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OPERATIONAL CHALLENGES AND METHODOLOGICAL CONSIDERATIONS IN MLS-BASED URBAN TOPOGRAPHIC MAPPING

Abstract:

Although Mobile Laser Scanning (MLS) has significantly enhanced the efficiency of urban topographic mapping, its performance in dense urban environments remains subject to multiple operational constraints. This paper examines key factors affecting data reliability, including GNSS signal degradation, IMU drift, occlusions, and point density variability, and analyzes their influence on point cloud integrity and the accuracy of the resulting digital topographic plan. Positioning accuracy may reach approximately 2–3 cm under favorable conditions, but can degrade to decimeter-level deviations in dense urban environments due to signal instability and trajectory uncertainties. Methodological considerations are proposed to improve robustness and quality control in MLS-based urban mapping.

Keywords: MLS, urban mapping, GNSS instability, point cloud accuracy, data quality, GNSS/IMU integration

ОПЕРАТИВНИ ИЗАЗОВИ И МЕТОДОЛОШКА РАЗМАТРАЊА У MLS-БАЗИРАНОМ УРБАНОМ ТОПОГРАФСКОМ МАПИРАЊУ

Сажетак:

Иако је Mobile Laser Scanning (MLS) технологија значајно унапредила ефикасност урбаног топографског мапирања, њена примена у густо изграђеним срединама подложна је бројним оперативним ограничењима. У раду се систематски анализирају кључни фактори који утичу на поузданост података, укључујући деградацију GNSS сигнала, IMU дрифт, појаву заклањања и варијабилност густине тачака. Разматра се њихов утицај на интегритет облака тачака и тачност израде дигиталног топографског плана. На основу практичног искуства у реалним условима, предложене су методолошке смернице у циљу повећања робусности и контроле квалитета MLS снимања у урбаном окружењу.

Кључне речи: MLS, урбано мапирање, нестабилност GNSS сигнала, тачност облака тачака, квалитет података, интеграција GNSS/IMU

1. INTRODUCTION

MLS technology has become an increasingly significant tool in contemporary geodetic and topographic surveying, particularly in urban environments where rapid data acquisition and high spatial detail are essential. The technological foundations and integration principles of MLS systems have been widely discussed in the literature [1], [2], [3]. By integrating LiDAR sensors with GNSS receivers and inertial measurement units (IMU), MLS systems enable the collection of dense three-dimensional point clouds while operating in dynamic conditions. The integration of GNSS and IMU subsystems and their influence on positioning stability have been extensively analyzed in previous studies [4], [5]. Compared to conventional terrestrial surveying methods, MLS significantly reduces field time and allows for efficient documentation of complex urban infrastructure. Several review studies emphasize the efficiency and productivity of MLS-based mapping in complex urban environments [1], [2], [10]. Previous studies have demonstrated that MLS enables significantly faster data acquisition and processing compared to conventional surveying methods, allowing efficient extraction of large volumes of spatial data [11], [12].

Despite these advantages, the application of MLS technology in dense urban areas presents a number of operational and methodological challenges. The accuracy and reliability of the final spatial products depend not only on the technical characteristics of the MLS system but also on environmental conditions, system configuration, trajectory stability, and data processing strategies. Urban environments are characterized by signal obstructions, multipath effects, occlusions caused by buildings and vegetation, and highly reflective surfaces, all of which can directly influence data quality and positional accuracy.

While numerous studies emphasize the efficiency and productivity of MLS-based mapping, less attention is often given to the systematic identification and analysis of its operational limitations in real-world urban surveys. In practice, issues such as GNSS signal degradation, IMU drift, variability in point density, and incomplete data capture can significantly affect the geometric integrity of the generated point cloud and, consequently, the accuracy of the derived digital topographic plan.

The objective of this paper is to identify, analyze, and systematize the key operational challenges and methodological considerations encountered during MLS-based urban topographic mapping. Based on practical implementation experience, the paper discusses the influence of environmental factors, system limitations, and data processing procedures on the quality of the final topographic product, and provides recommendations aimed at improving reliability and methodological robustness in future MLS surveys. Previous practical implementation of MLS for digital topographic mapping in regional conditions has been presented in earlier conference research [11].

2. MLS SYSTEM CONFIGURATION AND DATA ACQUISITION CONTEXT

MLS systems are based on the integration of multiple synchronized sensors mounted on a mobile platform, typically a vehicle. The core components include a LiDAR scanner, a GNSS receiver, and an IMU. The LiDAR sensor provides high-density three-dimensional measurements of surrounding objects, while GNSS and IMU systems determine the position and orientation of the platform in real time. The final accuracy of the generated point cloud depends on the stability and proper synchronization of these subsystems.

Unlike static terrestrial laser scanning, MLS operates in dynamic conditions, where the platform continuously moves through complex urban environments. This mobility enables rapid data acquisition over large areas but simultaneously introduces additional sources of uncertainty. Urban areas are characterized by tall buildings, narrow streets, dense vegetation, traffic, and reflective surfaces, all of which may influence GNSS signal reception, trajectory stability, and scanning geometry.

Data acquisition in such environments requires careful planning of survey routes, optimal driving speed, and consideration of environmental factors that may affect sensor performance. The quality of the collected data is therefore not determined solely by system specifications, but also by operational conditions and survey organization. These contextual factors form the basis for understanding the operational challenges discussed in the following sections.

3. OPERATIONAL CHALLENGES IN URBAN MLS SURVEYS

Although MLS technology enables efficient and large-scale data acquisition, its application in dense urban environments is influenced by several operational constraints that may compromise data reliability and geometric accuracy. Unlike controlled or open environments, urban areas introduce complex spatial and signal-related disturbances that directly affect trajectory determination and point cloud generation. Understanding these challenges is essential for ensuring the accuracy and completeness of the resulting digital topographic plan.

The following subsections systematically analyze the most significant operational factors encountered during MLS-based urban surveys.

3.1. GNSS SIGNAL INSTABILITY AND URBAN CANYON EFFECT

Accurate trajectory determination is a fundamental requirement for reliable MLS data. The position and orientation of the mobile platform are primarily determined through GNSS measurements integrated with IMU data. However, in dense urban environments, GNSS signal quality is often degraded due to obstruction and reflection caused by tall buildings and narrow street corridors, commonly referred to as the urban canyon effect.

Figure 1. Panoramic image acquired during MLS survey, illustrating urban canyon conditions and potential GNSS signal obstruction (photography by author).

As shown in Figure 1, limited sky visibility and dense vegetation significantly restrict satellite reception, increasing the likelihood of GNSS signal degradation. Similar positioning challenges in dense urban environments have been documented in trajectory estimation studies [4].

Signal blockage and multipath effects can lead to reduced satellite visibility, irregular signal geometry, and positional biases. These disturbances directly influence trajectory estimation and may introduce systematic shifts or local distortions in the generated point cloud. Under favorable conditions, positioning accuracy may reach approximately 2–3 cm, based on practical survey experience. In dense urban environments, however, errors may increase to decimeter-level deviations depending on environmental complexity and signal availability. In areas with prolonged signal interruption, reliance on inertial measurements increases, which may result in accumulated trajectory errors.

Consequently, GNSS instability represents one of the primary operational limitations of MLS in urban environments. Its impact is particularly significant in zones characterized by high-rise buildings, tunnels, bridges, and dense infrastructure, where continuous and stable satellite reception cannot be guaranteed.

Prolonged GNSS degradation in dense urban environments not only affects real-time positioning but may also introduce trajectory inconsistencies during data acquisition.

3.2. TRAJECTORY ERRORS AND IMU DRIFT

In urban environments where GNSS signal quality is degraded or temporarily unavailable, the MLS system increasingly relies on inertial navigation to maintain trajectory continuity. While the integration of GNSS and IMU measurements enables stable positioning under normal conditions, prolonged signal interruptions characteristic of urban canyon areas may significantly affect trajectory stability.

In such conditions, the integration of additional sensors, such as cameras and wheel odometers, can further improve data quality. Camera systems provide visual context that supports interpretation and feature extraction, while odometer measurements can enhance trajectory estimation during GNSS signal degradation.

IMU-based positioning is inherently subject to cumulative drift due to sensor noise, bias instability, and integration errors over time. The stochastic modeling of inertial sensor errors has been previously analyzed using autoregressive approaches [5]. When GNSS corrections are limited, these errors accumulate, resulting in horizontal shifts, vertical inconsistencies, and misalignment between overlapping scan strips. Such deviations directly influence the geometric coherence of the generated point cloud.

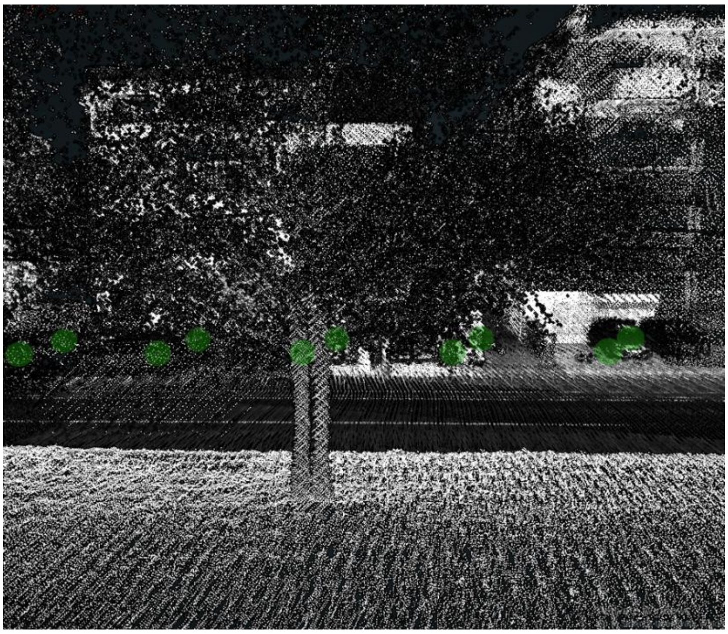

Figure 2. Point cloud representation of a tree captured in two MLS passes, illustrating misalignment caused by trajectory deviation and GNSS signal degradation in an urban environment (created by author).

As illustrated in Figure 2, complex objects such as vegetation may exhibit visible duplication or displacement when trajectory correction is insufficient. The positional discrepancy observed between two MLS passes demonstrates how GNSS instability propagates into geometric distortions within the final dataset.

In practical applications, these deviations necessitate post-processing procedures including trajectory adjustment, strip alignment, and integration of control references. The geometric reliability of the final digital topographic product therefore depends not only on nominal system accuracy but also on the effectiveness of correction algorithms applied during data processing.

These findings emphasize the importance of trajectory quality assessment in MLS-based urban mapping workflows.

3.3. OCCLUSIONS AND INCOMPLETE DATA CAPTURE

In addition to trajectory-related distortions, MLS data quality is further affected by physical obstructions within the urban environment.

In addition to trajectory-related uncertainties, one of the most significant operational challenges in urban MLS surveys is the occurrence of occlusions. Urban environments are characterized by dense building structures, parked vehicles, vegetation, street furniture, and other obstacles that obstruct the scanner’s line of sight. As a result, certain objects or parts of objects may not be captured during a single survey pass. The problem of ground and façade occlusions in urban MLS datasets has been addressed in recent research focusing on automatic detection of occluded regions [8].

Occlusions create shadow zones within the point cloud, leading to incomplete representation of façades, street elements, and ground features. In narrow streets or areas with high traffic density, these gaps may be particularly pronounced. The mobility of the platform, while advantageous for rapid data acquisition, limits the possibility of adjusting scanning angles to compensate for obstructed views.

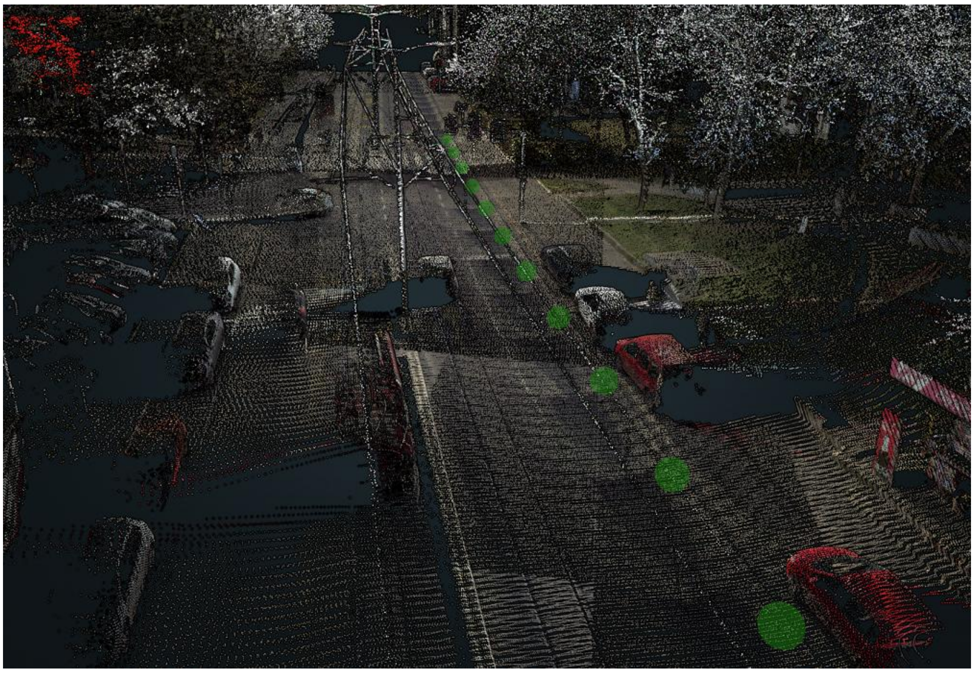

Figure 3. Point cloud visualization illustrating occlusion effects caused by urban obstacles and resulting data gaps (created by author).

As illustrated in Figure 3, occlusions caused by parked vehicles, vegetation, and surrounding urban elements generate shadow zones within the point cloud, leading to incomplete surface representation and localized reductions in point density. Incomplete data capture directly affects the reliability of feature extraction and vectorization during digital topographic plan production. Missing or partially scanned elements may require additional manual interpretation, supplementary field verification, or repeated data acquisition. In some cases, the absence of sufficient point density in occluded areas can reduce the geometric accuracy of mapped features.

Therefore, occlusions represent a structural limitation of MLS in complex urban settings and must be considered during survey planning, route design, and quality assessment procedures.

3.4. VARIABILITY OF POINT DENSITY

Point density represents a critical parameter in MLS-based mapping, as it directly influences the level of detail, feature detectability, and geometric precision of the resulting point cloud. Unlike static terrestrial laser scanning, where scanning geometry is controlled and stationary, MLS operates under dynamic conditions in which point density varies continuously. Point density variability and its impact on mapping accuracy have been discussed in recent optimization studies [6].

Several factors contribute to density variability, including vehicle speed, scanner rotation frequency, distance between the sensor and surrounding objects, and scanning angle. Higher driving speeds typically result in lower point density along the trajectory, while increased distance from vertical structures reduces the spatial resolution of captured features. Additionally, complex urban geometry may cause uneven distribution of points across façades, road surfaces, and infrastructure elements.

Variability in point density affects the reliability of automatic classification and feature extraction processes. Low-density areas may lead to incomplete edge detection, reduced accuracy in object delineation, and difficulties in identifying smaller elements such as curbs, road markings, or utility structures. Conversely, extremely high-density datasets increase processing time and computational load without necessarily improving practical mapping accuracy.

For these reasons, maintaining an optimal balance between acquisition speed and point density is essential. Survey planning must therefore consider both operational efficiency and the minimum density requirements necessary to ensure accurate and consistent digital topographic plan production.

3.5. REFLECTIVE AND COMPLEX SURFACES

The interaction between laser pulses and urban surface materials represents an additional source of uncertainty in MLS-based surveys. In urban environments, highly reflective, transparent, or irregular surfaces may influence the quality and consistency of recorded measurements.

Traffic signs, metallic elements, glass façades, and polished surfaces can produce strong reflections, partial returns, or distorted measurements. In some cases, reflective materials may generate noisy points or exaggerated intensity values, complicating automatic classification processes. Conversely, transparent or low-reflectivity surfaces, such as glass or dark materials, may produce weak or missing returns, resulting in incomplete representation within the point cloud.

Complex surface geometries further affect laser incidence angles, leading to variable measurement reliability depending on the relative position of the scanner and the object. Such effects may introduce local irregularities in surface reconstruction and influence the precision of extracted linear and planar features.

These material-dependent factors highlight that MLS data quality is not solely determined by positioning accuracy or point density, but also by the physical interaction between laser signals and surveyed objects. Consequently, careful interpretation and quality control are required during post-processing to mitigate potential distortions related to surface characteristics.

4. DATA PROCESSING AND INTERPRETATION LIMITATIONS

Beyond field-related operational challenges, the reliability of MLS-based urban mapping is significantly influenced by data processing and interpretation procedures. Although modern software platforms provide advanced tools for trajectory adjustment, strip alignment, and point cloud classification, the final quality of the digital topographic product depends heavily on processing strategy and operator expertise.

One of the primary limitations arises during trajectory correction and strip alignment. Even after GNSS/IMU integration, residual discrepancies between overlapping scan strips may remain. These inconsistencies require careful adjustment using control points or automated matching algorithms. Inadequate correction may result in geometric misalignments that propagate into the final vectorized outputs.

Point cloud classification represents another critical stage. Automatic classification algorithms are sensitive to density variability, noise, and surface characteristics. Misclassification of ground points, façade elements, or infrastructure features can introduce systematic errors in further processing. Consequently, manual verification and correction are often necessary, increasing processing time and introducing a degree of subjectivity into the workflow.

Feature extraction and vectorization also present methodological challenges. The interpretation of complex urban geometry from point clouds requires experience and consistency in applying mapping standards. Ambiguous object boundaries, incomplete data, or overlapping features may complicate accurate delineation within the digital topographic plan.

Therefore, MLS-based mapping is not solely a function of hardware performance; it is equally dependent on structured processing workflows, quality control procedures, and operator competence. These factors collectively influence the geometric integrity and reliability of the final topographic deliverables.

5. IMPACT ON DIGITAL TOPOGRAPHIC PLAN QUALITY

The operational and processing challenges discussed in the previous sections directly influence the geometric accuracy, completeness, and reliability of the resulting digital topographic plan. Since the final product is derived from the processed point cloud, any positional or structural inconsistencies within the dataset may propagate into the mapped features.

Trajectory errors caused by GNSS instability and IMU drift can result in horizontal or vertical displacements of mapped elements. Even small positional deviations may become significant when delineating linear features such as curbs, building edges, or utility infrastructure. In dense urban environments, cumulative trajectory errors may also affect the relative positioning of adjacent objects, leading to local distortions within the plan.

Occlusions and incomplete data capture impact the completeness of mapped features. Missing façade segments, partially scanned ground surfaces, or obscured infrastructure elements may require interpolation, manual reconstruction, or additional field verification. Such interventions introduce uncertainty and may reduce the overall consistency of the digital representation.

Variability in point density further influences the level of detail achievable during vectorization. Insufficient density may limit precise feature delineation, while uneven distribution of points can affect edge detection and surface modeling accuracy. Similarly, reflective or complex surfaces may introduce localized noise, complicating interpretation and classification.

Consequently, the quality of the digital topographic plan is not determined solely by nominal system specifications but by the combined influence of environmental conditions, trajectory stability, data density, and processing methodology. A comprehensive understanding of these interrelated factors is essential for maintaining geometric integrity and ensuring that MLS-derived products meet required surveying standards.

6. METHODOLOGICAL RECOMMENDATIONS

Based on the identified operational and processing challenges, several methodological considerations can be proposed to improve the reliability and consistency of MLS-based urban topographic mapping. A detailed methodological workflow for digital topographic plan production based on MLS data is presented in the author's previous master research [12].

First, careful survey planning is essential. Route design should account for potential GNSS signal obstruction, urban canyon zones, and areas with dense infrastructure. Whenever possible, survey trajectories should be optimized to ensure sufficient satellite visibility and minimize prolonged signal interruptions. In particularly constrained areas, complementary static GNSS observations or ground control points may be incorporated to strengthen trajectory adjustment.

Second, vehicle speed and scanning parameters must be adapted to urban complexity. Maintaining moderate and consistent driving speeds helps ensure adequate point density and reduces variability in spatial resolution. In areas characterized by complex geometry or critical infrastructure, repeated passes or multi-directional scanning may improve data completeness and reduce occlusions.

Third, robust post-processing procedures are crucial. Accurate trajectory correction, strip alignment, and systematic quality control checks should be implemented to detect and mitigate residual positional discrepancies. The integration of control points and cross-validation between overlapping scans can significantly enhance geometric coherence.

Finally, operator expertise and standardized workflows play a decisive role in maintaining data quality. Clear classification criteria, consistent feature extraction procedures, and structured quality assurance protocols reduce subjectivity and improve reproducibility of results.

By integrating these methodological measures, the impact of operational limitations can be minimized, thereby increasing the robustness and reliability of MLS-derived digital topographic plans in complex urban environments.

7. METHODOLOGICAL FRAMEWORK FOR EVALUATING MLS DATA QUALITY

Mobile Laser Scanning (MLS) data quality in urban environments is influenced by various operational, environmental, and system-related factors. To systematically assess their impact, a methodological framework can be defined based on parameters affecting the geometric accuracy and completeness of the resulting digital topographic plan.

Key factors include GNSS signal stability, IMU drift, occlusions, and point density variability, each contributing differently to positional accuracy and data reliability. In dense urban environments, GNSS-related positioning errors may range from several centimeters to decimeter-level deviations due to signal obstruction and multipath effects, while IMU drift can introduce cumulative errors during periods of reduced satellite visibility.

Occlusions lead to incomplete data capture, and point density variability affects the level of detail and reliability of feature extraction. Therefore, MLS data quality can be evaluated through trajectory accuracy, geometric consistency between overlapping scans, completeness of the point cloud, and adequacy of point density.

Such an approach provides a clearer understanding of how operational challenges influence the final digital topographic product.

8. CONCLUSION

Mobile Laser Scanning represents a powerful and efficient technology for urban topographic mapping, enabling rapid acquisition of high-density spatial data in complex environments. However, its practical application in dense urban areas is inherently influenced by multiple operational and methodological constraints. GNSS signal instability, IMU drift, occlusions, variability in point density, and surface-related measurement effects collectively impact the geometric integrity of the generated point cloud and, consequently, the quality of the resulting digital topographic plan.

The findings presented in this paper demonstrate that MLS-based mapping accuracy is not determined solely by system specifications, but by the interaction between environmental conditions, trajectory stability, data processing strategies, and quality control procedures. Understanding these interdependencies is essential for minimizing positional distortions and ensuring reliable spatial products.

Although MLS technology significantly enhances surveying efficiency, its successful implementation in urban contexts requires structured planning, careful trajectory correction, and rigorous processing workflows. By systematically addressing identified limitations, the robustness and methodological reliability of MLS-derived topographic products can be substantially improved.

The presented analysis highlights that MLS data quality in dense urban environments cannot be evaluated through isolated technical parameters alone but must be assessed through an integrated understanding of environmental constraints, trajectory behavior, and structural data completeness. Such a comprehensive perspective is essential for improving quality assurance protocols and advancing the methodological robustness of MLS-based urban mapping.

Therefore, these operational challenges not only affect raw data acquisition but also directly influence the geometric accuracy and completeness of the final digital topographic plan, emphasizing the need for integrated methodological evaluation.

Future developments should therefore focus on enhanced trajectory validation strategies and adaptive data acquisition planning tailored to complex urban conditions.

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