# Vertical Accuracy Assessment of Point Cloud and Digital Terrain Model Derived from Handheld LiDAR-SLAM Mobile Scanning in a Geometrically Poor Urban Environment

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*Abstract*

*This study evaluates the vertical accuracy of a point cloud and a digital terrain model derived from a handheld LiDAR-SLAM mobile laser scanner. Despite the growing use of handheld SLAM systems, studies focusing on the vertical accuracy of derived terrain products in geometrically poor urban environments remain limited. The investigation was performed using the FJD Trion P1 system and FJD Trion Model software within a geometrically poor urban environment characterized by a limited number of distinctive features and challenging conditions for SLAM-based localization. The generated point cloud was transformed to the coordinate reference system and height datum of the reference geodetic survey using four independently surveyed control points. In addition to the direct assessment of point cloud elevations, a digital terrain model was generated through ground classification and subsequent terrain modelling procedures, allowing the influence of the processing workflow on the final vertical accuracy to be evaluated. The direct comparison of 111 check points extracted from the point cloud against independently acquired total station reference measurements resulted in a vertical RMSE of 4.45 cm. Similarly, the derived digital terrain model achieved a vertical RMSE of 4.74 cm based on 136 check points from the reference geodetic survey. The close agreement between the RMSE values of the raw point cloud and the derived terrain model suggests that the applied ground classification and terrain modelling procedures introduce only a minor additional uncertainty into the results. Most check points showed deviations within 5 cm. The largest deviations, reaching up to 10 cm, were spatially concentrated within a limited part of the study area, indicating localized effects rather than a uniform systematic error. The results demonstrate that the combination of the FJD Trion P1 handheld LiDAR-SLAM system and FJD Trion Model can provide reliable centimetre-level vertical information in geometrically poor urban environments and support engineering and topographic surveying applications.*

**Keywords:** *Handheld LiDAR; SLAM; outdoor mobile laser scanning; digital terrain model; point clouds; vertical accuracy; urban environment.*

## 1. Introduction

In recent years, Mobile Laser Scanning (MLS) systems based on LiDAR and Simultaneous Localization and Mapping (SLAM) technologies have gained increasing popularity in surveying, mapping, and engineering applications. Their ability to rapidly acquire dense three-dimensional spatial data makes them an attractive alternative or complement to conventional geodetic surveying techniques. The increasing demand for efficient spatial data acquisition has stimulated the development of various modern geospatial technologies, including UAV-based photogrammetry and mobile mapping systems [1]. Recent studies indicate that SLAM-based portable laser scanning can complement or even replace conventional topographic techniques for certain surveying tasks [2].

The positioning and mapping performance of SLAM-based systems strongly depends on the availability of stable geometric features within the surveyed environment. Under favorable conditions, the highest accuracy is typically achieved when the survey trajectory forms a closed loop, allowing the SLAM algorithm to perform loop closure and minimize the accumulation of positioning errors. This process significantly reduces trajectory drift and improves the consistency of the generated point cloud.

However, the performance of SLAM-based mobile mapping systems may be compromised in geometrically poor environments characterized by repetitive or homogeneous structures and a limited number of distinctive features. In such conditions, the algorithm has fewer reference elements for reliable localization, which may lead to increased drift, reduced positioning stability, and degradation of the overall geometric quality of the resulting point cloud. Several studies have demonstrated that the quality of SLAM-derived point clouds strongly depends on the characteristics of the surveyed environment, particularly in underground and feature-poor scenarios [3].

Urban environments containing long road sections, sidewalks, and open paved surfaces often represent such challenging scenarios. Therefore, assessing the vertical accuracy of point clouds and digital terrain models derived from handheld mobile laser scanners under these conditions is essential for determining their suitability for surveying and engineering applications requiring centimetre-level accuracy. Although handheld LiDAR-SLAM systems have been increasingly investigated in recent years, independent scientific studies specifically evaluating the FJD Trion P1 scanner for engineering and topographic surveying applications remain insufficient.

The objective of this study is to evaluate the vertical accuracy of a point cloud and the corresponding digital terrain model derived from the FJD Trion P1 handheld mobile laser scanner in a geometrically poor urban environment by comparison with independent

reference measurements obtained using a total station. In addition, the study investigates the influence of ground classification and terrain modelling procedures on the final vertical accuracy of the derived products.

## 2. Study Area

The experimental test site covers an area of approximately 1400 - 1500 m², corresponding to an approximately 23 m × 64 m section of an urban road intersection comprising road carriageways, sidewalks, pedestrian crossings, traffic signal infrastructure, and adjacent open spaces (Fig. 1). The site was selected to represent a geometrically poor urban environment for evaluating the performance of handheld LiDAR-SLAM systems under challenging operating conditions [4]. Previous studies have demonstrated the applicability of handheld LiDAR systems in dense urban environments characterized by narrow streets [5]. In contrast, the present study focuses on an open urban intersection. Similar urban intersections characterized by extensive paved areas and heterogeneous traffic conditions have been investigated in previous mobile LiDAR studies [6].

The surveyed area is dominated by wide asphalt surfaces and paved sidewalks with relatively simple geometry. Permanent vertical objects are limited and consist mainly of traffic signal poles, street lighting poles, road signs, and young trees with limited canopy development. Although multi-storey residential buildings are present near the study area, they are situated approximately 20 m from the surveyed section and are separated from it by predominantly open spaces with low vegetation and undeveloped parcels. Consequently, the site is characterized by large planar surfaces, limited facade coverage, and an uneven distribution of vertical structures, providing only a small number of stable geometric references for scan matching and trajectory estimation and thus creating challenging conditions for SLAM-based localization.

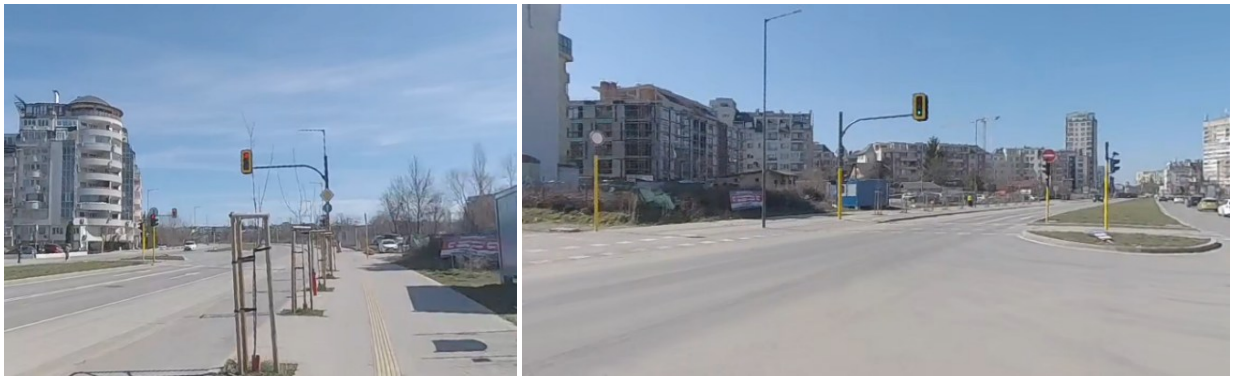

Fig. 1. General view of the study area.

In addition, the site is situated along a heavily trafficked boulevard. The continuous movement of vehicles occasionally restricted the operator's movement and introduced dynamic objects and temporary occlusions within the scene, creating realistic urban operating conditions for the evaluation of handheld mobile laser scanning systems.

## 3. Reference Survey

To provide an independent reference dataset for the accuracy assessment, a classical topographic survey was performed using a total station, with detail points acquired by the polar surveying method. The survey was originally performed for engineering design purposes and included the acquisition of the principal situational features within the study area, as well as a sufficient number of terrain points required for the generation of a digital terrain surface.

The surveyed objects comprised road edges, curbs, sidewalks, pavement corners, traffic signal poles, lighting poles, and other stable urban features exhibiting clearly defined geometric characteristics. In addition, terrain points were measured throughout the site to adequately represent the local topography and enable the construction of a reference terrain model.

The coordinates of all surveyed points were determined by total station observations, providing centimetre- to millimetre-level measurement precision. Owing to its substantially higher accuracy compared with the expected performance of the handheld LiDAR-SLAM system, the classical geodetic survey was adopted as the ground-truth reference dataset for the subsequent accuracy assessment.

## 4. Mobile Laser Scanning Data Acquisition

Data acquisition was performed using an FJD Trion P1 handheld mobile laser scanner. The system provides a measurement range of up to 40 m for targets with 10% reflectivity and up to 70 m for targets with 80% reflectivity and has a 360° vertical field of view and a 59° horizontal field of view, enabling the acquisition of dense three-dimensional data while moving through the surveyed area. Considering the relatively small dimensions of the test site (approximately 22 m × 64 m), the instrument's measurement range was fully sufficient to capture the surrounding urban features and provide adequate overlap between consecutive observations required for the SLAM-based reconstruction. The instrument has also been evaluated in recent scientific research, although in the context of forest inventory applications rather than topographic surveying [7].

The mobile laser scanning survey was carried out using a trajectory specifically adapted to the intensive traffic conditions within the study area. In contrast to an idealized acquisition scenario, the survey path was primarily determined by traffic regulations, pedestrian crossings, and the need to ensure the operator's safety during data collection (Fig. 2).

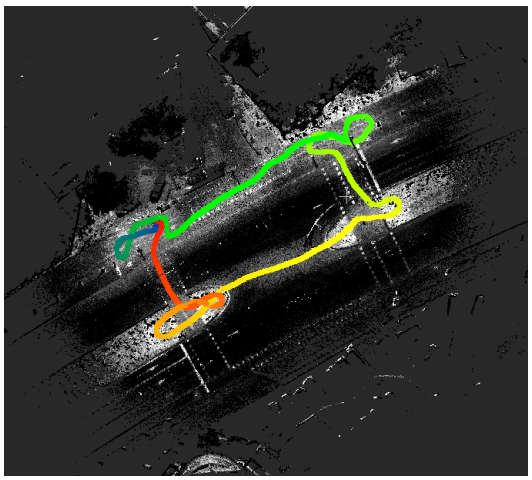

Fig. 2. Handheld mobile laser scanning trajectory within the study area.

The final acquisition trajectory had a total length of 213.9 m and was completed in approximately 6 min 15 s. Despite the challenging urban conditions, the trajectory included three loop closures, which are beneficial for constraining the SLAM solution and reducing the accumulation of trajectory drift.

An additional challenge during data acquisition was the continuous movement of vehicles within the surveyed intersection. Traffic occasionally required temporary stops, changes in walking speed, and minor deviations from the intended path. From the perspective of SLAM-based localization, such conditions may introduce additional uncertainties. Sudden changes in motion, prolonged stationary periods, temporary occlusion of surrounding features by passing vehicles, and the presence of dynamic objects in close proximity to the scanner can reduce the availability of stable geometric references used for scan matching and trajectory estimation. These effects become particularly relevant in geometrically poor environments, where the number of permanent and distinctive features is already limited.

**5. Point Cloud Processing and Transformation**

The acquired mobile laser scanning data were processed using the FJD Trion Model software environment. Following the initial SLAM-based reconstruction, the generated point cloud was transformed to the coordinate reference system and height datum of the reference geodetic survey using four independently surveyed control points (Fig. 3).

The selected control points correspond to clearly identifiable and stable urban features, namely the centres or well-defined corners of utility manholes, which can be reliably recognized both in the point cloud and in the total station measurements. The transformation enabled a direct comparison between the mobile laser scanning data and the independently acquired reference measurements. The resulting georeferencing achieved a final Root Mean Square Error (RMSE) of 4.59 cm, reflecting the overall residual discrepancies at the transformation control points.

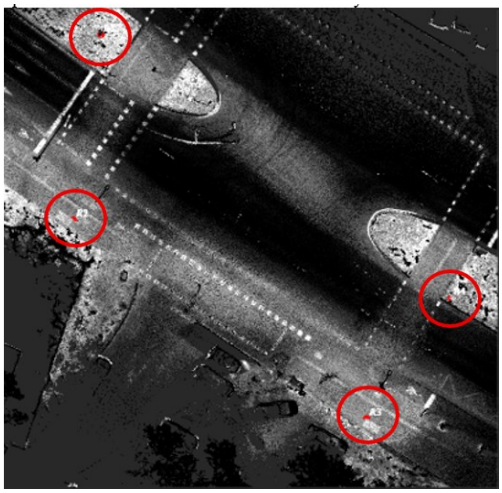

Fig. 3. Location of the transformation control points.

In addition to the three-dimensional point cloud, an orthophoto (Fig. 4) was generated from the imagery acquired by the integrated 360-degree camera during the scanning process. The orthophoto provides useful visual context and facilitates the identification and localization of objects, supporting the interpretation of the surveyed scene and the comparison with the reference geodetic survey. Although the integrated 360-degree camera provides valuable visual information and enables point cloud colourization, the quality of the imagery may be affected by illumination conditions. Strong sunlight and pronounced shadows can be clearly visible in the acquired images and may reduce their usefulness for visual interpretation and object identification. Therefore, when colourized point clouds or orthophotos are required, careful consideration should be given to the time of data acquisition and prevailing lighting conditions.

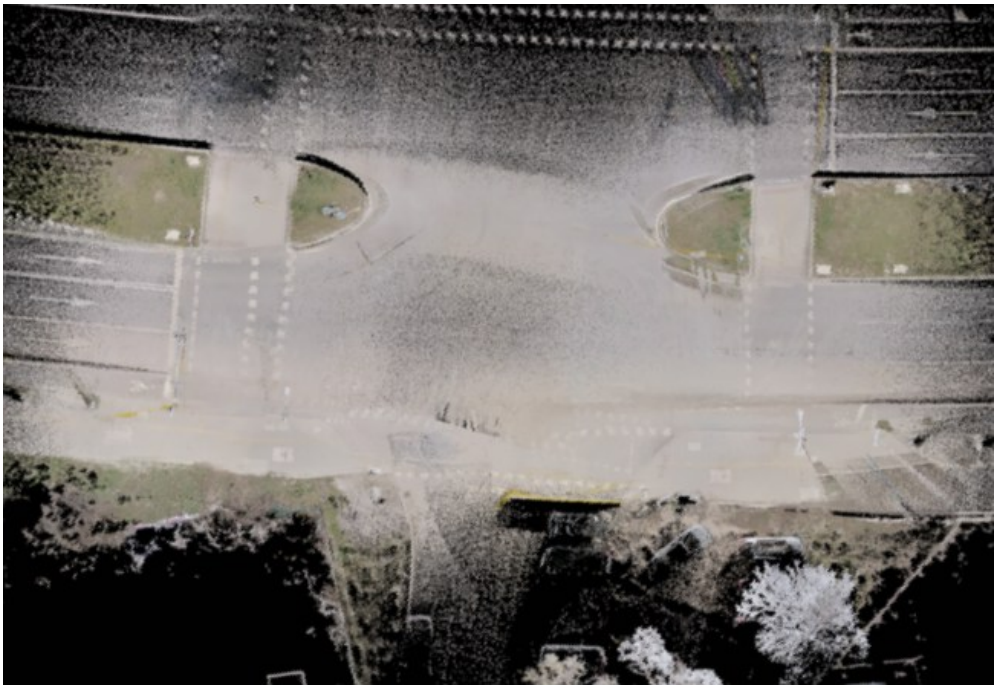

Fig. 4. Orthophoto generated from the integrated 360° camera.

## 6. Digital Terrain Model Generation and Vertical Accuracy Assessment

### *6.1 Vertical Accuracy Assessment of the Raw Point Cloud*

To evaluate the vertical accuracy of the mobile laser scanning data independently of the subsequent terrain modelling procedures, an analysis was performed using 111 independent check points extracted directly from the point cloud. The check points were selected and uniformly distributed across the study area, including road carriageways, bicycle lanes, sidewalks, and green areas with varying slopes and surface materials.

For each check point, the elevation obtained from the point cloud was compared with the corresponding elevation measured during the reference geodetic survey:

$$\Delta Z_i = Z_{MLS,i} - Z_{\mathrm{Re}f,i} \tag{1}$$

Several points showing unrealistically large deviations in the metre range were excluded from the analysis, as they were caused by noise in the point cloud, most commonly due to passing vehicles. The vertical accuracy was subsequently quantified by the Root Mean Square Error:

$$RMSE_Z = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\Delta Z_i^2} \tag{2}$$

This direct comparison eliminates the influence of ground classification, contour generation, and TIN interpolation, allowing the accuracy of the raw LiDAR-SLAM data to be assessed.

The comparison resulted in a vertical RMSE of 4.45 cm. The observed residuals ranged from −8 cm to +10 cm. The absolute elevation differences were grouped into four classes (0 cm, 1–2 cm, 3–5 cm, and >5 cm). For each class, both the number of check points and its percentage relative to the total of 111 check points were calculated and the results are presented in table 1. The majority of the observations (74%) exhibited absolute elevation differences not exceeding 5 cm, whereas only 26% of the check points showed deviations greater than 5 cm.

The spatial distribution of the classified differences is presented in Fig. 5 using a corresponding colour scale. The obtained results suggest that the handheld LiDAR-SLAM system is capable of providing centimetre-level vertical information under geometrically challenging urban conditions.

Tab. 1. Distribution of elevation differences between the MLS point cloud and the reference survey.

| Deviation range (cm) | Number of check points | Percentage of total (%) |
|---|---|---|
| Zero difference | 11 | 10 |
| 1-2 | 30 | 27 |
| 3-5 | 41 | 37 |
| >5 | 29 | 26 |
| Total: 111 points | | |

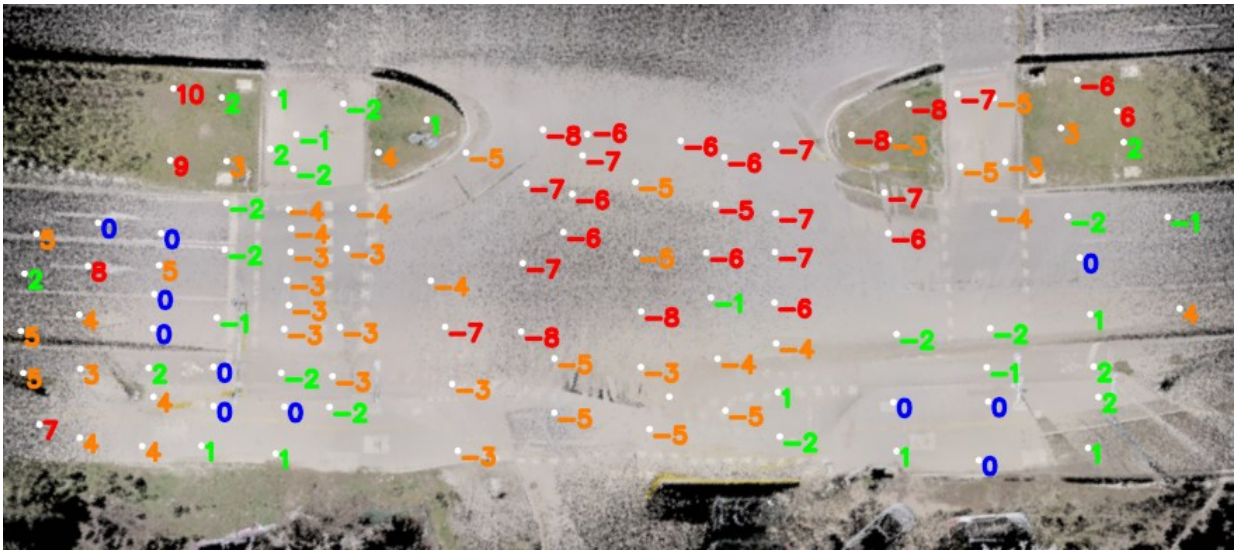

Fig. 5. Spatial distribution of elevation differences between the point cloud and the reference survey.

Also, from the 111 check points, 67 (60%) exhibited negative elevation differences, whereas only 33 (30%) showed positive differences, with 11 points (10%) presenting no difference. This predominance of negative residuals suggests a weak systematic tendency towards lower elevations in the MLS-derived data.

### *6.2 Vertical Accuracy Assessment of the Derived Digital Terrain Model*

The next stage of the processing workflow involved the automatic classification and extraction of the ground level from the acquired point cloud using the FJD Trion Model software. Based on the classified ground points, contour lines with interval 10 cm were generated and subsequently imported into Autodesk Civil 3D, where they were used to construct a continuous terrain surface (TIN).

A total of 136 independent check points were selected following the same criteria as those applied in the point cloud analysis and were distributed throughout the entire study area. The points were spaced at approximate intervals of 2 to 5 m to ensure representative coverage of the derived terrain surface. The four control points used for the point cloud transformation were again excluded from the accuracy assessment to ensure the independence of the evaluation.

As in the previous analysis, the elevation differences for all check points were first computed with respect to the total station reference measurements, and the vertical RMSE was subsequently determined. The resulting vertical RMSE was 4.74 cm, while the observed residuals ranged from −10 cm to +10 cm.

The distribution of the absolute elevation differences is summarized in table 2, while their spatial distribution is illustrated in Fig. 6 using the same classification scheme as that applied in the previous analysis.

Tab. 2. Distribution of elevation differences between the MLS-derived terrain model and the reference survey.

| Deviation range (cm) | Number of check points | Percentage of total (%) |
|---|---|---|
| Zero difference | 15 | 11 |
| 1-2 | 40 | 29 |
| 3-5 | 47 | 34 |
| >5 | 34 | 25 |
| Total: 136 points | | |

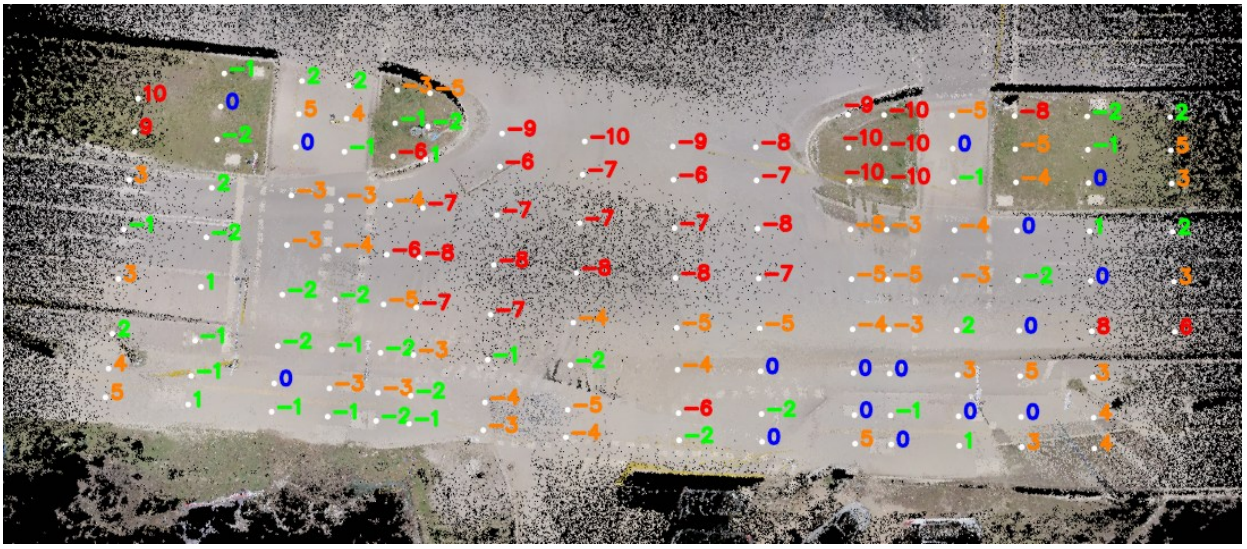

Fig. 6. Spatial distribution of elevation differences between the derived terrain model and the reference survey.

A similar distribution of positive and negative residuals was observed for the derived terrain model. Of the 136 check points, 88 (65%) exhibited negative elevation differences, whereas only 32 (23%) showed positive differences, with 16 points (12%) presenting no difference. This predominance of negative residuals again indicates a tendency of the derived terrain model to produce slightly lower elevations than those obtained from the reference geodetic survey within the study area.

## 7. Discussion

The direct assessment of the point cloud resulted in an RMSE of 4.45 cm, whereas the derived digital terrain model resulted in a slightly higher value of 4.74 cm. The difference between the two estimates is only 0.29 cm, indicating that the ground classification and terrain modelling procedures introduce only a minor additional uncertainty into the final results. It is also noteworthy that both RMSE values are very close to the georeferencing RMSE of 4.59 cm obtained from the transformation control points. This similarity suggests that the overall accuracy of the derived products is largely controlled by the quality of the point cloud transformation and the underlying SLAM solution, whereas the subsequent terrain modelling procedures contribute only a minor additional uncertainty. The achieved RMSE values may be partly attributed to the challenging acquisition conditions, including intensive traffic, which constrained the survey trajectory, and the limited availability of stable geometric features required for robust SLAM-based localization.

Although performed using a different mobile mapping configuration, similar investigations have reported centimetre-level vertical accuracies for LiDAR-derived terrain models when compared with independent reference measurements [8]. The achieved vertical accuracy may also be attributed to the use of independently surveyed control points for point cloud transformation.

In addition to the close agreement between the RMSE values, the percentage distributions of the elevation differences obtained from the point cloud and the derived terrain model are also nearly identical. For both datasets, approximately 37–40% of the check points exhibited absolute elevation differences not exceeding 2 cm, while nearly 74% of the observations showed deviations within 5 cm.

The largest elevation differences (5–10 cm) are spatially concentrated within two localized areas, particularly in the analysis of the derived terrain model. One group of discrepancies is located within the small grass-covered areas, while the second is situated near the centre of the surveyed intersection.

The discrepancies observed within the small grass-covered areas are likely associated with the more variable micro-topography of these surfaces. Due to the relatively small size and their uneven terrain, part of the local relief is smoothed during contour generation with a contour interval of 10 cm. A smaller contour interval would provide a more detailed representation of the terrain surface and would likely reduce the observed differences.

The localized concentration of negative residuals in the central part of the intersection may have a different origin. This area is characterized by an almost complete absence of permanent objects and geometric features that could support SLAM-based localization. Such conditions are consistent with previous findings indicating that feature-poor environments may promote the accumulation of SLAM drift [9]. In addition, no transformation control point was available near this area. Therefore, the observed deviations may indicate the presence of localized drift effects, potentially influenced by the spatial configuration of the transformation control points or by a combination of both factors. However, this interpretation should be regarded as a preliminary hypothesis of the authors rather than a definitive conclusion. Further investigations involving alternative trajectory configurations and different control point distributions would be required to verify this assumption.

## 8. Conclusion

The presented case study demonstrates that the combination of the FJD Trion P1 handheld LiDAR-SLAM system and the adopted processing workflow implemented in FJD Trion Model is capable of providing reliable centimetre-level vertical information even under challenging urban conditions characterized by intensive traffic and a limited number of stable geometric features. The direct assessment of the point cloud and the derived digital terrain model, evaluated against the independent classical geodetic survey, resulted in RMSE values of 4.45 cm and 4.74 cm, respectively. The close agreement between these results indicates that the applied ground classification and terrain modelling procedures preserve the quality of the original data and enable the generation of terrain products suitable for engineering and topographic applications. Nevertheless, particular attention should be paid to the selection of the contour interval, especially in small areas characterized by frequent slope changes and pronounced micro-topographic variability, where an excessively large contour interval may smooth local terrain features and introduce additional vertical discrepancies.

In both the point cloud and terrain model analyses, negative elevation differences predominated over positive ones, suggesting a slight tendency of the MLS-derived products to produce lower elevations than those obtained from the reference geodetic survey.

The findings also highlight the importance of careful placement of transformation control points, particularly in areas characterized by a limited number of stable geometric features, where localized drift effects may be more likely to occur. This observation is consistent with previous studies emphasizing that the use and spatial distribution of ground control points play a critical role in minimizing transformation errors and ensuring the reliability of MLS-derived products [10].

Overall, the results indicate that handheld LiDAR-SLAM technology represents a valuable alternative or complement to conventional topographic surveying methods for the rapid acquisition of terrain information in complex urban environments.

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