Digitizing Physical Accessibility in Urban Scenes: From Point Cloud Processing to GIS-Based Analysis

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Abstract

Urban accessibility is a crucial factor in achieving inclusive and sustainable development, as emphasized by Goal 11 of the UN 2030 Agenda. This paper presents the early outcomes of the PRIN 2022 research project *“ACROSS: A static and dynamic database for historic urban contexts accessibility”*, funded by the Italian Ministry of Education, University, and Research. The ACROSS project explores innovative methodologies for assessing and enhancing accessibility within historic urban centers, focusing on the integration of Geomatics and data-driven approaches. Specifically, it aims to generate both static and dynamic databases that support inclusive urban planning by identifying permanent and temporary physical barriers. The research involves three academic institutions: the University of Brescia, Politecnico di Milano, and the University of Modena and Reggio Emilia, each contributing to different aspects of the project. Central to the methodology is the use of Handheld Mobile Laser Scanners (HMLS) for acquiring dense and accurate 3D point clouds of Mantua’s historic core. Data collection strategies were optimized for minimal urban disturbance, and the acquired datasets underwent classification and feature extraction to identify accessibility-related elements such as sidewalks, pole-like structures, trash cans, and covered areas. A semi-automated workflow was developed to extract geometric parameters and convert them into GIS-ready layers. These layers were integrated with municipal and open-source datasets into a comprehensive GIS platform, supporting multi-criteria analysis and accessible path planning. Preliminary results confirm the suitability of HMLS for urban surveys and highlight the importance of integrating manual refinement with algorithmic processing to handle class-specific segmentation. The findings reinforce the value of Geomatics in supporting inclusive urban planning, offering a replicable framework for other historic cities seeking to enhance accessibility through digital and spatial analysis. Future developments will expand the GIS database and explore AI-based solutions for dynamic accessibility management.

1. Introduction

Inclusivity is a fundamental principle of today's society and, as such, it is recognized at multiple levels, national and international. The United Nations, in its Agenda 2030, places inclusiveness, for example, among its sustainable development goals; in particular, Goal 11 sets out to "Make cities and human settlements *inclusive*, safe, resilient and sustainable".

Inclusivity can have different declinations and targets, and concern physical or sensory aspects of individuals dealing with private or public spaces. Each of these declinations requires specific study in identifying the most appropriate solutions. However, at the methodological level, there is a common need to start from recognizing individual needs and verifying the surrounding environment to determine its strengths or weaknesses. This second operation can be conducted in various ways, ranging from site inspections by professionals to crowd-based approaches, where the entire population is involved. It is necessary, however, that this first analysis of the environment be as free as possible from subjective opinions and interpretations. This means, to some extent, looking for systems to measure and inventory, in the most objective terms, the characteristics of the environment concerning inclusiveness.

In this research context, Geomatics can play a fundamental role as it allows for the acquisition of data -mostly geometric- with known characteristics (i.e. accuracy and reliability) and, through further processing (e.g., algorithms), the estimation of additional parameters which could be directly related to the general topic of accessibility. These indicators/parameters form the basis for all subsequent evaluations and assessments aimed at designing accessibility. Even more importantly, they contribute to the creation of a database that is useful for drafting urban planning tools intended to promote inclusivity and reduce barriers.

Within this framework, the nationally recognized research project PRIN 2022, titled "*ACROSS: A static and dynamic database for historic urban contexts accessibility*", is funded by the Italian Ministry of Education, University, and Research. This project, involving three research units (the University of Brescia, Politecnico di Milano, and the University of Modena and Reggio Emilia), focuses on historic urban centers, aiming to combine the inclusivity of public spaces with the possibility for everyone to access the historical and cultural values of the historical centre.

This paper describes some recent advancements of this project focusing particularly on the Geomatics methods and approaches exploited to reach the project’s goals. The paper is organized as follows: Section 2 presents related works to the topic of managing urban accessibility through Geomatics; the research project is described in detail in section 3, focusing on the parameters/indicators that should be computed from the point cloud to support the decision-making process. The following section 4 addresses the topics of public space digitization and data processing up to the extraction of some parameters’ values. Section 5 presents the results, while Section 6 sets up the discussion and draws out conclusions.

2. Related works

Physical accessibility in urban environments is a topic if great interest, which was investigated by several authors and with various approaches. Regarding Geomatics approaches typically researchers exploit point cloud or GIS-based analysis to reach the purposes (Balado et al., 2019; Stefanidi and Bartzokas-Tsiompras, 2024), and usually focus on sidewalks and pedestrian-related paths. When referring to modern urban environment, typically, the accessibility assessment could pass through curbs and ramps detection on sidewalks (Ishikawa, Kubo and Amano, 2018; Che, Olsen and Turkan, 2024). Instead, when referring to historic cities, where standard objects are not the rule, and where curbs are not always present, pedestrian areas have less standard feature, requiring more specific approaches (Treccani et al., 2023).

Several instruments and techniques could be used to gather useful data for further processing. Some researcher investigated the possibility given by airborne point clouds (Song et al., 2023), or using aerial images (Hosseini et al., 2022), or exploiting smartphone point clouds (Meng et al., 2025), or even using street view images (Ning et al., 2022). Within this context the possibility given by portable mobile mapping system, or handheld mobile laser scanners (Jurado et al., 2024) remain to be studied.

Regarding data processing, lastly, many approaches involve the classification of point clouds and of urban ground elements exploiting machine learning methods (Hou and Ai 2020; Halabya and El-Rayes, 2020) and exploiting tailormade workflows which involve the use of various techniques and data processes methods (Xia et al., 2024; Zhou et al., 2024; Luaces et al., 2021; Treccani et al., 2023).

3. Project "ACROSS: A static and dynamic database for historic urban contexts accessibility"

The project focuses on building a database that collects and organizes both obstacles and limiting elements that characterize the physical accessibility of historic centers. The approach is primarily at the urban scale, aiming to create a tool that not only supports the owners and managers of cities or cultural heritage sites but can also be used by all city users, particularly in historic centers. The project integrates contributions from various disciplines, including architectural design, restoration, technical architecture, Geomatics, and computer vision (Arenghi et al., 2025). This multidisciplinary approach is essential to define key aspects of accessibility within the highly specific context of historic built environments.

The research tasks are divided among the three university units involved. The University of Brescia is responsible for the theoretical definition of parameters, including both accessibility and cultural aspects (e.g., Treccani and Marconcini 2022). The University of Modena and Reggio Emilia focuses on the use of real-time data (Parascandolo et al., 2025), such as security camera footage from historic centers. Through artificial intelligence and anomaly detection algorithms, these data help identify temporary obstacles that may appear after the initial 3D model acquisition phase. The Politecnico di Milano unit is in charge of digitizing the built environment and extracting parameters from the point cloud, and subsequently developing a GIS platform, integrating the extracted parameters into the cartographic system.

The case study chosen for the research project is the historic urban center of Mantua, which is an interesting case for several reasons. Mantova was declared in 2008 by UNESCO to be a World Heritage Site. The urban center is rich in cultural heritage from different eras, and it includes various scenarios typical of historic cities. Furthermore, from a formal point of view, Mantua is currently being studied extensively in terms of accessibility, both because a plan to remove architectural barriers (in Italian: PEBA *Piano per Eliminazione Barriere Architettoniche*) is being developed by the municipality and because the Superintendency is conducting studies on urban accessibility. Both the municipality and the Superintendency have given their full support to the project.

4. Project phases

4.1 Digitization of historical urban context

The digitization of historic urban contexts is a well-established practice; however, it requires specific considerations depending on the survey's objectives, particularly in the selection of instruments and techniques. This is especially relevant today, as Geomatics offers a wide range of possibilities.

The survey scale of this project falls between architectural and urban levels, approximately 1:100, where the geometric tolerance is around 2 cm. This value appears compatible with certain threshold values we have to take in consideration for accessibility purposes, such as the height of a step (intended as vertical obstacle). Other accessibility-related features, such as the height of joints between pavement tiles, require a definitively higher precision of the survey instruments and do not fall within this survey. Other key requirements for digitization include the ability to perform rapid data acquisition, the capability to capture not only geometric information but also color, and, finally, the possibility of georeferencing data within a known reference system.

Many instruments can achieve these results, but sensor integration and the need to streamline the process make mobile laser scanners the most commonly used tools, particularly handheld or backpack-mounted models. However, Global Navigation Satellite System (GNSS) receivers do not always provide reliable data throughout the entire acquisition process due to the well-known challenges of historic city centers (where urban canyon-like scenes are very common, and consequently it is common to have a loss of signal). For this reason, georeferencing is often postponed to a later stage or performed using alternative methods.

Based on these requirements, several Handheld Mobile Laser Scanner (HMLS) were identified and tested in urban settings for the project's purposes. Among these: Stonex X70 GO, Stonex X120, Emesent Hovermap, Geoslam ZEB Horizon. Other digitization approaches were excluded, at least for the time being. Among them, drone-based photogrammetry would be particularly interesting to test; however, logistical challenges related to operating in historic city centers make its implementation complex.

The area of Mantua identified for the tests includes the pedestrian and vehicular routes and the square areas from the train station to the heart of the historic centre. The survey of these areas was carried out in several stages, trying to carry it out at times when the presence of people and other fixed or mobile obstacles (e.g. bicycles, cars) was as low as possible.

However, it should be noted that a presence of ‘noise’ from such situations is always present, even when surveying in the early hours of the day. All the instruments mentioned above were used to carry out the survey, in some cases providing complete overlapping of areas (e.g. Piazza Alberti in the historic centre was surveyed by all instruments) and in other cases using only one system.

In all cases, we tried to keep spit the area to be surveyed into small acquisition missions (a few hundred metres), ensuring a survey mission consisting of several loops to aid in the correct reconstruction of the trajectory, and measuring a series of Ground Control Points (GCP) with a GNSS receiver to ensure the correct georeferencing of the surveyed data. The GNSS receiver used was the Leica GS18 connected in RTK to the HxGN SmartNet network. A data overlap was always guaranteed between one acquisition mission and the next one. For the surveys with Stonex X 70 GO and X120, colour data was also acquired, while for the surveys with Emesent Hovermap and GeoSlam Zeb Horizon, only the Intensity value was acquired.

4.2 Parameters extraction and GIS layers production

The second phase of the project involves the semi-automatic process to extract meaningful accessibility features and parameters from the point cloud data. The main steps of this phase could be summarized as follows:

1. Data annotation: exploiting manual annotation and Machine Learning based algorithms the original point cloud data are classified according to urban-level classes;
2. Parameter extraction: a sequence of custom-made algorithms that allow to identify specific elements and features within the classified point cloud (e.g., sidewalk geometric features, obstacles, shadow areas) and convert the retrieved pieces of information into vector format stored in a shapefile;
3. Data visualization and exploitation: gathering all the data in shapefile format from previous step, and other useful data from existing dataset (e.g., from the municipality, national database, and open source database), and conveying them to a unique GIS project where it’s possible to perform further data analysis, generate useful visualizations, compute accessible paths and design urban changes.

As said, a preliminary step before defining additional algorithms is the classification phase. Classes were defined in order to both correctly represent the elements of urban areas and to identify useful elements for the project purposes (e.g., sidewalks). The selected classes are the following: unclassified, road, sidewalk, ground (including man-made and natural ground), building, pole-like element (traffic sign, pole light), barrier (including bollards and short walls), signboard, trash can, shelter, bench, pedestrian, car, vegetation (low and high). To reach the purpose, datasets were firstly manually annotated, with the double purpose of both producing a Groud Truth (GT) to assess the accuracy of automatic classification approaches and to produce a reliable dataset to use for further steps of the procedure. About the automatic classification, the primary focus was on assessing whether commercial classification software could be helpful to the purpose. Given the specificality of the defined classes, automatic classification on commercial software is not straightforward possible, and require a manual refinement of the firstly segmented classes. Following this approach we have used Leica 3D Reshaper engine to classify the data and refined manually the result. The development of custom-made approaches to classification, including the development of a Deep Learning model is currently still under investigation.

The automatic extraction of features from the point cloud was initially carried out following a method previously developed by the authors of this research. Thanks to this method (Treccani et. al, 2023), it was possible to calculate geometric characteristics of sidewalks, such as their width, longitudinal and tangential slopes, height of the sidewalk relative to the road, and paving material. The previously mentioned method is based on the use of data from mobile mapping systems mounted on cars and thus with trajectories coincident with the center of the road. In the case of these tests, HMLS were used with paths and trajectories that passed over sidewalks or partially over the road but not coincident with the center of the road. To overcome this problem, we manually identified fictitious trajectories within the city streets. The parameters related to the sidewalks were then calculated by dividing them into linear portions of 2-meter width along the sidewalk path. Sidewalk portions were converted into nodes and edges to generate a vector network which, together with sidewalk attributes previously computed, was georeferenced and stored within a shapefile.

Further processing algorithms were developed by python coding in order to extract and vectorize other meaningful data from the point cloud. Classified data was used directly for detecting and analyzing the location of benches, trash cans, and pole-like elements (e.e., light poles, street signs). These elements are helpful for accessibility management because if they are placed on the sidewalks or on pedestrian paths they could be obstacles to the movement also reducing the available width of the sidewalk itself. A method (schematized in Figure 1) was developed to analyze the point cloud using only the points belonging to one of those class. Starting from these points we isolated the individual elements (e.g., each trash can) by segmenting the point cloud according to the aggregation clusters of the points. Based on the fact that points belonging to the same trash can will be close to each other but far from points belonging to other trash cans we used the DBSCAN algorithm to segment points belonging to different clusters from each other. After that was done, and then the individual elements were identified, we proceeded to define the main dimensions of the element. To do this we identified the oriented bounding box and extracted its three dimensions, saved as an attribute and denoted as length 1, length 2, and height of the element. Finally, the geometric center of the element was used to generate a shapefile consisting of points; each point contained attributes such as the 3 dimensions in space and the class to which it belongs.

Then, another parameter considered useful for accessibility management is the identification of covered areas (by porches, gazebos, eaves or other elements). In order to identify these elements, it was decided to proceed similarly to what was done for shadowed areas by Balado et. al (2020). In our approach (Figure 2) the point cloud was divided into cells by creating a grid along the XY axes. The next steps were based on the characteristics of the cells. Since from the survey position (at human height and also walking inside the covered areas) it was possible to detect both the pavement and the element that creates a cover, only the cells that contain points both at ground level and at a higher level were selected. At this initial selection, cells were then further skimmed, going to select only those in which the elevation difference exceeded a value of 2 meters (assuming that the covered areas were above an elevation of 2 meters above ground level). The resulting cells were then used to make a Boolean intersection with the location of the footpaths. If the portion of the path lied within a covered area (at least for the 50%) it was identified as a covered path.

After having identified the city elements (of various types) and saved them in shapefile layers, it was decided to create a Geographic Information System (GIS) project in which to include all the elements useful for carrying out analyses and designs relevant to the project's objective: urban accessibility management. To create the GIS, the network of pavements with their respective attributes, the location of trash cans, benches, lampposts and road signs were included. Additional layers were also included, made available by the municipal administration, open-source data (e.g., OpenStreetMap), and other data made available by Regional and National authorities.

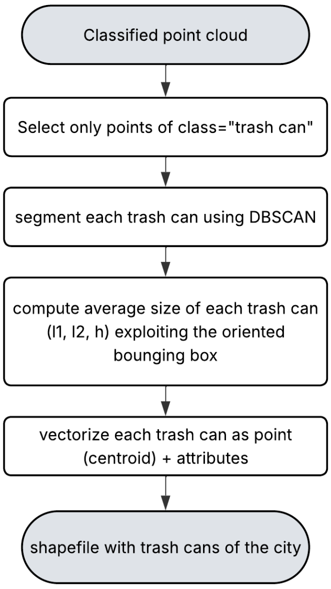

Figure 1. Scheme of the procedure used to extract and vectorize the position and attributes of benches, pole-like objects, and trash cans within the test dataset. In the scheme the class “trash can” is used as example.

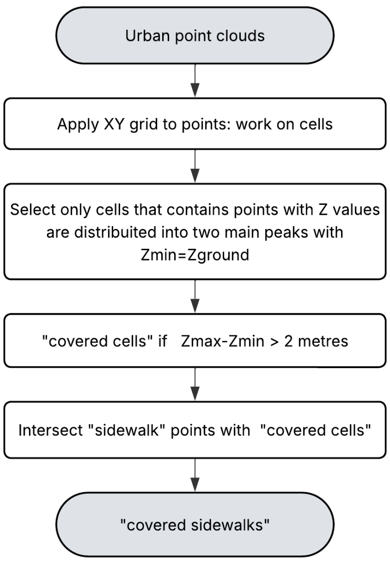

Figure 2. Scheme of the procedure used to identify covered areas within the urban point cloud, and covered sidewalks.

The GIS database thus created will become a relevant tool for urban planning and accessibility management. To this end, we are developing methods that allow the calculation of accessible routes within the city, developing Boolean operations that take into account the attributes of all shapefiles included in the project itself. We are also planning to calculate accessible routes with various levels of accessibility and adapted to the specific needs of potential users. Finally, this GIS will be used to implement urban regeneration projects aimed at improving the city's accessibility. These projects will benefit from analyses (also carried out using artificial intelligence) that take into account all the information included in the project.

5. First results of the project

Data acquisition was completed by carrying out various data acquisition campaigns over time, attempting to operate in the early hours of the day in order to minimize the presence of people and vehicles not involved in the operations, while still having good lighting conditions for the photographs taken with the instruments and for the colouring of the point clouds.

The resulting database consists of 12 point clouds georeferenced in the WGS84 UTM32N reference system (EPSG:32632). The total number of points is 1.1 billion, with an extent of approximately 2.9 linear kilometres of pedestrian paths surveyed. Additional information on the point clouds is given in Table 1, while Figure 3 and Figure 4 show the point database inserted in QGIS with the distinction of the various sources and some views of the full point cloud. The main objects in the survey are pedestrian areas (pavements, crossings, and pedestrian squares), vehicular areas (roads), buildings, and other components of street furniture. Vehicles and people in motion are certainly sources of noise.

Instrument	N. of points	Attributes
Stonex X120	129 million	Intensity + RGB
Stonex X70 GO	551 million	Intensity + RGB
Emesent Hovermap	183 million	Intensity
Geoslam ZEB Horizon	228 million	Intensity

Table 1. Characteristics of the datasets acquired with the various HMLS used in this research

Figure 3. Map of the areas surveyed for the purposes of the project using various HMLS. In red data acquired by Stonex X120, in blue the ones acquired by Stonex X70 GO, in green the ones acquired by Emesent Hovermap, and in yellow the ones acquired by Geoslam ZEB Horizon. There is an overlapping area in the city where all instruments were used.

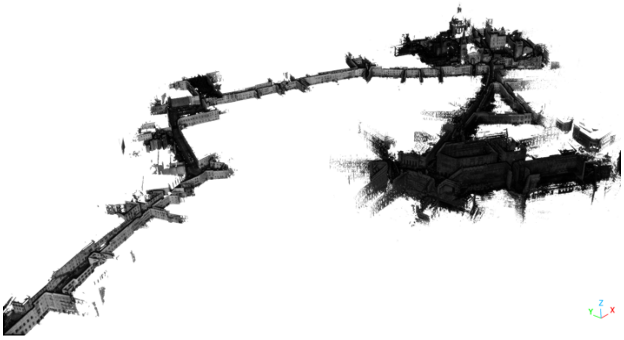

Figure 4. Full view of the point cloud dataset used within the project. Points are coloured according to Intensity attribute.

Since the project is still ongoing, and the data acquisition phase has just been completed, the subsequent data processing and shapefile generation phases were performed only on the data acquired with Stonex X120 (coloured red in Figure 3). In this regard, the sidewalks and their attributes were correctly identified, calculated for two-metre length portions, for a total of 550 segments. Then, the positions of trash cans, lampposts, and road signs were vectorised. In the calculation for the DBSCAN algorithm, Euclidean distance was used as a parameter and a threshold value of at least 10 points and a maximum distance of 0.5 metres were used to consider points in the same cluster for the “trash can” class, while a lower value (0.1 m) was used for the “pole-like objects” class to take into account situations with various distinct but close elements present in the dataset. There are no benches in the portion of the dataset analysed; while 18 trash can, 55 pole-like objects were correctly identified and stored into a shapefile together with their dimensional attributes. The result of these operations is shown in Figure 5.

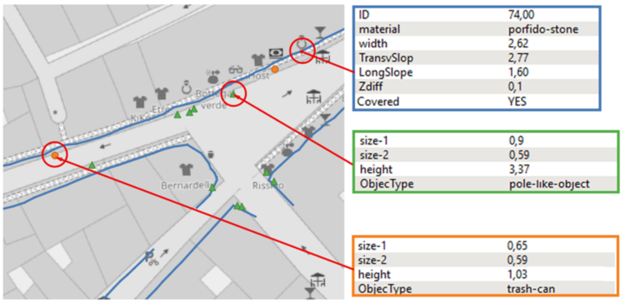

Figure 5. Some of the urban elements automatically identified and vectorized within the point cloud. It is possible to see the localization of sidewalks (blue lines) with some attributes (on the right) including width, longitudinal and transversal slope, covered areas, and materials. In the image it is also possible to see trash can position (orange circles), and pole-like elements positions (green triangles), together with their attributes.

The resulting shapefiles were then stored within a GIS project, together with other data coming from various sources. The data derived from the local Administrator (typically available for visualisation only on their webGIS, and provided on request for this project) contain: the location of points of interest and shops in the city, the location of bus stops, and parking areas with accessible parking spaces. Additional information was then added to the GIS project from open source datasets, such as OpenStreetMap (e.g., the location of all parking areas in general) and the Topographic GeoDatabase of the Lombardy Region (e.g., location of porticoed areas within the city). Figure 6 shows the GIS project developed within ArcGIS Pro.

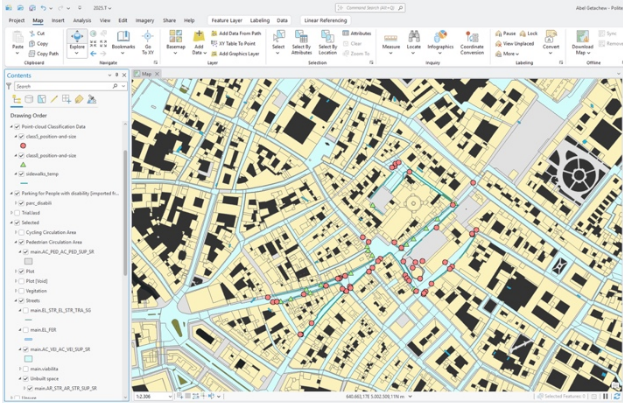

Figure 6. Screenshot from the ArcGIS Pro project were all the information extracted from the point cloud and vectorized into shapefile are stored (eg.,. sidewalk network position and attributes, trash can position and attributes, pole-like object position and attributes). The project also contains data from OSM (e.g., parking lots), local administration (e.g., points of interest and shops in the city, the location of bus stops, and parking areas with accessible parking spaces), regional administration (e.g., porches position and building footprint).

6. Discussion and Conclusions

In this article, we have reported on the first results of the ACROSS project, which are very promising. In this project, after defining the urban elements relevant to accessibility management, methods for surveying urban areas with HMLS systems were developed and tested, algorithms and procedures for extracting information from the point cloud and vectorising it were created, and a GIS platform was created with all the information collected, including data from other sources such as open-source databases and local authorities.

The tests conducted so far have shown that HMLS are suitable tools for surveying urban areas with centimetre-level accuracy, as in the case of the ACROSS project. These tools have proven to be fast in terms of survey execution and processing times. The tests conducted revealed that it is essential to divide the survey into many small acquisition missions (lasting about 10-12 minutes each), in which closed-loop trajectories were always guaranteed and in which a minimum of 3 GCPs were always measured, which helped in georeferencing and correctly reconstructing the trajectory. Processing the data with and without GCPs showed that the presence of GCPs helps to improve the accuracy of the final result, which is in the order of centimetres.

Furthermore, since the areas of interest in this project are urban pedestrian areas, the possibility of surveying while walking allowed data to be acquired by moving directly over them and therefore closer than with an MLS mounted on a car. The disadvantage of this approach is certainly the heavy presence of pedestrians, but by carrying out the survey at times when there are fewer people (e.g. early in the morning), this influx can be minimised.

As regards the classification of the point cloud, this project has shown that in the presence of very specific classes, a good approach consists of an initial automatic classification with more generic classes followed by manual refinement towards more specific classes. The procedures developed for identifying elements and vectorising them have also proved effective, above all because they are based on a reliable and accurate classification of the point cloud. The position of all elements in shapefiles guarantees the possibility of carrying out future analyses on this data, including mutual interference (e.g. which trash cans are obstacles to walking on the sidewalk?).

This study demonstrates that Geomatics is a discipline that can provide great support to accessibility management and increase urban accessibility in historic cities through point cloud processing and GIS-based approaches and analyses. Future phases of the project, in addition to the development of various analyses on GIS data, will include the identification and mapping of tactile paving routes and the identification of the state of maintenance of urban pavements. Future research could also provide an opportunity to compare various HMLS in terms of point density, ease of use, processing time, trajectory reconstruction correctness, and quality and accuracy of results.

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