orthophoto of the city and thus contextualize the quality of the point cloud concerning the urban context. It may be noted that the areas with lower quality were in correspondence with the presence of vegetation (trees with large canopies), or in very narrow streets with buildings closer to the road, thus true urban canyons. It may be noticed that in squares (with more open space) the quality tended to be higher.

The typical section of the surveyed streets is shown in Fig. 15. This section, with buildings of modest height leaning against streets of narrow width, was essentially constant throughout almost the entire survey, except near the two squares and along the walls. As can be seen, actual urban canyon conditions occurred, which are known to be a source of signal loss and multipath effect for GNSS receivers. Such a situation may have affected both the trajectory reconstruction and the measure of checkpoints. Looking carefully at, for example, the checkpoints with larger errors in Fig. 8, e.g., points 48, 51, and 41, it can be seen that they were aligned on the same road and probably that area was affected more than others by signal loss.

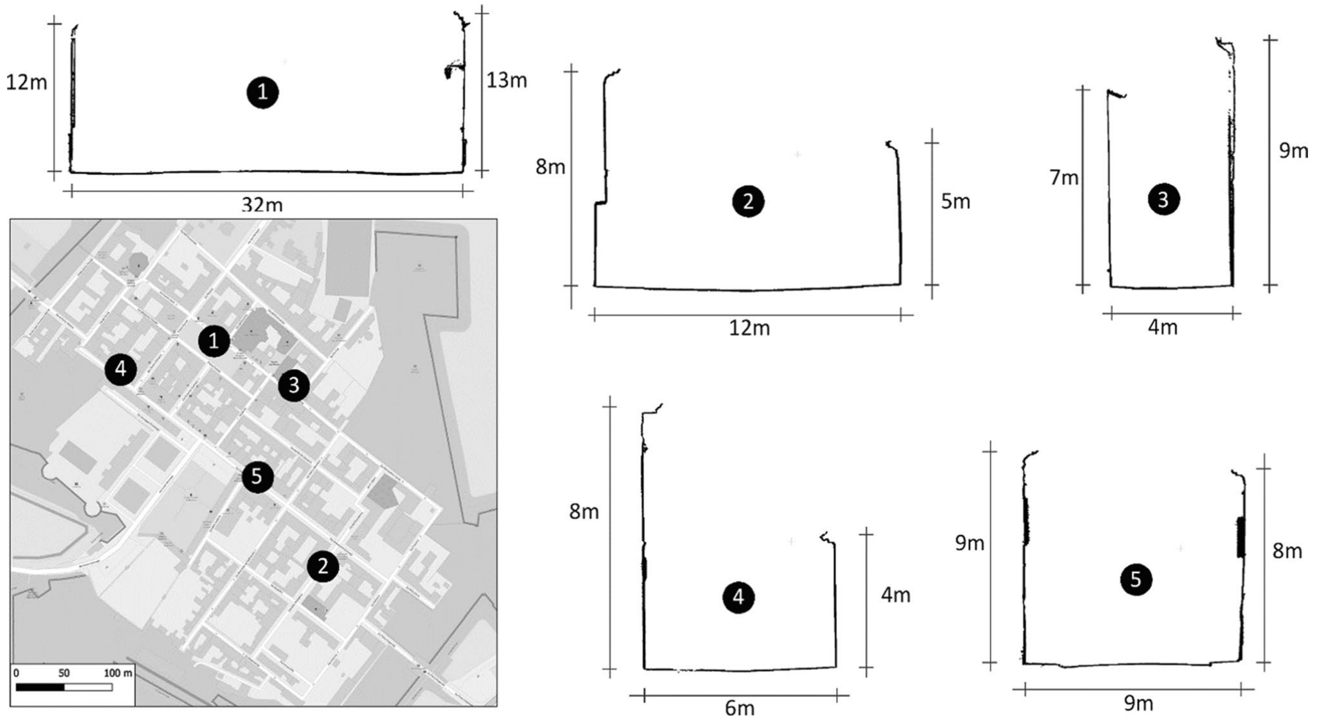


Fig. 15 Different sections of the point cloud showing that in different areas of the city, there may be instances where GNSS signal loss occurs due to *urban canyons*

Regarding the survey configuration, the portions of corner facades with missing data could be recovered in several ways. A first way would be to change the survey path by having these areas surveyed twice with opposite trajectories so that the missing area would be covered. Another method would be to integrate the missing data with scans made with TLS or other systems.

About the density of the points on the measured objects, it was observed that it is linked both to the speed of the vehicle and the position of the measured objects concerning it. It could be observed that objects that are part of road surfaces and the lower parts of building facades have a higher density (as they are closer to the instrument), while the higher parts of buildings have a lower density (as they are further away from the instrument, and as there are projecting elements that cast a shadow). The distance of the objects measured by the instrument cannot be easily changed, as the position of the instrument is bound to the driving position of the vehicle along the roadway, and it is positioned above the vehicle. Instead, the driving speed of the vehicle can be changed. A lower speed can ensure a higher point density by reducing the spacing between consecutive scanner profiles. It follows that a lower speed means a greater amount of data and an inevitably greater amount of time and computing resources to process the data.

Image reconstruction suffered greatly from lighting problems because the panoramic image used to color the point cloud was the result of stitching eight other images, each with different lighting conditions. To solve this problem it would be necessary to use a different system, for example, the more recent Leica TRK family, which mounts a panoramic camera (with additional, optional rear, front, and side cameras) and has an improved exposure correction system.

Closing the discussion concerning the analysis of the survey data, it was generally noted that among the different analysis methods, there was consistency between the areas with higher and lower quality throughout the survey, for which, as mentioned above, the main problems may have been caused by signal loss due to urban canyons or vegetation.

From the analyses, it could be concluded that the survey system exploited can be effective in surveying built heritage and extensive cultural heritage sites and historic urban areas. Large areas could be surveyed in a short time by the MMS, with a high density of points on the ground and a lower density of points on building facades, especially in higher areas and therefore further away from the instrument. Comparable densities were found in roads with very different widths, proving that the average density on the ground and the upper part of the facades had two very different values, but was consistent throughout the survey. As clearly visible from Figure 10, the density on ground surfaces was more homogeneous, while the density in facades was higher on the lower parts, lowering moving upwards. The upper parts of the facade had also several shadows (and consequently missing data) due to the projecting surfaces of the facade elements. Plus, given the location of the instrument, it was not possible to detect building roofs. Still, these could be integrated by using other systems, such as the use of unmanned aerial systems (UAS) or aerial laser scanning (ALS).

Finally, the system was able to give a result adequate for the urban scale even when operating in a historical area that had several special features (e.g., the street pattern, the presence of several intersections, and closed roads), presenting an overall accuracy of 0.15–0.20 m. The data thus allows for possible subsequent urban analysis and modeling; in fact, the results show that the point cloud is comparable with urban scale usage; so it is suitable for the 1:1000 urban scale, which has an acceptable error of 20 cm and a tolerance of 60 cm. Lastly, further processing could lead to semantic segmentation and use for urban area management using the point cloud.

Tests developed to integrate the MMS surveyed dataset and the DBGT cartographic dataset showed that the particular acquisition point of such instrument (i.e., from the ground) allows a new point of view for cartographic production, which tends to have a view only from above. The use of MMS datasets could allow for a reduction in costs and time associated with respect to the recognition performed on the ground during map production, providing a useful and reliable novel tool.

Conclusions

This paper described the development of an MMS survey of a historic urban area, providing practical conditions to perform the survey, and analyzing the resulting point cloud for its suitability for urban management and modeling. The survey of the historic city of Sabbioneta was performed with Leica Pegasus:Two. The survey was conducted in 40 min and covered almost the entire historic city, a total of 7.7 km of road, with a resulting point cloud of 1.2 billion points. The resulting data from the survey was then analyzed in detail with three different levels of control: using specific visualization software from Leica, comparing with checkpoints, making sections looking for misalignments, and making a visual assessment of the point cloud.

From the tests conducted, MMS proved to be an excellent method for surveying a historic city, capable of correctly and completely surveying the ground surfaces, but with less coverage on building facades and no possibility of surveying roofs, which are both interesting aspects for the management and conservation of a historic city. Despite the peculiarities of a historic urban area that could be challenging for the correct execution of a MMS survey, the system was able to quickly and correctly survey the urban area of interest. The resulting point cloud was considered adequate for urban modeling and management purposes. In addition, the use of such data for integration and map production has been tested and shown to have much potential.

Indeed, the point cloud resulting from the survey presented by this paper was used in another work (Treccani 2022; Treccani et al. 2023) to compute pedestrian routes and physical accessibility assessments in Sabbioneta, leveraging on point cloud processing through machine learning techniques; the dataset proved to be effectively suitable for those processes. In fact, the results obtained showed that the density of points on the ground and the quality of the data acquired were sufficient to correctly apply machine learning processes to segment the point cloud with high scores of the performance metrics.

In the future, it will be possible to carry out further tests related to the analysis of the point cloud for maintenance of road and pedestrian areas, and tests of segmentation of the point cloud with artificial intelligence methods for semantic segmentation, looking for specific classes related to historical urban scenarios. Plus, the integration and exploitation of cartographic data will be pursued, also considering integration with other surveying tools such as Portable Mobile Mapping Systems (PMMS), UAS, and ALS.

Acknowledgments The authors would like to thank Leica Geosystem Italy for providing the instrument Leica Pegasus:Two and technical support for data processing.

Funding Open access funding provided by Politecnico di Milano within the CRUI-CARE Agreement.

Data availability The data that support the findings of this study are available upon reasonable request.

Declarations

Conflict of interest The authors declare no competing interests.

References

Al-Bayari O (2019) Mobile mapping systems in civil engineering projects (case studies). Appl Geomat 11:1–13. https://doi.org/10.1007/s12518-018-0222-6

Belotti P, Conzi F, Dell'Orto C, Federici M, Fregonese L, Garnero G, Guastamacchia E, Guzzetti F, Pinto L, Scaioni M (2021) The project to complete the regional topographic geodatabase in Lombardy, Italy. Proc ICA 4:12. https://doi.org/10.5194/ica-proc-4-12-2021

Brumana R, Quilici S, Oliva L, Previtali M, Attico D, Roncoroni F, Stanga C (2023) Immersive Appian way health infrastructure: human centric digital twin (the PAAA Archeological Park of the Appian Way 12km state-own section, UNESCO candidature). Int Arch Photogramm Remote Sens Spatial Inf Sci 48:311–318. https://doi.org/10.5194/isprs-archives-XLVIII-M-2-2023-311-2023

Che E, Jung J, Olsen MJ (2019) Object recognition, segmentation, and classification of mobile laser scanning point clouds: a state of the art review. Sensors 19(4):810. https://doi.org/10.3390/s19040810

Chiabrando F, Sammartano G, Spano A, Spreafico A (2019) Hybrid 3D models: when geomatics innovations meet extensive built heritage complexes. ISPRS Int J Geo-Information. https://doi.org/10.3390/ijgi8030124

CloudCompare (2022) CloudCompare (version 2.X) [GPL software]. http://www.cloudcompare.org

CloudCompare (2023) Density. https://www.cloudcompare.org/doc/wiki/index.php/Density. Accessed on: 2023-07-01.

Di Stefano F, Pierdicca R, Malinverni ES, Corneli A, Naticchia B (2023) Point cloud classification of an urban environment using a semi-automatic approach. Int Arch Photogramm Remote Sens Spatial Inf Sci 48:131–138. https://doi.org/10.5194/isprs-archives-XLVIII-1-W1-2023-131-2023

Elhashash M, Albanwan H, Qin R (2022) A review of mobile mapping systems: from sensors to applications. Sensors 22(11):4262. https://doi.org/10.3390/s22114262

Farella E, Menna F, Nocerino E, Morabito D, Remondino F, Campi M (2016) Knowledge and valorization of historical sites through 3D documentation and modeling. Int Arch Photogramm Remote Sens Spatial Inform Sci 41:255–262

Franzini M, Casella V, Niglio O (2023) Leica blk2go point cloud classification with machine learning algorithms: the case study of sant'eusebio's crypt in Pavia (Italy). Int Arch Photogramm Remote Sens Spatial Inf Sci 48:593–600. https://doi.org/10.5194/isprs-archives-XLVIII-M-2-2023-593-2023

Guidi G, Russo M, Ercoli S, Remondino F, Rizzi A, Menna F (2009) A Multi-Resolution Methodology for the 3D Modeling of Large and Complex Archeological Areas. Int J Architec Comput 7:39–55. https://doi.org/10.1260/147807709788549439

Javanmardi M, Javanmardi E, Gu Y, Kamijo S (2017) Towards high-definition 3D urban mapping: road feature-based registration of mobile mapping systems and aerial imagery. Remote Sens. https://doi.org/10.3390/rs9100975

Javed AR, Shahzad F, Rehman S, Zikria YB, Razzak I, Jalil Z, Xu G (2022) Future smart cities requirements, emerging technologies, applications, challenges, and future aspects. Cities 129. https://doi.org/10.1016/j.cities.2022.103794

JungHoon K (2022) Smart city trends: A focus on 5 countries and 15 companies. Cities 123:103551. https://doi.org/10.1016/j.cities.2021.103551

Leica Geosystems (2023) Leica Pegasus:Two mobile sensor platform. https://leica-geosystems.com/it-it/products/mobile-mapping-systems/capture-platforms/leica-pegasus_two. Accessed on: 2023-07-01

Lorenzi A (2020) Sabbioneta. Progetto di una città. LetteraVentidue, Siracusa

Ma L, Li Y, Li J, Wang C, Wang R, Chapman MA (2018) Mobile laser scanned point-clouds for road object detection and extraction: A review. Remote Sens 10:1–33. https://doi.org/10.3390/rs10101531

Martino A, Breggion E, Balletti C, Guerra F, Renghini G, Centanni P (2023) Digitization approaches for urban cultural heritage: last generation MMS within Venice outdoor scenarios. Int Arch Photogramm Remote Sens Spatial Inf Sci 48:265–272. https://doi.org/10.5194/isprs-archives-XLVIII-1-W1-2023-265-2023

Mortaheb R, Jankowski P (2022) Smart city re-imagined: City planning and GeoAI in the age of big data. J Urban Manag. https://doi.org/10.1016/j.jum.2022.08.001

Murtiyoso A, Grussenmeyer P, Suwardhi D, Awalludin R (2018) Multi-scale and multi-sensor 3D documentation of heritage complexes in urban areas. ISPRS Int J Geo-Inform. https://doi.org/10.3390/ijgi7120483

Nieto-Julian J, Farratell J, Bouzas Cavada M (2022) Moyano J (2022) Collaborative workflow in an HBIM project for the restoration and conservation of cultural heritage. Int J Architect Heritage 10(1080/15583058):2073294

Pasquinelli A, Agugiaro G, Tagliabue LC, Scaioni M, Guzzetti F (2019) Exploiting the potential of integrated public building data: energy performance assessment of the building stock in a case study in Northern Italy. ISPRS Int J Geo-Inform 8. https://doi.org/10.3390/ijgi8010027

Rodriguez-Gonzalvez P, Jimenez Fernandez-Palacios B, Munoz-Nieto L, Arias-Sanchez P, Gonzalez-Aguilera D (2017) Mobile LiDAR system: new possibilities for the documentation and dissemination of large cultural heritage sites. Remote Sens 9. https://doi.org/10.3390/rs9030189

Sammartano G, Spanò A (2018) Point clouds by SLAM-based mobile mapping systems: accuracy and geometric content validation in multisensor survey and stand-alone acquisition. Appl Geomat 10:317–339. https://doi.org/10.1007/s12518-018-0221-7

Soilán M, Sánchez-Rodríguez A, del Río-Barral P, Perez-Collazo C, Arias P, Riveiro B (2019) Review of laser scanning technologies and their applications for road and railway infrastructure monitoring. Infrastructures 4(4):58. https://doi.org/10.3390/infrastructures4040058

Tanduo B, Martino A, Balletti C, Guerra F (2022) New tools for urban analysis: a SLAM-based research in Venice. Remote Sens 14. https://doi.org/10.3390/rs14174325

Tanduo B, Teppati Losè L, Chiabrando F (2023) Documentation of complex environments in cultural heritage sites. A slam-based survey in the Castello del Valentino basement. Int Arch Photogramm Remote Sens Spatial Inf Sci 48:489–496. https://doi.org/10.5194/isprs-archives-XLVIII-1-W1-2023-489-2023

Treccani D (2022) Point cloud processing for physical accessibility evaluation in historical urban environments. In: The case of UNESCO Site of Sabbioneta. Phd thesis, Politecnico di Milano

Treccani D, Fernández A, Díaz-Vilariño L, Adami A (2023) Automating the inventory of the navigable space for pedestrians on historical sites: towards accurate path planning. Int J Appl Earth Observ Geoinform 122. https://doi.org/10.1016/j.jag.2023.103400

Vacca G, Dessi A (2022) Geomatics supporting knowledge of cultural heritage aimed at recovery and restoration. Int Arch Photogramm Remote Sens Spatial Inf Sci 48:909–915. https://doi.org/10.5194/isprs-archives-XLIII-B2-2022-909-2022

Wang Y, Chen Q, Zhu Q, Liu L, Li C, Zheng D (2019) A survey of mobile laser scanning applications and key techniques over urban areas. Remote Sens 11:1–20. https://doi.org/10.3390/rs11131540

Wang H, Chen X, Jia F, Cheng X (2023) Digital twin-supported smart city: status, challenges and future research directions. Expert Syst Appl 217. https://doi.org/10.1016/j.eswa.2023.119531

Wegen O, Dollner J, Richter R (2022) Concepts and challenges for 4D point clouds as a foundation of conscious, smart city systems. In: Gervasi O, Murgante B, Misra S, Rocha A, Garau C (eds) Proceedings of the Computational Science and Its Applications – ICCSA 2022 Workshops. Springer International Publishing, Cham, pp 589–605. https://doi.org/10.1007/978-3-031-10536-4_39