remote sensing

MDPI

Article

Introducing SLAM-Based Portable Laser Scanning for the Metric Testing of Topographic Databases †

Eleonora Maset [1,*,‡], Antonio Matellon [1,2,‡], Simone Gubiani [1], Domenico Visintini [1] and Alberto Beinat [1]

1 Polytechnic Department of Engineering and Architecture (DPIA), University of Udine, Via delle Scienze, 206, 33100 Udine, Italy; matellon.antonio@spes.uniud.it (A.M.); gubiani.simone@spes.uniud.it (S.G.); domenico.visintini@uniud.it (D.V.); alberto.beinat@uniud.it (A.B.)

2 Department of Engineering and Architecture (DIA), University of Trieste, Via Alfonso Valerio, 6/1, 34127 Trieste, Italy

* Correspondence: eleonora.maset@uniud.it

† This paper is an extended version of our work Matellon, A.; Maset, E.; Visintini, D.; Beinat, A. Assessing the Quality of a Topographic Database using SLAM Technology: Proposal for an Operational Procedure. Published in Proceedings of the Italian Conference on Geomatics and Geospatial Technologies, ASITA, Padua, Italy, 9–13 December 2024.

‡ These authors contributed equally to this work.

Highlights

What are the main findings?

- The use of SLAM-based portable laser scanning for the metric testing of a large-scale topographic database is proposed and evaluated.
- Three approaches (*point-to-cloud*, *line-to-cloud*, and *line-to-line*) are implemented to compare the vector features of the topographic database with SLAM-based point clouds.

What are the implications of the main findings?

- SLAM-based surveys can complement, or even replace, classical topographic techniques, making quality control of topographic databases faster and more efficient.
- The use of SLAM devices in this domain opens new opportunities for verifying and updating cartographic products, with significant benefits in terms of cost and time.

Abstract

The advent of portable laser scanners leveraging Simultaneous Localization and Mapping (SLAM) technology has recently enabled the rapid and efficient acquisition of detailed point clouds of the surrounding environment while maintaining a high degree of accuracy and precision, on the order of a few centimeters. This paper explores the use of SLAM systems in an uncharted application domain, namely the metric testing of a large-scale, three-dimensional topographic database (TDB). Three distinct operational procedures (*point-to-cloud*, *line-to-cloud*, and *line-to-line*) are developed to facilitate a comparison between the vector features of the TDB and the SLAM-based point cloud, which serves as a reference. A comprehensive evaluation carried out on the TDB of the Friuli Venezia Giulia region (Italy) highlights the advantages and limitations of the proposed approaches, demonstrating the potential of SLAM-based surveys to complement, or even supersede, the classical topographic field techniques usually employed for geometric verification operations.

Keywords: topographic database; simultaneous localization and mapping; portable laser scanning; metric testing; vectorization

check for updates

Academic Editor: Giuseppe Casula

Received: 1 August 2025
Revised: 24 September 2025
Accepted: 25 September 2025
Published: 27 September 2025

Citation: Maset, E.; Matellon, A.; Gubiani, S.; Visintini, D.; Beinat, A. Introducing SLAM-Based Portable Laser Scanning for the Metric Testing of Topographic Databases. *Remote Sens.* **2025**, *17*, 3316. https://doi.org/10.3390/rs17193316

1. Introduction

Access to up-to-date geospatial data is essential to support sustainable development, risk assessment, resource allocation, and urban planning, ultimately contributing to the efficient and responsible stewardship of the territory. Nowadays, the demand for geospatial information is increasing, especially with the growing interest in 3D city models and digital twins—advanced tools that can significantly enhance urban management capabilities [1,2]. In order to furnish policymakers and planners with the information they require to make decisions that are both well-informed and reliable, it is imperative that the data meet rigorous standards of accuracy [3]. In this regard, official cartographic products released by public institutions hold particular significance, as their geometric and semantic accuracy is verified through strict testing procedures before they are published [4].

Geometric verification and formal quality controls are usually performed at distinct stages of map-product processing and require the collection of ground-truth datasets [3]. Thus, an independent survey must be conducted using technology capable of achieving a level of accuracy that significantly exceeds that of the data to be verified (at least 3 times higher [5,6]). For instance, to validate an aerial photogrammetric survey, a first control is applied to the raw images acquired, checking, among other things, along-track and across-track overlaps, as well as minimum and maximum image scales [7]. Subsequently, a verification of the bundle adjustment results is undertaken. To this end, a series of well-defined and uniquely identifiable checkpoints is typically measured using accurate topographic instruments, such as total stations and Global Navigation Satellite System (GNSS) receivers, in order to verify that the differences between the topographically measured coordinates and the photogrammetric ones comply with the tolerances established in the tender specifications [8]. In a similar manner, the vertical accuracy of Airborne Laser Scanning (ALS) surveys is quantitatively evaluated, as a general rule, by comparing the elevations of GNSS-measured ground checkpoints and the corresponding elevations obtained from the ALS dataset [9]. Point clouds acquired with a Terrestrial Laser Scanner (TLS) can also be employed as reference data. This approach was adopted, for example, in the evaluation of the vertical accuracy of the ALS survey as part of the digital twin project for the metropolitan area of Milan in Italy [4,10]. To verify the planimetric accuracy of ALS data, instead, some studies [6,11] proposed focusing on building roofs, comparing points obtained from the intersection of three roof planes, estimated from the ALS point cloud, with the corresponding photogrammetric-derived checkpoints. Furthermore, Vosselman [12] used ridge lines of gable roofs to evaluate the relative planimetric accuracy among overlapping strips in part of the national ALS survey in the Netherlands.

Photogrammetric and ALS surveys are the primary sources for the production of a topographic database (TDB), namely a digital, vector-based three-dimensional topographic map in which physical features are modeled as georeferenced and topologically structured entities represented by points, lines, or polygons. Given these characteristics, the quality control of a TDB must be carried out across multiple levels. As underlined in [13], the first step is to evaluate the logical consistency of the data produced and ensure that it adheres to the logical schema defined a priori. This includes the verification of the geometric primitives used and the types of data stored in the database fields, the identification of potential anomalies in vector geometries (e.g., self-intersections, double vertices), and the assessment of topological consistency. While the initial testing process can be executed automatically on the entire TDB using appropriate verification algorithms, the second level of quality control necessitates field surveys and the acquisition of a reference set to validate the accuracy of the geometric information contained in the TDB, verifying that the discrepancies with respect to the ground truth comply with the requisite tolerances. In this context, the most common approach relies on checkpoints selected for their distinctiveness and the ease with which they can be identified and measured. The coordinates of the vertices of the geometric features in the TDB are then compared with the checkpoint coordinates that have been directly measured in the field using traditional topographic techniques [13,14]. Despite the fact that this testing procedure is highly reliable and has been extensively adopted, it is evident that the method is not without its drawbacks. The process of ground-truth data acquisition is indeed notably time-consuming, which necessarily limits the number of samples that can be verified.

It is therefore worthwhile to explore an alternative surveying method that is both efficient and capable of providing a level of accuracy suitable for the metric testing of a topographic database. Portable Laser Scanners (PLSs) based on Simultaneous Localization and Mapping (SLAM) technology have the potential to fulfill this function, as they allow for complete and rapid mapping of the surrounding area simply by walking through it, even in GNSS-denied environments [15]. Nowadays, these systems are applied in a variety of fields, including industrial sites, confined spaces, and, more generally, complex environments such as caves and mines [16,17]. Moreover, due to their compactness and ease of use, PLSs can be used in outdoor scenarios [18], ranging from forest inventory to cultural heritage documentation [19,20], frequently in conjunction with other geomatics techniques to achieve a multi-scale and multi-sensor approach [21–23]. Introduced to the market in the early 2010s, first-generation SLAM instruments offered positional accuracies typically ranging from a few centimeters up to 10 cm. Nonetheless, the data acquisition process was subject to considerable drift over long trajectories and high noise levels, constraining the spatial resolution and geometric reliability of the resulting point clouds [24–26]. The recent evolution and improvement of sensors and SLAM algorithms have led to the availability of commercial systems capable of guaranteeing higher performance [27,28].

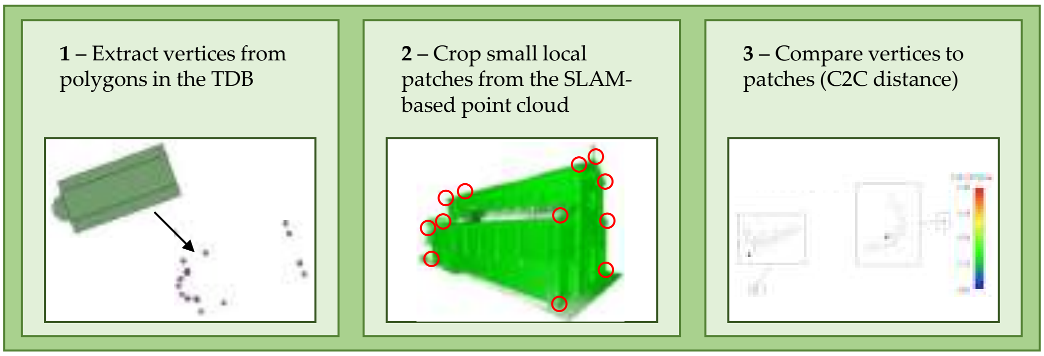
As previously noted, in line with the rule set forth in [5,6], geometric verification procedures require an independent survey conducted with instruments that can achieve an accuracy at least threefold greater than that of the data under evaluation. In this context, SLAM devices, which ensure precision and accuracy appropriate for representation scales of 1:100–1:200 [29–31], fulfill the requirements for verifying three-dimensional topographic databases at scales of 1:1000–1:5000, as the accuracy of SLAM data is approximately one order of magnitude higher than that of the TDB.

In light of the aforementioned aspects, this paper suggests the use of portable laser scanning systems for acquiring point clouds that can serve as reference datasets in the implementation of formal quality control procedures. To enable a comparison between the vector features of the TDB and the SLAM-derived point cloud, three distinct operational procedures are proposed (Figure 1) and critically examined:

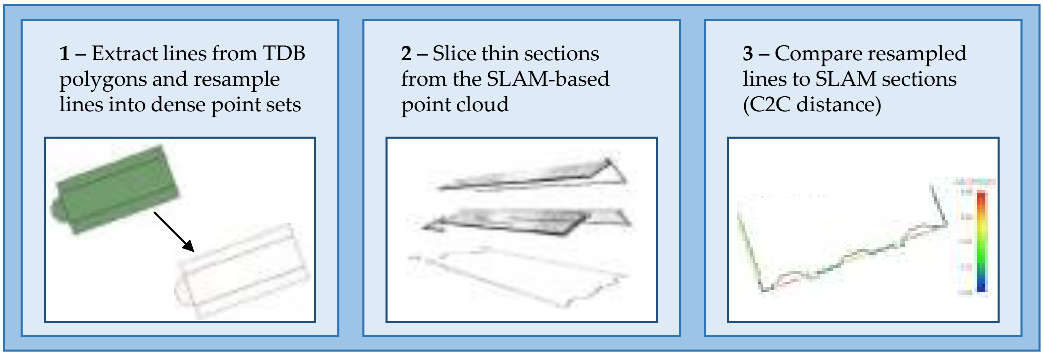
1. *Point-to-cloud* comparison: At each geometric vertex of a given TDB object, local patches are extracted from the SLAM-based point cloud and compared with the corresponding coordinates stored in the TDB.
2. *Line-to-cloud* comparison: Sections of the SLAM-based point cloud corresponding to the object of interest are isolated and analyzed in relation to the lines representing that object in the TDB.
3. *Line-to-line* comparison: Lines are vectorized from the SLAM-based point cloud and then evaluated against the corresponding linear features in the TDB.

The contributions of this paper are twofold. First, it demonstrates that point clouds acquired using SLAM devices can be effectively employed for the metric validation of large-scale topographic databases. Second, it goes beyond traditional validation methods based solely on checkpoint coordinate comparisons by considering complete vector geometries and implementing line-to-line comparison techniques.

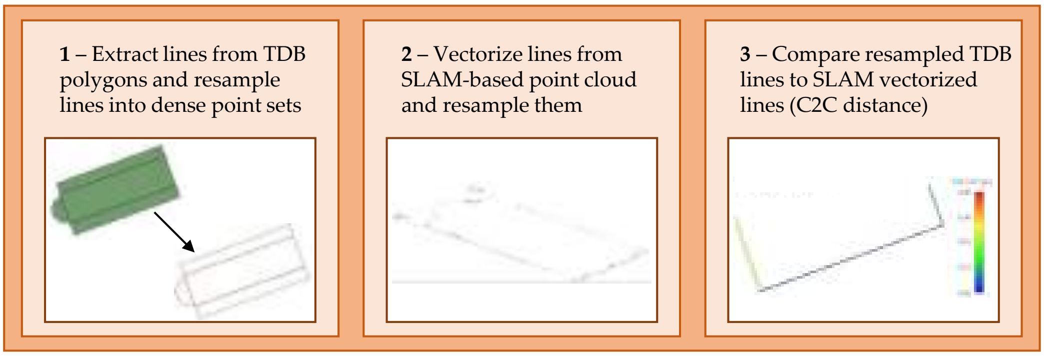
This paper is organized as follows. Section 2 describes the proposed approaches for the metric testing of a TDB (Section 2.1), the case studies used to validate the methods (Section 2.2), and the SLAM data acquisition process (Section 2.3). The results are reported in Section 3, while Section 4 provides a critical discussion of the developed procedures, highlighting advantages and limitations with respect to traditional topographic methods usually applied in this context. Finally, Section 5 presents the conclusions and suggests future research directions.



(**a**) *Point-to-cloud*



(**b**) *Line-to-cloud*



(**c**) *Line-to-line*

Figure 1. Graphical overview of the three operational procedures employing SLAM-based point clouds as reference data to evaluate the metric quality of a three-dimensional topographic database.

2. Materials and Methods

2.1. Proposed Approaches

The testing approaches outlined in this paper leverage the strengths of SLAM systems, transcending conventional point-to-point comparisons between the three-dimensional coordinates derived from traditional topographic surveys and the corresponding vertices of database objects. Indeed, using a SLAM-based dataset as the ground truth provides considerable methodological flexibility when evaluating a TDB, offering several possibilities for comparing the reference and evaluated sets.

The following sections provide a comprehensive description of each proposed methodology, with particular emphasis on the key procedural steps. While the implementation details and specific software tools used in the case studies are also described, it is important to note that alternative software solutions may be equally applicable. Moreover, it is assumed that the geometric features in a topographic database are generally represented as polygons—composed of line segments defined by vertices—whereas the SLAM data are provided as a point cloud, in which each point is associated with three spatial coordinates (x, y, z).

2.1.1. *Point-to-Cloud* Comparison

The first proposed testing approach, summarized in Figure 1a, aims to compare the vertices of the geometries contained in the TDB with the corresponding portions of the analyzed objects represented in the SLAM-based point cloud. Assuming that the vector features in the database are modeled as polygonal elements, the initial step consists of extracting all vertices that define these polygons. For the purpose of comparison, manually identifying a single corresponding point within the SLAM-based dataset is not feasible, as the point cloud acquired using a PLS is discrete and, although relatively dense, lacks continuity. Consequently, a small subset of points—referred to as a patch—is extracted from the point cloud in the neighborhood of the object part under evaluation. Finally, the spatial discrepancy between the compared entities—a vertex and the corresponding point cloud patch—is quantified through a Cloud-to-Cloud (C2C) distance measurement, with the SLAM-derived point cloud serving as the reference dataset, i.e., the ground truth acquired in the field. The patch extraction process is performed manually to avoid erroneous correspondences that could arise from applying a C2C analysis between all database vertices and the entire point cloud. In this context, manual patch selection is functionally equivalent to the identification of checkpoints in conventional validation procedures.

From an operational standpoint, vertex extraction from polygonal features can be efficiently performed using the dedicated *Extract Vertices* command within the *Geometry Tools* implemented in the QGIS software environment (v. 3.40.0 Bratislava) [32]. Furthermore, the extraction of small patches from the point cloud, along with the C2C comparison between the TDB vertices and the SLAM-derived data, is carried out using the open-source software CloudCompare (v. 2.14.alpha) [33].

2.1.2. *Line-to-Cloud* Comparison

The second approach involves assessing the distance between the linear features that define object boundaries in the topographic database and the corresponding points from the PLS-derived point cloud. As illustrated in Figure 1b, the workflow begins by converting the polygonal features of the TDB into their perimeter lines. Subsequently, cross-sections (slices) of the SLAM-based point cloud are extracted along the edges of the objects, enabling direct comparison between the vector lines and the reference dataset. To compute the distances between the linear geometries and the point cloud, each line is resampled into a dense set of discrete points. This transformation allows the analysis to be framed as a C2C distance computation.

In this case as well, the initial extraction of linear features can be carried out using QGIS. Since this operation typically generates a single polyline for each object, it may be beneficial to explode the polyline into individual line elements. This segmentation enhances the level of control during the subsequent analysis phase, particularly by allowing for the selective exclusion of lines lacking corresponding SLAM points—for example, in occluded areas where the reference point cloud is incomplete. To cut out relevant slices from the SLAM-based point cloud, a software capable of handling sectional views, such as Autodesk ReCap Pro (v. 25.1.1.317 2024) [34], is employed. The subsequent conversion of vector lines into dense point representations is performed in CloudCompare using the *Sample Points* function. Based on preliminary experiments, a sampling density of 100 points per meter was adopted to ensure adequate spatial resolution. Finally, C2C distance calculations are also conducted within the CloudCompare environment.

2.1.3. *Line-to-Line* Comparison

The third proposed testing methodology (Figure 1c) is based on a line-to-line assessment. In this case, the two elements under evaluation are the linear geometries extracted from the topographic database and the lines derived through a vectorization process applied to the SLAM-based point cloud. Initially, the object boundary lines are extracted from the TDB, as described in Section 2.1.2. Vectorization then involves the manual reconstruction of geometric features by snapping line segments to the SLAM-derived point cloud. This operation is carried out in Autodesk AutoCAD (v. 154.0.0 2025) [35], either directly on the full point cloud or, preferably, on sectional slices, to enhance precision and facilitate the digitization process.

Following vectorization, the procedure aligns with the previously described *line-to-cloud* approach. Specifically, both the TDB features and the vectorized lines are converted into high-density point sets through resampling, enabling a C2C distance analysis. In this case, the vectorized lines—aligned with the SLAM-based point cloud—serve as the reference dataset for comparison.

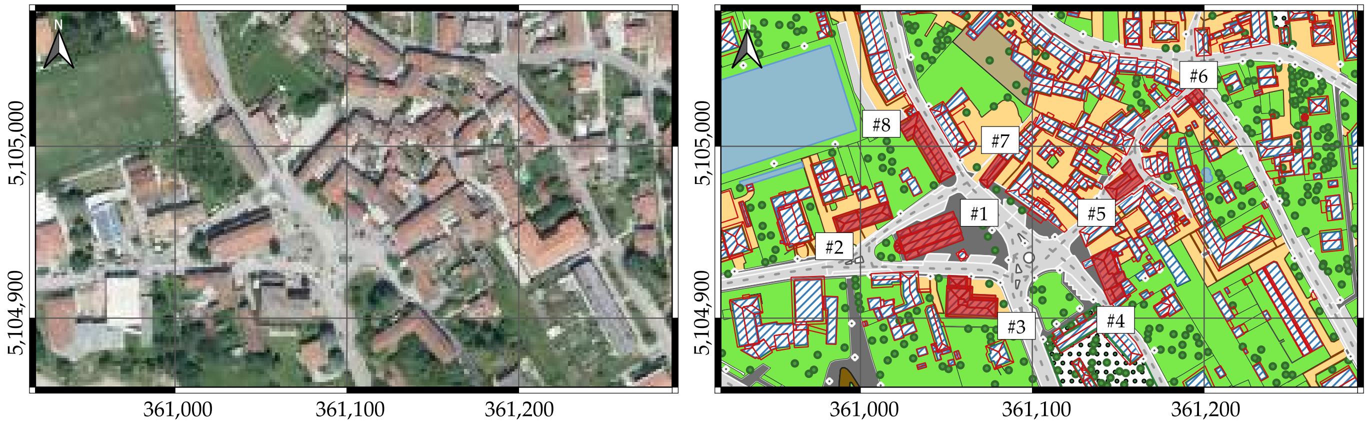
2.2. Study Areas

The assessment of the proposed testing approaches was conducted within two study areas located in the municipality of Udine, in the Friuli Venezia Giulia region of northeastern Italy. In 2017, the regional administration of Friuli Venezia Giulia initiated an extensive geospatial mapping program aimed at updating the territorial spatial datasets and associated cartographic products. As a foundational phase of the project, comprehensive ALS, photogrammetric, and hyperspectral imagery surveys were carried out across the region, covering approximately 7900 km^2. These acquisitions resulted in the production of several high-resolution geospatial layers, including a Digital Terrain Model (DTM), Digital Building Model (DBM), and Digital Surface Model (DSM), each with a spatial resolution of 50 cm/pixel. Furthermore, true orthophotos with a resolution of 10 cm/pixel and orthorectified hyperspectral images at 1 m/pixel were generated. For additional technical details, see [36].

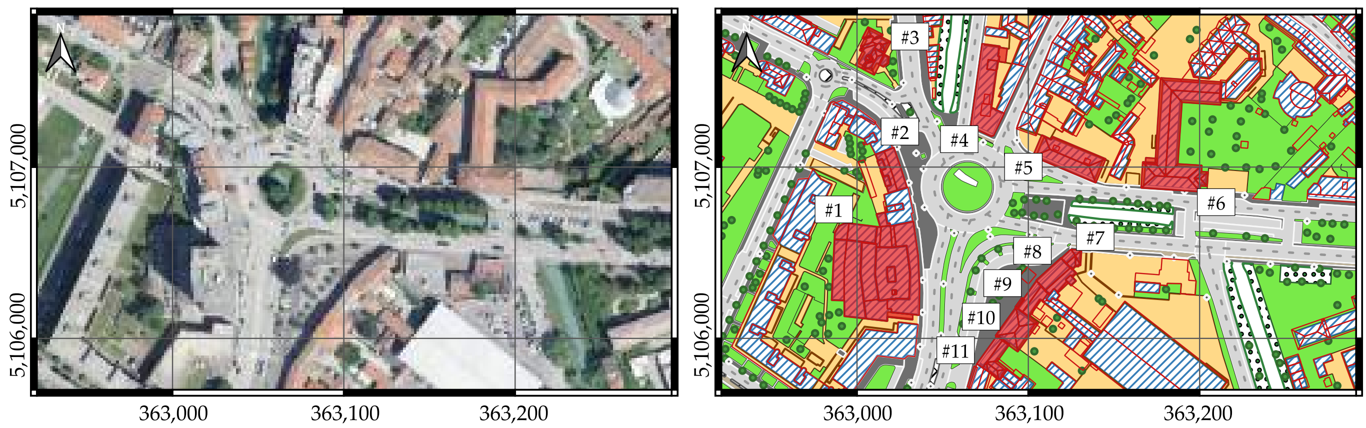
Of particular relevance to this study is the ongoing effort to modernize the regional technical cartography through the development of an updated, structured three-dimensional TDB. Currently, this database has been implemented for the main urban centers within the region and is available at varying cartographic scales—1:1000, 1:2000, or 1:5000—depending on the spatial complexity and planning requirements of each area. The database architecture complies with the specifications outlined in the Italian Ministerial Decree of 10 November 2011, "Technical rules for the definition of the content specification of the geotopographic databases", which adopts the GeoUML conceptual modeling methodology and aligns with ISO/TC211 international standards for geographic information [37]. The database is hierarchically structured: individual feature classes (i.e., homogeneous groups of spatial entities sharing attributes and behavior) are grouped into thematic categories, which are in turn organized into higher-level layers. For example, the feature classes *Natural Watercourse*, *Channel*, and *Water Pipeline* are categorized under the *Hydrographic Network* theme, which constitutes one of the thematic components that comprise the broader *Hydrography* layer [36].

All newly produced cartographic datasets are accessible through the regional geoportal *Eagle.fvg* [38], where they can be freely consulted and downloaded by the public, supporting transparency and data reuse in line with open data principles. Prior to publication, all data underwent metric testing and quality control procedures.

For this study, two test areas within the municipality of Udine were selected, each characterized by distinct spatial and urban features. The first site is the central square of the Rizzi district—hereafter referred to as *Piazza Rizzi*—located in the northern part of the city (46.083875°N, 13.203434°E). The area features a church with a bell tower and some older, predominantly low-rise buildings. It is situated in a peripheral part of the city, characterized by low population density and limited vegetation (Figure 2a). The second case study, *Piazzale Cella*, is located in the southern part of Udine (46.055085°N, 13.229793°E). It is not notable for historical or architectural landmarks but functions primarily as a major transit hub. The area is characterized by some modern, multi-story buildings and dense roadside vegetation, which significantly obstruct visibility across the square (Figure 2b).



(**a**) Study area 1—*Piazza Rizzi*.



(**b**) Study area 2—*Piazzale Cella*.

Figure 2. Orthophoto (**left**) and top view of the topographic database (**right**) of the two study areas within the municipality of Udine. The buildings selected for the validation of the proposed testing approaches are depicted in red. Coordinates are expressed in the cartographic reference system RDN2008/UTM zone 33N (EPSG:6708).

For the municipality of Udine, the TDB was developed at a scale of 1:2000 and is distributed in *shapefile* format, with each feature class provided as a separate file. While the proposed testing procedures are, in principle, applicable to all feature classes within the database, this paper focuses on two specific classes selected for their particular significance and frequent use in traditional topographic validation: *Building Volumetric Units*—defined as elementary, homogeneous building volumes—and *Roofing Elements*, which encompass the various components of a building's roof structure, such as pitches, terraces, domes, and similar features. Given that the entities in the *Building Volumetric Units* class are not fully three-dimensional—each is modeled as a horizontal polygon positioned at the elevation of the building's foot—only a planimetric accuracy evaluation was carried out for this class. Conversely, the *Roofing Elements* class comprises inherently three-dimensional features, allowing for the assessment of both horizontal (planimetric) and vertical (altimetric) accuracy.

As illustrated in Figure 2, the testing procedures were implemented on 8 buildings located in the *Piazza Rizzi* area and 11 buildings in the *Piazzale Cella* site. The buildings were selected to ensure a balanced spatial distribution across the sites and to capture a representative variability in terms of geometry, scale, and intended use.

2.3. SLAM Data Acquisition and Validation

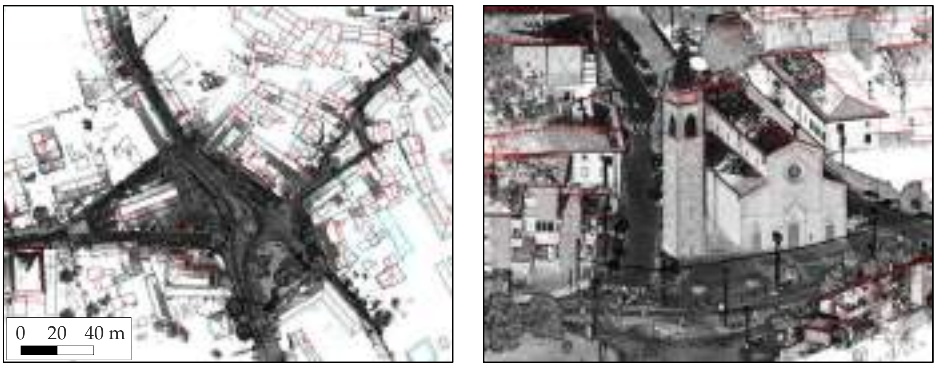
The instrument utilized to acquire the ground-truth three-dimensional surveys of the study areas was the Stonex X120^{GO} (Stonex srl, Paderno Dugnano—Milan, Italy) [39], a portable laser scanning system based on SLAM algorithms (Figure 3a). The device is equipped with a Light Detection and Ranging (LiDAR) sensor performing a dual rotation: around its own axis, guaranteeing a data acquisition field of 360° horizontally, and around a second inclined axis, which allows it to record a band of points with a width of 270° vertically. The instrument's extreme versatility allows for an acquisition rate of approximately 320,000 points/s, within a range of distances from 0.5 m to 120 m. The measurement precision, as specified by the manufacturer, is 6 mm, while the overall accuracy is on the order of a few centimeters [31], making the device potentially well-suited for applications such as the validation of topographic databases. The PLS is also equipped with three RGB cameras, each with a resolution of 5 megapixels, allowing the simultaneous capture of three photos per shot. These images are used to assign color information to the points acquired by the laser scanner sensor.

(**a**) Stonex X120^{GO} with RTK module (**b**) Survey of *Piazza Rizzi*

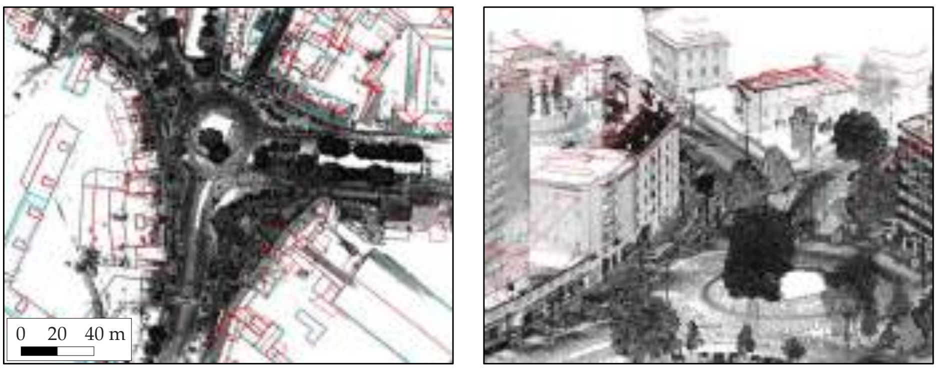
Figure 3. (**a**) The SLAM device (Stonex X120^{GO} [39]) used for reference data acquisition and (**b**) the operator during the survey of the first case study (*Piazza Rizzi*).

The PLS used in this study can also be operated in conjunction with a GNSS module. This module, which connects to the laser scanner via Bluetooth, is capable of receiving signals from all four major GNSS constellations: Galileo, BDS, GLONASS, and GPS. The main advantage of this module lies in its ability to directly georeference the SLAM-based point cloud using GNSS signals. This georeferencing process can be performed even if GNSS data are available for only half the duration of the survey, which is sufficient to ensure accurate positioning. Moreover, the system supports real-time connectivity to regional permanent GNSS networks, enabling the use of Network Real-Time Kinematic (NRTK) positioning for enhanced spatial accuracy.

For the first study site (*Piazza Rizzi*), the field survey (Figure 3b) lasted approximately 20 min, following a trajectory of about 1.1 km. The subsequent post-processing phase, conducted using the dedicated GOPost (v. 74) software [40], required 50 min. Similarly, the second study area (*Piazzale Cella*) involved a 20-min survey along an 800 m trajectory, followed by 35 min of office-based post-processing. In both cases, post-processing was conducted using a workstation Intel(R) Xeon(R) w5-3435X CPU @3.10 Ghz (Intel, Santa Clara, CA, USA) , equipped with 256 GB RAM and two Nvidia GeForce RTX 4080 Super 16 GB GPUs (NVIDIA, Santa Clara, CA, USA). The final point clouds consisted of 151 M points for the first case study (Figure 4a) and 103 M points for the second site (Figure 4b), respectively. Prior to applying the testing procedures, the buildings selected as samples were isolated from the full point cloud, enabling analysis on more manageable subsets. Both SLAM datasets were georeferenced correctly in the same reference system as the topographic database (EPSG:6708), thanks to the NRTK connection to the regional permanent GNSS network "Antonio Marussi".



(**a**) *Piazza Rizzi*



(**b**) *Piazzale Cella*

Figure 4. Top view (**left**) and three-dimensional view (**right**) of the SLAM-derived point clouds for the two study areas. Vector geometries from the topographic database are overlaid, with *Building Volumetric Units* rendered in cyan and *Roofing Elements* in red. To enhance visual clarity, only the *Roofing Elements* are displayed in the three-dimensional view.

To corroborate the metric accuracy of the acquired point clouds and verify consistency with the instrument's technical specifications and literature-reported performance, an additional survey was carried out for both case studies. In this phase, checkpoints were collected using the Leica GS07 GNSS antenna (Leica Geosystems, Heerbrugg, CH, Switzerland), ensuring homogeneous spatial distribution across the study areas. The GNSS checkpoints were measured on flat, planar surfaces extending over sufficiently large areas and free from significant elevation variations. The comparison with the SLAM-derived point clouds was performed by calculating the elevation difference between each checkpoint and the closest point in the SLAM-based cloud, using the C2C function implemented in CloudCompare.

3. Results

The application of the three proposed testing approaches to the case studies yielded C2C distance values for each point in the evaluated sets, whether a database vertex or a point generated through line resampling, depending on the specific methodology. To properly assess the geometric accuracy of each polygonal feature in the database, cumulative statistics should be derived from the raw C2C analysis. As specified in the technical documentation of the Friuli Venezia Giulia TDB, in accordance with the Italian national guidelines [41], accuracy should be verified using the Root Mean Square Error (RMSE). For the planimetric component, the RMSE can be defined as follows:

$$\text{RMSE}_{xy} = \sqrt{\frac{\sum_{i=1}^{n}(x_{c,i} - x_{r,i})^2 + (y_{c,i} - y_{r,i})^2}{n}} \tag{1}$$

while the altimetric component is defined as

$$\text{RMSE}_{z} = \sqrt{\frac{\sum_{i=1}^{n}(z_{c,i} - z_{r,i})^2}{n}} \tag{2}$$

where $(x_{c,i}, y_{c,i}, z_{c,i})$ are the coordinates of the ith compared point (i.e., from the topographic database), $(x_{r,i}, y_{r,i}, z_{r,i})$ are the coordinates of the corresponding reference point (i.e., from the SLAM survey), and n is the total number of evaluated samples.

Before analyzing the outcomes of the metric assessment of the topographic database, it is essential to present the validation results of the SLAM-based point clouds for the two study sites. Table 1 shows the comparison between the SLAM data and the GNSS-measured checkpoints, reporting both the arithmetic mean and the RMSE_z values. The analysis produced RMSE_z values of 5.1 cm and 2.1 cm for the two study sites, respectively—figures that align with those commonly reported in the literature for elevation errors in point clouds acquired using portable laser scanning systems. Moreover, these values are an order of magnitude lower than the accuracy thresholds defined in the tender specifications for the geometric elements of a topographic database at a 1:2000 scale, which are set at 50 cm for planimetric accuracy and 40 cm for altimetric accuracy. Accordingly, the SLAM-derived point clouds can be considered validated and suitable for use as ground truth in the evaluation of the topographic database.

Table 1. Results of the accuracy assessment of the SLAM-based point clouds. The validation was carried out on a number of checkpoints by comparing the SLAM data with the corresponding GNSS-measured coordinates.

Study Area	Total GNSS Points	Mean$_z$ [m]	RMSE$_z$ [m]
Piazza Rizzi	7	−0.036	0.051
Piazzale Cella	8	−0.017	0.021

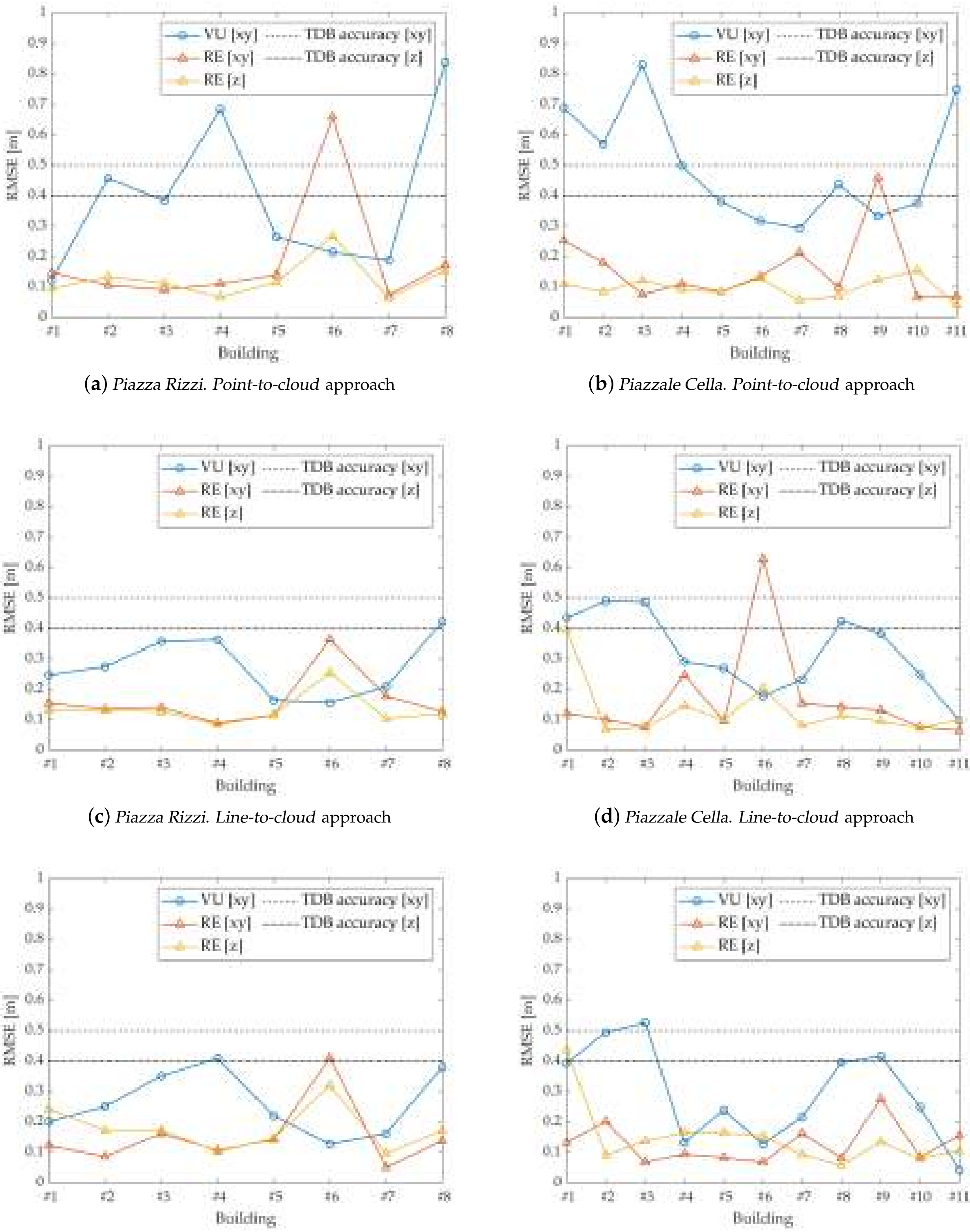
Turning to the results of the database verification, the RMSE values obtained for each building and each testing procedure are presented in the graphs in Figure 5. Overall, the majority of the analyzed *Roofing Elements* clearly met the required accuracy thresholds in both the planimetric (xy) and altimetric (z) dimensions. Moreover, the RMSE values produced by the three proposed approaches were largely consistent for this object class. In contrast, the results for the *Building Volumetric Units* exhibited more significant deviations from the SLAM-based reference data, although most still fell within the 50 cm threshold. Notably, the *line-to-cloud* and *line-to-line* approaches yielded outcomes that differed considerably from those of the *point-to-cloud* method, which identified 6 out of 19 buildings as exceeding the specified accuracy limits (Figure 5a,b).

When considering the aggregate results—computed across all buildings within each study site (Tables 2 and 3) and collectively for all 19 evaluated buildings (Table 4)—the high level of accuracy achieved for the *Roofing Elements* became more evident. Indeed, the combined aggregate $RMSE_{xy}$ metric (Table 4) ranged from 0.133 m to 0.201 m, corresponding to the *line-to-line* and *line-to-cloud* methods, respectively. These values are less than half of the 50 cm planimetric accuracy threshold specified in the tender. Similarly, the combined aggregate $RMSE_z$ values ranged from 0.109 m (*point-to-cloud*) to 0.198 m (*line-to-line*), remaining well below the specified limit of 40 cm. The accuracy with which the TDB objects of the *Building Volumetric Units* class were created was, instead, lower. The combined aggregate analysis showed that the lowest $RMSE_{xy}$ value, 0.312 m from the *line-to-line* method, was significantly higher than the results for the *Roofing Elements* class, yet it remained within the specified threshold. For completeness, it should be noted that the TDB polygons were vectorized from photogrammetric and ALS data with an accuracy suitable for producing a TDB at a 1:2000 scale, i.e., 10–20 cm. Considering additional random and gross errors that may arise during the vectorization process, the RMSE values observed in the assessed TDB features are consistent with expectations.

Furthermore, it is worth noting that the aggregate results showed strong agreement among the three proposed methodologies for the *Roofing Elements* object class. The largest discrepancy was observed in the $RMSE_z$ values between the *point-to-cloud* and *line-to-line* approaches for the *Piazzale Cella* case, with values of 0.106 m and 0.209 m, respectively. A similarly high level of agreement was observed between the *line-to-cloud* and *line-to-line* methods when applied to the *Building Volumetric Units* class, with maximum differences in $RMSE_{xy}$ limited to 3.2 cm (Table 3). However, notable discrepancies arose when comparing these results to those obtained using the *point-to-cloud* approach. Specifically, this method yielded $RMSE_{xy}$ values approximately 10 cm higher for the *Piazza Rizzi* site (Table 2) and up to 20 cm higher for the *Piazzale Cella* site and the overall aggregated dataset (Tables 3 and 4), relative to the other two approaches. These differences were primarily due to the limited number of samples that could be assessed using the *point-to-cloud* methodology, as well as the presence of some database vertices affected by significant positional errors. This issue is further detailed and discussed in the following section.

Table 2. Aggregate results obtained using the proposed testing procedures for the *Piazza Rizzi* study area. The total number of points used in the RMSE computation is also reported.

	Volumetric Units		***Roofing Elements***		
	N. Points	**$RMSE_{xy}$ [m]**	**N. Points**	**$RMSE_{xy}$ [m]**	**$RMSE_z$ [m]**
Point-to-cloud	40	0.412	111	0.177	0.118
Line-to-cloud	49,945	0.315	104,589	0.145	0.124
Line-to-line	50,335	0.302	97,972	0.135	0.187



(**a**) *Piazza Rizzi. Point-to-cloud* approach

(**b**) *Piazzale Cella. Point-to-cloud* approach

(**c**) *Piazza Rizzi. Line-to-cloud* approach

(**d**) *Piazzale Cella. Line-to-cloud* approach

(**e**) *Piazza Rizzi. Line-to-line* approach

(**f**) *Piazzale Cella. Line-to-line* approach

Figure 5. Results of the three proposed approaches applied to the evaluated case studies. The abbreviations 'VU' and 'RE' refer to *Volumetric Units* and *Roofing Elements*, respectively. The planimetric and altimetric accuracy requirements specified in the tender for the geometric elements are indicated as 'TDB accuracy [xy]' and 'TDB accuracy [z]', respectively.

Table 3. Aggregate results obtained using the proposed testing procedures for the *Piazzale Cella* study area. The total number of points used in the RMSE computation is also reported.

	Volumetric Units		***Roofing Elements***		
	N. Points	**RMSE$_{xy}$ [m]**	**N. Points**	**RMSE$_{xy}$ [m]**	**RMSE$_z$ [m]**
Point-to-cloud	49	0.567	124	0.176	0.106
Line-to-cloud	46,966	0.353	83,370	0.254	0.197
Line-to-line	47,318	0.321	87,258	0.129	0.209

Table 4. Combined aggregate results of the proposed testing procedures for the *Piazza Rizzi* and *Piazzale Cella* study areas. The total number of points used in the RMSE computation is also reported.

	Volumetric Units		***Roofing Elements***		
	N. Points	**RMSE$_{xy}$ [m]**	**N. Points**	**RMSE$_{xy}$ [m]**	**RMSE$_z$ [m]**
Point-to-cloud	89	0.504	235	0.171	0.109
Line-to-cloud	96,911	0.334	187,959	0.201	0.160
Line-to-line	97,653	0.312	185,230	0.133	0.198

4. Discussion

All procedures employed in this study proved effective for validating a topographic database, demonstrating advantages in terms of operational efficiency and reduced survey time compared to traditional topographic techniques based on total stations. Whilst conventional topographic surveying offers a high degree of accuracy, it presents several limitations in environments characterized by complex morphologies, intricate architectural configurations, or dense, occluding vegetation. The need for real-time interpretation and on-site selection of discrete points introduces subjectivity and increases the risk of critical omissions, particularly in areas with limited visibility or spatial ambiguity. Once fieldwork is completed, any point of interest that was misidentified or not recorded is typically irrecoverable.

Conversely, PLS systems based on SLAM technology allow for the continuous and comprehensive acquisition of three-dimensional spatial data, as shown in Figure 4. This approach eliminates the need for prior selection of survey targets, as relevant geometric information can be extracted during post-processing from the resulting three-dimensional model. As a result, SLAM-based workflows demonstrate improvements in the completeness, reproducibility, and overall reliability of reference datasets, particularly in environments such as the two study areas examined in this work, where conventional techniques are limited by operational constraints or contextual complexity.

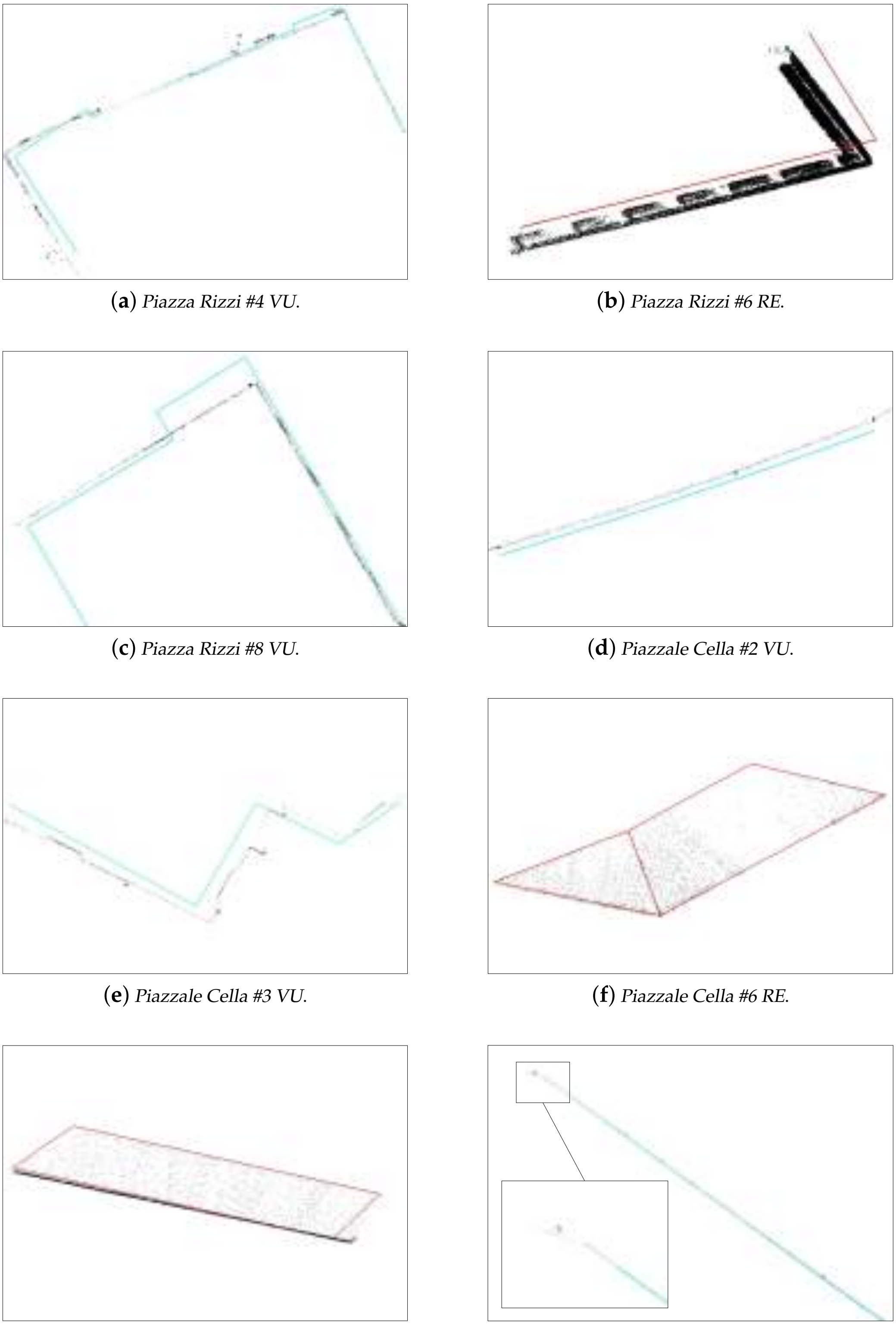
Among the advantages of using PLS instruments is the possibility of performing a straightforward and comprehensive qualitative assessment of geometric inaccuracies within the TDB. For example, Figure 6 illustrates the buildings with the highest RMSE values, either at the level of the *Building Volumetric Units* or within the *Roofing Elements*. By visually comparing the lines of the TDB objects with the SLAM-based point cloud, irregular shifts between the vectorized lines and their actual positions can be observed, as shown in Figure 6b,d–f. Shape inaccuracies of the TDB objects are evident in Figure 6a,c, while gross errors—where the vectorized lines of the TDB terminate several decimeters before the actual roof or building edge—are depicted in Figure 6g,h.

An in-depth analysis of each SLAM-based methodology proposed for the quality control of the topographic database reveals that each exhibits distinct strengths and limitations. As detailed in Section 3, the three approaches produced consistent results in most cases, demonstrating strong concordance in the metric evaluations. In other instances, however, notable discrepancies were observed—primarily due to the differing abilities of each method to manage complex geometric configurations. These divergences highlight the importance of assessing the suitability of each methodology and critically comparing their performance on a case-by-case basis. To illustrate this, Tables 5 and 6 present representative examples of agreement and disagreement among the three methods, respectively.

First and foremost, it is important to underline that the *point-to-cloud* methodology is the most closely aligned with conventional topographic validation techniques, which rely on the measurement of a limited set of reference checkpoints. However, this approach inherits many of the same limitations. In particular, the number of points that can be effectively compared is often very limited—either due to occlusions that reduce the visibility of building vertices or because of the complex and irregular geometry of the structures themselves. A relevant example is provided by the third case in Table 6, which refers to the *Volumetric Units* feature of Building #3 in *Piazzale Cella*. In this instance, the building's complex geometry and the presence of a surrounding perimeter wall hindered the complete acquisition of its lower portions. More critically, they prevented the accurate extraction of corresponding patches in the SLAM point cloud at the building-edge points, represented as polygon vertices in the topographic database. By contrast, the *line-to-cloud* and *line-to-line* approaches extended the assessment beyond discrete, well-visible features (i.e., vertices), facilitating the analysis of the full vector geometry. This enabled a more comprehensive and robust verification of overall metric accuracy by leveraging extended linear features—such as entire wall segments—represented as lines in the topographic database.

The constraints that characterize the *point-to-cloud* methodology not only reduce the spatial representativeness of the analysis but also increase the risk of skewing the overall deviation estimate due to the influence of a few localized outliers, which ultimately compromises the reliability and completeness of the validation process. A representative example is provided by Building #8 in the *Piazza Rizzi* case study (case 2 in Table 6). As shown, a single high error at one vertex on the right side of the *Building Volumetric Units* led to an $RMSE_{xy}$ value of 0.839 m, which would result in the building failing the compliance check. By contrast, the *line-to-cloud* and *line-to-line* approaches assessed the whole geometric feature rather than isolated edge points. As a result, the influence of the localized positional error, affecting only a small segment of the entire feature, was attenuated, yielding significantly lower $RMSE_{xy}$ values of 0.422 m and 0.380 m, respectively.

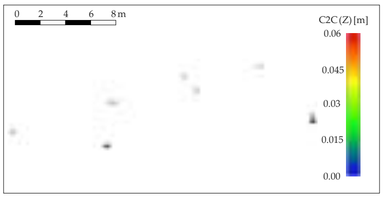
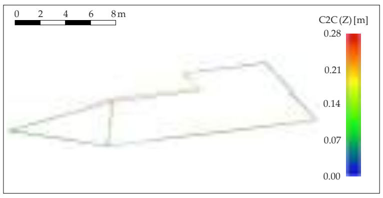
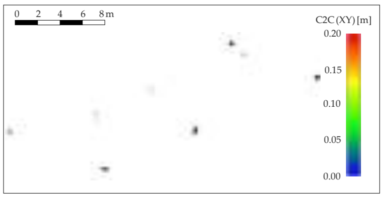
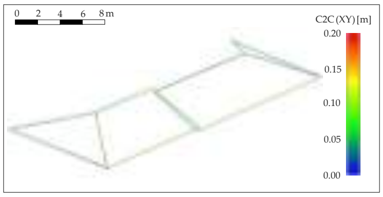
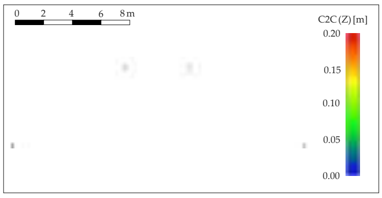
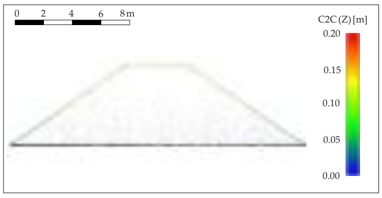
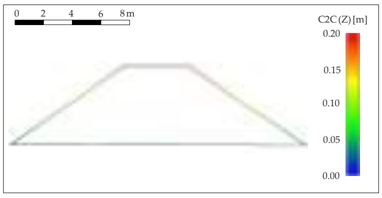
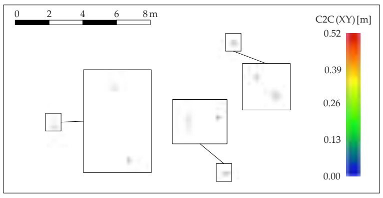
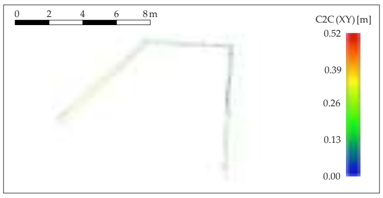
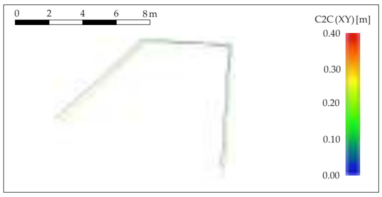
The *line-to-cloud* methodology represents an effective technique that is both rapid and straightforward to implement. However, compared to the third approach (*line-to-line*), it presents a notable limitation, as illustrated for Building #1 in the *Piazza Rizzi* study area (see Table 6). Portable laser scanners are capable of capturing centimeter-level details, such as the architectural elements of the church portals in this case. Yet, due to the scale of representation, such fine features should not be included in the TDB. Thus, significant discrepancies may arise when comparing the SLAM-based point cloud with the TDB geometry, highlighting differences that are not relevant at the intended cartographic scale. This issue was not observed in the *line-to-line* approach, where the vectorization was consistent with the database scale (1:2000 in this study), and finer details were deliberately excluded. This demonstrates that the *line-to-line* methodology is more suitable for achieving a balanced and scale-consistent comparison between SLAM data and TDB features.



(**a**) *Piazza Rizzi #4 VU.* (**b**) *Piazza Rizzi #6 RE.* (**c**) *Piazza Rizzi #8 VU.* (**d**) *Piazzale Cella #2 VU.* (**e**) *Piazzale Cella #3 VU.* (**f**) *Piazzale Cella #6 RE.* (**g**) *Piazzale Cella #9 RE.* (**h**) *Piazzale Cella #11 VU.*

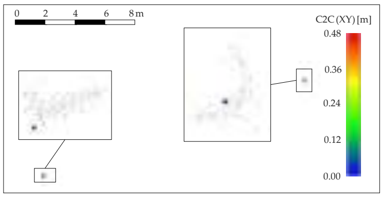
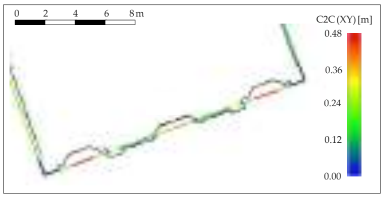
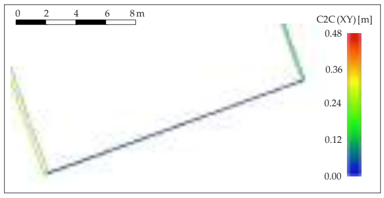
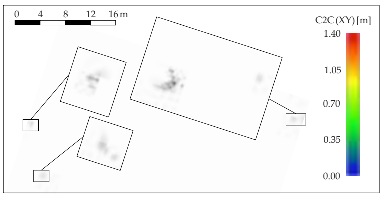
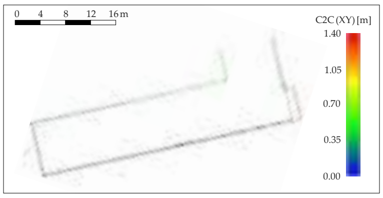
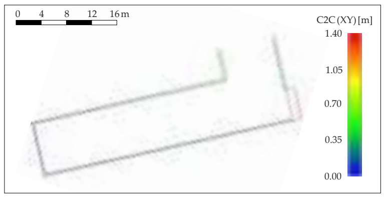
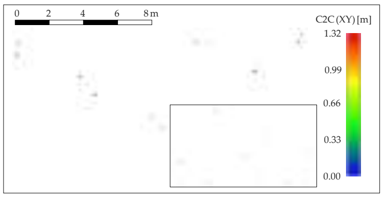
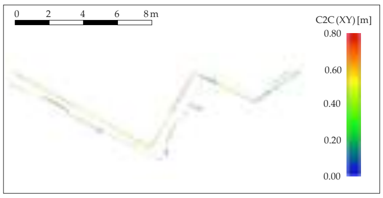
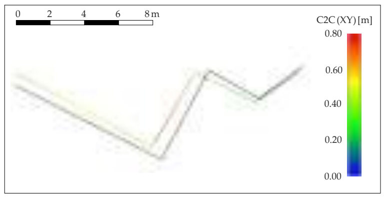
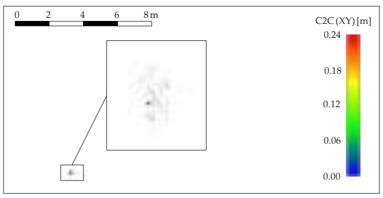
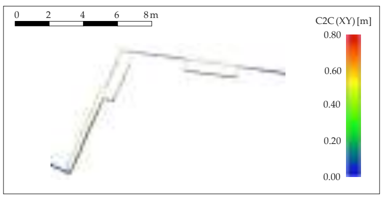
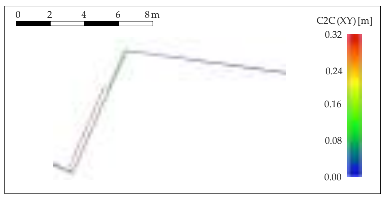
Figure 6. Examples of test cases with high RMSE values. The comparison is performed between sections of the SLAM-based point cloud and the corresponding TDB objects. The abbreviations 'VU' and 'RE' denote *Volumetric Units* (shown in cyan) and *Roofing Elements* (shown in red), respectively.

Table 5. Representative examples of concordance among the three procedures. The abbreviations 'VU' and 'RE' refer to *Volumetric Units* and *Roofing Elements*, respectively.

Case Study	*Point-to-Cloud*	*Line-to-Cloud*	*Line-to-Line*
1. *Piazza Rizzi* #4 RE	 RMSE$_z$ = 0.067 m	 RMSE$_z$ = 0.085 m	 RMSE$_z$ = 0.103 m
2. *Piazza Rizzi* #2 RE	 RMSE$_{xy}$ = 0.106 m	 RMSE$_{xy}$ = 0.135 m	 RMSE$_{xy}$ = 0.087 m
3. *Piazzale Cella* #10 RE	 RMSE$_z$ = 0.154 m	 RMSE$_z$ = 0.073 m	 RMSE$_z$ = 0.080 m
4. *Piazzale Cella* #7 VU	 RMSE$_{xy}$ = 0.293 m	 RMSE$_{xy}$ = 0.232 m	 RMSE$_{xy}$ = 0.216 m

It could be argued that additional errors may arise during the vectorization process in the *line-to-line* method, potentially affecting the metric validation of the TDB. To investigate this aspect, a comparison was conducted between the *Roofing Elements* vectorized from the SLAM data—subsequently used as ground truth for verifying the topographic database—and the SLAM point cloud itself. The RMSE$_{xy}$ across all buildings was 0.089 m, and the RMSE$_z$ was 0.044 m. These values, particularly the higher RMSE$_{xy}$, were mainly attributable to simplifications made during vectorization that omitted minor architectural details. Consequently, the error introduced by manual vectorization in the *line-to-line* method was on the order of a few centimeters, indicating that the approach remains appropriate for the geometric validation of the TDB. Moreover, the *line-to-line* method is also the most robust with respect to occlusions. When gaps occur in the point cloud, the vectorization process can often interpolate the missing segments by connecting points at the edges of the gap. In contrast, such gaps represent irrecoverable missing information in the other two methods, hindering the verification of the corresponding portions of the TDB object.

Table 6. Representative examples of discrepancies among the three procedures. The abbreviations 'VU' and 'RE' refer to *Volumetric Units* and *Roofing Elements*, respectively.

	Point-to-Cloud	***Line-to-Cloud***	***Line-to-Line***
1. *Piazza Rizzi* #1 VU	 $RMSE_{xy}$ = 0.122 m	 $RMSE_{xy}$ = 0.247 m	 $RMSE_{xy}$ = 0.201 m
2. *Piazza Rizzi* #8 VU	 $RMSE_{xy}$ = 0.839 m	 $RMSE_{xy}$ = 0.422 m	 $RMSE_{xy}$ = 0.380 m
3. *Piazzale Cella* #3 VU	 $RMSE_{xy}$ = 0.830 m	 $RMSE_{xy}$ = 0.486 m	 $RMSE_{xy}$ = 0.527 m
4. *Piazzale Cella* #4 RE	 $RMSE_{xy}$ = 0.110 m	 $RMSE_{xy}$ = 0.247 m	 $RMSE_{xy}$ = 0.095 m

Overall, when the geometries are simple—a condition that favors the *line-to-cloud* approach—and there are no issues related to visibility or vertex extraction—as required by the *point-to-cloud* method—the three procedures exhibit strong agreement (as illustrated by the examples in Table 5). This suggests that, under standard conditions, all approaches are capable of delivering consistent and reliable results.

It is also worth noting that, for the two approaches involving the conversion of vector lines into point sets, tests were carried out using sampling densities that varied by three orders of magnitude. In addition to the experiment conducted at 100 points/m, two further tests were performed at 10 points/m and 1000 points/m. However, no significant differences were observed among the results. This analysis reveals that the sampling density parameter is not critical, as its variation does not substantially affect the outcomes, and the adopted value of 100 points/m represents an effective and balanced choice.

A common limitation shared by all three methodologies is the requirement for manual operator intervention. Future work will focus on introducing automation, particularly through the preliminary semantic segmentation of the SLAM-derived point cloud. Classifying the cloud into categories such as buildings, roofs, and infrastructure would significantly streamline data management and analysis. For example, *line-to-cloud* comparisons could be performed directly on roof points without the need for manual extraction of relevant sections. Additionally, the integration of automatic or semi-automatic vectorization algorithms would enhance the efficiency of the *line-to-line* comparison process.

Finally, some additional considerations concern the intrinsic quality of the analyzed TDB. Regardless of the method applied, it is evident that *Building Volumetric Units* exhibit greater inaccuracies compared to *Roofing Elements*. This discrepancy can be attributed both to differences in the modeling techniques employed and to the nature of the source data. Specifically, the *Building Volumetric Units* were generated through vectorization from stereo images, whereas the *Roofing Elements* were derived with higher precision from an ALS point cloud. The outcomes of this study suggest that SLAM technology can serve not only as a validation tool but also as a viable surveying method for TDB creation and modeling—particularly for features that are difficult to capture through aerial surveys.

5. Conclusions

This study explored a novel application of PLSs, proposing the use of SLAM-derived point clouds as ground-truth data for the metric validation of a large-scale, three-dimensional topographic database. This represents a significant shift in perspective: unlike most studies in the literature, where SLAM point clouds are typically validated against higher-accuracy techniques such as terrestrial laser scanning or photogrammetry, here they are instead employed as reference datasets for assessing the quality of the geometric features in a TDB. This inversion of roles is justified by the fact that the resolution and accuracy achievable with modern portable SLAM systems are sufficient to support validation tasks at mapping scales of 1:1000 and 1:2000.

To achieve this objective, three distinct operational procedures were developed and applied in a comparative analysis between the vector geometries in the topographic database and the SLAM-acquired point cloud: *point-to-cloud*, *line-to-cloud*, and *line-to-line*. The results confirmed the effectiveness of all three approaches for validation purposes. However, the *line-to-line* method proved to be the most practical, as it allows for the comparison of geometrically homogeneous elements following the preliminary vectorization of the SLAM point cloud. This approach facilitates consistent handling of large datasets and enables the simplification of geometries in line with cartographic conventions and the requirements of the target mapping scale.

In conclusion, SLAM technology is a promising solution for a wide range of future applications, particularly in fields such as cartographic updating and change detection. In the former, the operational flexibility and high information density of SLAM acquisitions can support rapid and targeted updates to cartographic data, especially in urban or rapidly evolving environments. In the latter, the ability to quickly generate three-dimensional models of the same area at different epochs enables systematic comparisons, which are valuable for detecting morphological changes, new constructions, or anomalies. These potential applications further underscore the relevance of SLAM-based approaches not only for validation purposes but also as strategic tools for the ongoing management and evolution of territorial databases.

Author Contributions: Conceptualization, E.M., A.M., and A.B.; methodology, E.M., A.M., and S.G.; validation, E.M.; formal analysis, E.M., A.M., and S.G.; investigation, A.M. and S.G.; data curation, A.M. and S.G.; writing—original draft preparation, E.M. and A.M.; writing—review and editing, E.M., A.M., S.G., D.V., and A.B.; visualization, E.M. and A.M.; supervision, D.V. and A.B.; project administration, A.B. All authors have read and agreed to the published version of the manuscript.

Funding: This research was partially funded by the strategic plan of the University of Udine within the framework of the project "ESPeRT".

Data Availability Statement: The topographic database analyzed in this study is publicly accessible and can be downloaded from ref. [38]. The SLAM-based point clouds are available upon request to the corresponding authors.

Acknowledgments: This article is a revised, expanded, and enhanced version of the paper titled 'Assessing the Quality of a Topographic Database using SLAM Technology: Proposal for an Operational Procedure' [42], which was presented at the Italian Conference on Geomatics and Geospatial Technologies (#ASITA2024, Padua, Italy, 9–13 December 2024). At the time of this article's submission, the conference proceedings had not yet been published.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

ALS	Airborne Laser Scanning
C2C	Cloud-to-Cloud
TDB	Topographic Database
DBM	Digital Building Model
DSM	Digital Surface Model
DTM	Digital Terrain Model
GNSS	Global Navigation Satellite System
IMU	Inertial Measurement Unit
LiDAR	Light Detection and Ranging
NRTK	Network Real-Time Kinematic
PLS	Portable Laser Scanner
SLAM	Simultaneous Localization and Mapping
TLS	Terrestrial Laser Scanner

References

1. Ketzler, B.; Naserentin, V.; Latino, F.; Zangelidis, C.; Thuvander, L.; Logg, A. Digital twins for cities: A state of the art review. *Built Environ.* **2020**, *46*, 547–573. [CrossRef]
2. Botín-Sanabria, D.M.; Mihaita, A.S.; Peimbert-García, R.E.; Ramírez-Moreno, M.A.; Ramírez-Mendoza, R.A.; Lozoya-Santos, J.d.J. Digital twin technology challenges and applications: A comprehensive review. *Remote Sens.* **2022**, *14*, 1335. [CrossRef]
3. Congalton, R.G.; Green, K. *Assessing the Accuracy of Remotely Sensed Data: Principles and Practices*; CRC Press: Boca Raton, FL, USA, 2019.

4. Franzini, M.; Casella, V.M.; Monti, B. Assessment of Leica CityMapper-2 LiDAR data within Milan's digital twin project. *Remote Sens.* **2023**, *15*, 5263. [CrossRef]
5. Höhle, J.; Höhle, M. Accuracy assessment of digital elevation models by means of robust statistical methods. *ISPRS J. Photogramm. Remote Sens.* **2009**, *64*, 398–406. [CrossRef]
6. Höhle, J. The assessment of the absolute planimetric accuracy of airborne laserscanning. *Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci.* **2012**, *38*, 145–150. [CrossRef]
7. Maffeis, A.; Pinto, L. A software package to check aerial blocks from GPS/IMU-assisted cameras. *Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci.* **2008**, *37*, 849–855.
8. Casella, V.; Franzini, M.; Kocaman, S.; Gruen, A. Geometric accuracy assessment of ADS40 imagery under various network configurations. *Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci.* **2008**, *37*, 627–632.
9. Liu, X. Accuracy assessment of LiDAR elevation data using survey marks. *Surv. Rev.* **2011**, *43*, 80–93. [CrossRef]
10. Franzini, M.; Casella, V.; Monti, B. The digital twin of the metropolitan area of Milan: Quality assessment of aerial and terrestrial data. In Proceedings of the Italian Conference on Geomatics and Geospatial Technologies, Padua, Italy, 9–13 December 2024; Springer: Berlin/Heidelberg, Germany, 2024; pp. 152–171.
11. Höhle, J.; Pedersen, C. A new method for checking the planimetric accuracy of digital elevation models data derived by airborne laser scanning. In Proceedings of the 9th International Symposium on Spatial Accuracy Assessment in Natural Resources and Environmental Sciences, Leicester, UK, 20–23 July 2010; University of Leicester: Leicester, UK, 2010; pp. 253–256.
12. Vosselman, G. Automated planimetric quality control in high accuracy airborne laser scanning surveys. *ISPRS J. Photogramm. Remote Sens.* **2012**, *74*, 90–100. [CrossRef]
13. Carrion, D.; Maffeis, A.; Pinto, L. Metodi e modelli per il controllo di qualità di Data Base Topografici multiscala. In Proceedings of the 12th ASITA National Conference, L'Aquila, Italy, 21–24 October 2008; pp. 661–667.
14. Borrelli, S.; Caracciolo, T.; Maffeis, A.; Marra, V.; Pellicanò, A.; Pinto, L.; Scarnati, G.; Surace, L. Il controllo in corso d'opera del DB topografico della Regione Calabria. In Proceedings of the 14th ASITA National Conference, Brescia, Italy, 9–12 November 2010; pp. 337–344.
15. Otero, R.; Lagüela, S.; Garrido, I.; Arias, P. Mobile indoor mapping technologies: A review. *Autom. Constr.* **2020**, *120*, 103399. [CrossRef]
16. Grasso, N.; Dabove, P.; Piras, M. The use of SLAM and UAV technology in geological field for monitoring: The case study of the Bossea cave. *Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci.* **2023**, *48*, 73–79. [CrossRef]
17. Trybała, P.; Kasza, D.; Wajs, J.; Remondino, F. Comparison of low-cost handheld lidar-based SLAM systems for mapping underground tunnels. *Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci.* **2023**, *48*, 517–524. [CrossRef]
18. Di Stefano, F.; Chiappini, S.; Gorreja, A.; Balestra, M.; Pierdicca, R. Mobile 3D scan LiDAR: A literature review. *Geomat. Nat. Hazards Risk* **2021**, *12*, 2387–2429. [CrossRef]
19. Maset, E.; Valente, R.; Iamoni, M.; Haider, M.; Fusiello, A. Integration of photogrammetry and portable mobile mapping technology for 3D modeling of cultural heritage sites: The case study of the Bziza temple. *Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci.* **2022**, *43*, 831–837. [CrossRef]
20. Conti, A.; Pagliaricci, G.; Bonora, V.; Tucci, G. A comparison between terrestrial laser scanning and hand-held mobile mapping for the documentation of built heritage. *Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci.* **2024**, *48*, 141–147. [CrossRef]
21. Chiabrando, F.; Sammartano, G.; Spanò, A.; Spreafico, A. Hybrid 3D models: When geomatics innovations meet extensive built heritage complexes. *ISPRS Int. J.-Geo-Inf.* **2019**, *8*, 124. [CrossRef]
22. Perfetti, L.; Vassena, G.; Fassi, F. Preliminary survey of historic buildings with wearable mobile mapping systems and UAV photogrammetry. *Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci.* **2023**, *48*, 1217–1223. [CrossRef]
23. Li, F.; Achille, C.; Vassena, G.P.M.; Fassi, F. The application of three dimensional digital technologies in historic gardens and related cultural heritage: A scoping review. *Heritage* **2025**, *8*, 46. [CrossRef]
24. Nocerino, E.; Menna, F.; Remondino, F.; Toschi, I.; Rodríguez-Gonzálvez, P. Investigation of indoor and outdoor performance of two portable mobile mapping systems. In Proceedings of the Videometrics, Range Imaging, and Applications XIV, Munich, Germany, 26–27 June 2017; SPIE: Bellingham, WA, USA, 2017; Volume 10332, pp. 125–139.
25. Tucci, G.; Visintini, D.; Bonora, V.; Parisi, E.I. Examination of indoor mobile mapping systems in a diversified internal/external test field. *Appl. Sci.* **2018**, *8*, 401. [CrossRef]
26. Maset, E.; Cucchiaro, S.; Cazorzi, F.; Crosilla, F.; Fusiello, A.; Beinat, A. Investigating the performance of a handheld mobile mapping system in different outdoor scenarios. *Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci.* **2021**, *43*, 103–109. [CrossRef]
27. Askar, C.; Scheider, A.; Sternberg, H. Evaluation of a state-of-the-art indoor Mobile Mapping System in a complex indoor environment. *ZfV-Z. Für Geodäsie Geoinf. Landmanag.* **2023**, *5*, 300–309.
28. Teppati Losè, L.; Rinaudo, F.; Grasso, N.; Bonfanti, C.; Kappes, S. Moving toward the next generation of HMLS—Testing and validating the performances of second-generation SLAM systems compared to predecessors. *Sensors* **2025**, *25*, 2488. [CrossRef] [PubMed]

29. Sammartano, G.; Spanò, A. Point clouds by SLAM-based mobile mapping systems: Accuracy and geometric content validation in multisensor survey and stand-alone acquisition. *Appl. Geomat.* **2018**, *10*, 317–339. [CrossRef]
30. Matrone, F.; Colucci, E.; Ugliotti, F.; Del Giudice, M. From an integrated survey with MMS to a Scan-to-BIM process for educational purposes. *Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci.* **2023**, *48*, 279–286. [CrossRef]
31. Matellon, A.; Maset, E.; Beinat, A.; Visintini, D. Surface reconstruction from SLAM-based point clouds: Results from the datasets of the 2023 SIFET benchmark. *Remote Sens.* **2024**, *16*, 3439. [CrossRef]
32. QGIS. 2025. Available online: https://qgis.org/ (accessed on 29 July 2025).
33. CloudCompare. 2025. Available online: https://cloudcompare.org/index.html (accessed on 29 July 2025).
34. Autodesk ReCap Pro. 2025. Available online: https://www.autodesk.com/it/products/recap/overview?term=1-YEAR&tab=subscription (accessed on 29 July 2025).
35. Autodesk AutoCAD. 2025. Available online: https://www.autodesk.com/it/products/autocad/overview?term=1-YEAR&tab=subscription (accessed on 29 July 2025).
36. Maset, E.; Visintini, D.; Beinat, A. On the role of geomatics and official regional cartography in the Interconnected Nord-Est Innovation Ecosystem. In Proceedings of the Italian Conference on Geomatics and Geospatial Technologies, Padua, Italy, 9–13 December 2024; Springer: Berlin/Heidelberg, Germany, 2024; pp. 172–183.
37. *ISO 19109:2015*; Geographic Information—Rules for Application Schema. ISO: Geneva, Switzerland, 2015.
38. Eaglefvg Webgis. 2025. Available online: https://eaglefvg.regione.fvg.it/eagle/main.aspx?configuration=guest (accessed on 29 July 2025).
39. Stonex X120GO SLAM Laser Scanner. 2025. Available online: https://www.stonex.it/it/prodotto/x120go-slam-laser-scanner/ (accessed on 29 July 2025).
40. Stonex GOPost. 2025. Available online: https://www.stonex.it/it/project/x120go-slam-laser-scanner/#software (accessed on 29 July 2025).
41. Brovelli, M.A.; Cina, A.; Crespi, M.; Lingua, A.; Manzino, A.; Garretti, L. *Ortoimmagini e Modelli Altimetrici a Grande Scala. Linee Guida*; CISIS (Centro Interregionale di Coordinamento e Documentazione per le Informazioni Territoriali): Rome, Italy, 2011.
42. Matellon, A.; Maset, E.; Visintini, D.; Beinat, A. Assessing the Quality of a Topographic Database using SLAM Technology: Proposal for an Operational Procedure. In Proceedings of the Italian Conference on Geomatics and Geospatial Technologies, ASITA, Padua, Italy, 9–13 December 2024; *in press*.