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A Hybrid System Integrating SLAM and TLS for Efficient Spatial Data Acquisition

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Abstract

This paper presents a hybrid TLS (Terrestrial Laser Scanning)—SLAM (Simultaneous Localization and Mapping) framework for spatial data acquisition that integrates mobile laser scanning (Hovermap) with high-precision terrestrial laser scanning (RIEGL TLS). The proposed approach combines the efficiency of SLAM-based data capture with the geometric reliability of TLS reference measurements, enabling fast and accurate generation of spatial datasets that support decision-making in architecture, urban planning, facility management, and digital transformation workflows. A key contribution of the study is a structured workflow for acquisition and processing, including TLS reference loop design, segmented SLAM data acquisition, and a dual-level validation strategy. The framework additionally incorporates partial measurement redundancy, enabling internal self-verification of data consistency and improving robustness against potential measurement errors and SLAM drift. The proposed workflow was validated in a continuously operating public building, demonstrating that high-quality spatial data can be acquired without disrupting building functionality. The resulting datasets support the generation of point clouds and CAD (Computer-Aided Design)/BIM (Building Information Modeling)-ready documentation, confirming the practical applicability of the proposed approach in reality-capture workflows and decision-support processes, including BIM, digital twin development, and other design-oriented applications.

Keywords: terrestrial laser scanning (TLS); mobile laser scanning (MLS); simultaneous localization and mapping (SLAM) point cloud integration; hybrid mapping framework; spatial data acquisition; reality capture; digital twin; BIM documentation

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1. Introduction

The rapid acquisition of reliable spatial data has become increasingly important for supporting decision-making processes in architecture, urban planning, facility management, and digital transformation workflows. High-quality spatial information constitutes the foundation for Building Information Modelling (BIM) [1,2], Heritage BIM (HBIM) [3,4], digital twin development [5–7], and a wide range of analytical and design-oriented applications [8–11]. As the scale and complexity of built environments continue to increase, there is a growing demand for data acquisition methods that combine efficiency, accuracy, and operational flexibility.

Various technologies are currently used for spatial data acquisition, including Terrestrial Laser Scanning (TLS) [12–14], Aerial Laser Scanning (ALS) [15], Mobile Laser Scanning (MLS) [16,17], photogrammetry [18–20], and mobile laser scanning based on

Simultaneous Localization and Mapping (SLAM) [21–23]. Each of these approaches offers specific advantages and limitations with respect to acquisition speed, geometric accuracy, completeness of the captured information, and operational requirements. Consequently, numerous studies have explored hybrid approaches that combine different sensing technologies to improve overall performance. However, the effectiveness of such systems depends not only on the selected technologies but also on the detailed acquisition workflow, including scanning strategies, trajectory planning, data registration procedures, and quality control mechanisms.

Terrestrial laser scanning is widely recognized as one of the most accurate methods for three-dimensional documentation of existing buildings and urban environments [24,25]. TLS systems provide highly detailed and geometrically reliable point clouds that can serve as a reference for advanced modelling and analytical applications. Nevertheless, the acquisition process is relatively time-consuming due to the need for multiple scanner positions and the time required for individual scans. Furthermore, despite their high accuracy, static scans inevitably contain occlusions resulting from limited viewpoints and line-of-sight restrictions. On the other hand, the density and quality of TLS data facilitate the identification and removal of transient objects such as pedestrians or temporary equipment, which commonly occur in operational facilities.

In contrast, mobile SLAM-based laser scanning enables significantly faster data acquisition by continuously recording spatial information while the operator moves through the surveyed environment. This capability is particularly valuable when documenting buildings that remain in everyday use, where minimizing disruptions to occupants and ongoing activities is essential. However, the increased efficiency is accompanied by reduced geometric accuracy [26], susceptibility to trajectory drift, and increased sensitivity to dynamic objects encountered during scanning. Moving people, opening doors, and other temporary environmental changes may negatively affect the quality and stability of SLAM-based reconstructions, especially in complex indoor environments.

This paper presents a hybrid TLS–SLAM framework that combines the geometric reliability of terrestrial laser scanning with the operational efficiency of mobile SLAM acquisition. Although the combined use of TLS and SLAM has been previously investigated [27,28], the novelty of the proposed approach lies not in the combination of these technologies itself, but in the design of an integrated and verifiable acquisition strategy. The proposed methodology provides detailed guidelines for planning and conducting spatial surveys in operational buildings. It introduces a structured workflow based on TLS reference loop design, segmented SLAM data acquisition, data integration, and embedded error analysis and quality control. In particular, segmentation of SLAM acquisition and partial measurement redundancy enable consistency checks between individual datasets and facilitate the identification of potential errors and trajectory drift during the integration process. Particular attention is also devoted to minimizing disruptions to building users while maintaining the level of geometric accuracy required for BIM, digital twin development, and analytical applications. The proposed workflow was validated through a case study involving a large public building that remained fully operational throughout the survey process. Due to confidentiality and privacy requirements, only selected portions of the building documentation are presented; however, the provided results are sufficient to evaluate the effectiveness of the proposed approach.

Despite the growing adoption of reality-capture technologies in the architecture, engineering, and construction sector, there remains a need for complete and verifiable acquisition workflows that address not only data capture but also the assessment of data reliability. This is particularly relevant for SLAM-based acquisition, where increased operational flexibility may be accompanied by uncertainty related to trajectory drift and measurement

conditions. Therefore, this study aims to develop and validate a practical hybrid acquisition methodology that integrates TLS and SLAM within a structured measurement and verification process. The proposed methodology is intended to support the generation of reliable spatial information for BIM, digital twin development, design-oriented analyses, and decision-making processes in architecture and urban planning.

2. Materials and Methods

The methodology presented in this study is structured in two complementary parts. The first part, presented in Section 2.1, describes the proposed TLS–SLAM spatial data acquisition framework at a general methodological level, independently of specific scanning systems, software platforms, or processing tools. This formulation is intended to define the principles of the approach in a tool-independent manner, allowing its application with different TLS and SLAM systems and processing environments. The second part, presented in Section 2.2, describes the implementation and validation of the proposed framework in a specific case study, providing detailed information on the measurement equipment, acquired datasets, processing procedures, registration methods, accuracy assessment, and data optimization. This distinction separates the methodology's general principles from its practical implementation and validation in the investigated building.

2.1. General Principles of the Proposed Spatial Data Acquisition Framework

The proposed spatial data acquisition methodology is based on the integration of terrestrial laser scanning (TLS) and mobile SLAM scanning into a single acquisition and validation workflow. The fundamental concept is to utilize TLS measurements as a geometrically reliable reference, while SLAM scanning is employed to rapidly acquire detailed spatial information from individual building zones (Figure 1). In this approach, TLS serves not only as a source of high-accuracy geometric data but also as a reference for the registration, validation, and quality assessment of the entire dataset.

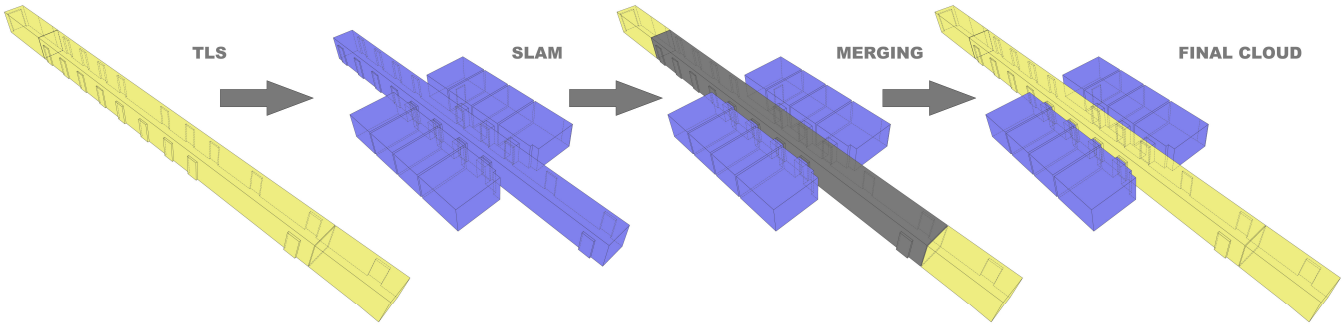


Figure 1. Conceptual scheme of the hybrid TLS–SLAM framework showing TLS corridor reference (yellow), SLAM room segment (blue), their overlap (grey), and the resulting cleaned spatial data.

2.1.1. Main TLS Reference Framework (Loops)

The first stage of the proposed methodology consists of establishing the primary TLS reference framework, comprising one or more reference loops that form the geometric backbone of the entire survey process. In building-scale applications, a reference loop is typically established along the main circulation routes, such as corridors, staircases, and other communication spaces connecting different parts of the building. Where appropriate, an additional loop may extend beyond the building envelope and return to the starting point via an alternative route. A key aspect of the proposed method is that the reference loops should form a closed geometric structure, enabling the consistency of the survey to be verified at their endpoints or points of closure (Figure 2). In justified cases, such as single-story buildings or urban-scale surveys, a single horizontal, vertical, or other

appropriately configured reference loop may be sufficient, depending on the characteristics and scale of the survey.

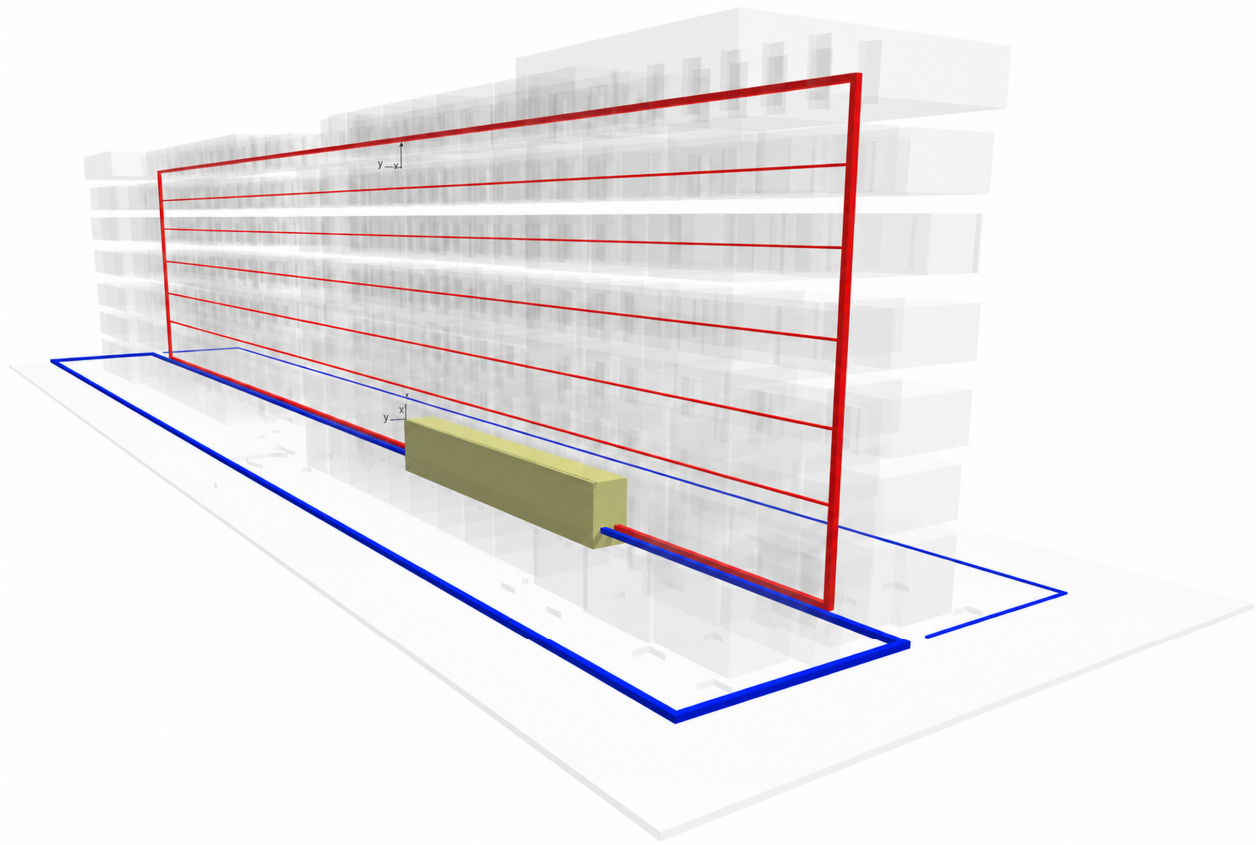


Figure 2. Main reference loops used for TLS data acquisition and registration: the horizontal loop (blue lines) and the vertical multistorey loop (red lines). The lines indicate the paths along which consecutive TLS scan positions were distributed, forming closed loops that provided the main reference framework for registering the individual scans. The yellow cuboid represents a section of the scans acquired along a complete loop, which was subsequently used for TLS data integration, as shown in Figure 1.

The design of the reference framework should provide sufficient geometric redundancy and include common, clearly identifiable features at locations where different sections of the survey are expected to be connected or verified. Such features may include window frames, façade details, building entrances, structural elements, or other distinctive architectural features. These spatial references facilitate the registration and independent verification of the acquired TLS data.

2.1.2. Segment-Based SLAM Acquisition

After establishing the TLS reference framework, detailed spatial data are acquired using mobile SLAM scanning. Instead of performing a single large-scale SLAM survey, the proposed methodology divides the building into a series of smaller acquisition segments. Each segment typically includes several adjacent rooms connected to the main circulation route represented by the TLS reference loop.

To ensure reliable registration and quality control, every SLAM segment should partially overlap with the TLS framework. This overlap provides common spatial information that enables the SLAM and TLS point clouds to be mutually aligned and subsequently evaluated for consistency and potential SLAM drift.

The segmentation strategy reduces the accumulation of localization errors, limits the influence of dynamic environmental conditions (e.g., moving people or repositioned elements such as chairs or doors), and simplifies the identification of problematic datasets requiring additional verification.

2.1.3. Point Cloud Integration and Validation

The processing workflow begins with the registration and optimization of the TLS dataset to generate the reference point cloud. The quality of the resulting point cloud should be assessed through loop-closure analysis, involving the verification of consistency between the initial and final sections of the TLS trajectory. This analysis may be supported by control points distributed throughout different parts of the surveyed facility. Prior to integration, the TLS and SLAM point clouds are subjected to general cleaning to remove noise, reflections, moving objects, and other artifacts.

Once the TLS point cloud has been successfully validated, the individual SLAM data segments are registered to and integrated with it. The accuracy of each segment can then be assessed by analyzing geometric discrepancies between the SLAM data and the TLS reference cloud. The proposed system enables validation not only within the primary connection zone between the SLAM segment and the TLS loop, but also by using additional TLS scanner positions, such as those belonging to an external loop. This dual-control mechanism provides an effective means of detecting registration errors and residual SLAM drift.

2.1.4. Point Cloud Cleaning and Optimization

The final stage of the workflow involves the optimization of the integrated dataset. Since the TLS framework provides the highest geometric reliability, overlapping regions acquired by both TLS and SLAM should be selectively cleaned by removing redundant SLAM points from the main reference loop. As a result, the final point cloud preserves the geometric accuracy of the TLS backbone while retaining the rapid and comprehensive coverage provided by the SLAM segments. The resulting integrated point cloud can serve as a reliable spatial basis for the preparation of architectural documentation and other downstream BIM-oriented applications.

2.2. Validation of the Proposed Spatial Data Acquisition Framework

The framework presented in this article (Figure 3) was validated in a large-scale public building constructed in the second half of the twentieth century, which remained fully operational and in use for its intended purpose throughout the entire survey campaign. The facility represented a typical corridor-based layout with rooms located on both sides of the circulation routes, a configuration commonly found in office buildings, hotels, educational facilities, and other public-use buildings. The total surveyed area amounted to approximately 36,000 m^2, while one of the main TLS reference loops extended over approximately 250 m. The building consisted of six above-ground floors and one underground level. Owing to the widespread occurrence of similar spatial layouts, the observations derived from this case study may be transferable to other buildings of comparable typology.

2.2.1. Data Acquisition

The reference TLS spatial dataset was acquired using a RIEGL VZ-400i terrestrial laser scanner. The survey included both the interior and façade geometry of the building, as well as its immediate surroundings (Figure 2). The scanning was divided into separate TLS projects corresponding to individual sections of the building and its floors. This organization enabled continuous quality control during data acquisition and processing while optimizing the volume of acquired data. The number of scan positions within a

single project did not exceed 200. In total, 2073 TLS scan positions were recorded (Table 1), and the resulting dataset formed the geometric backbone of the proposed hybrid system.

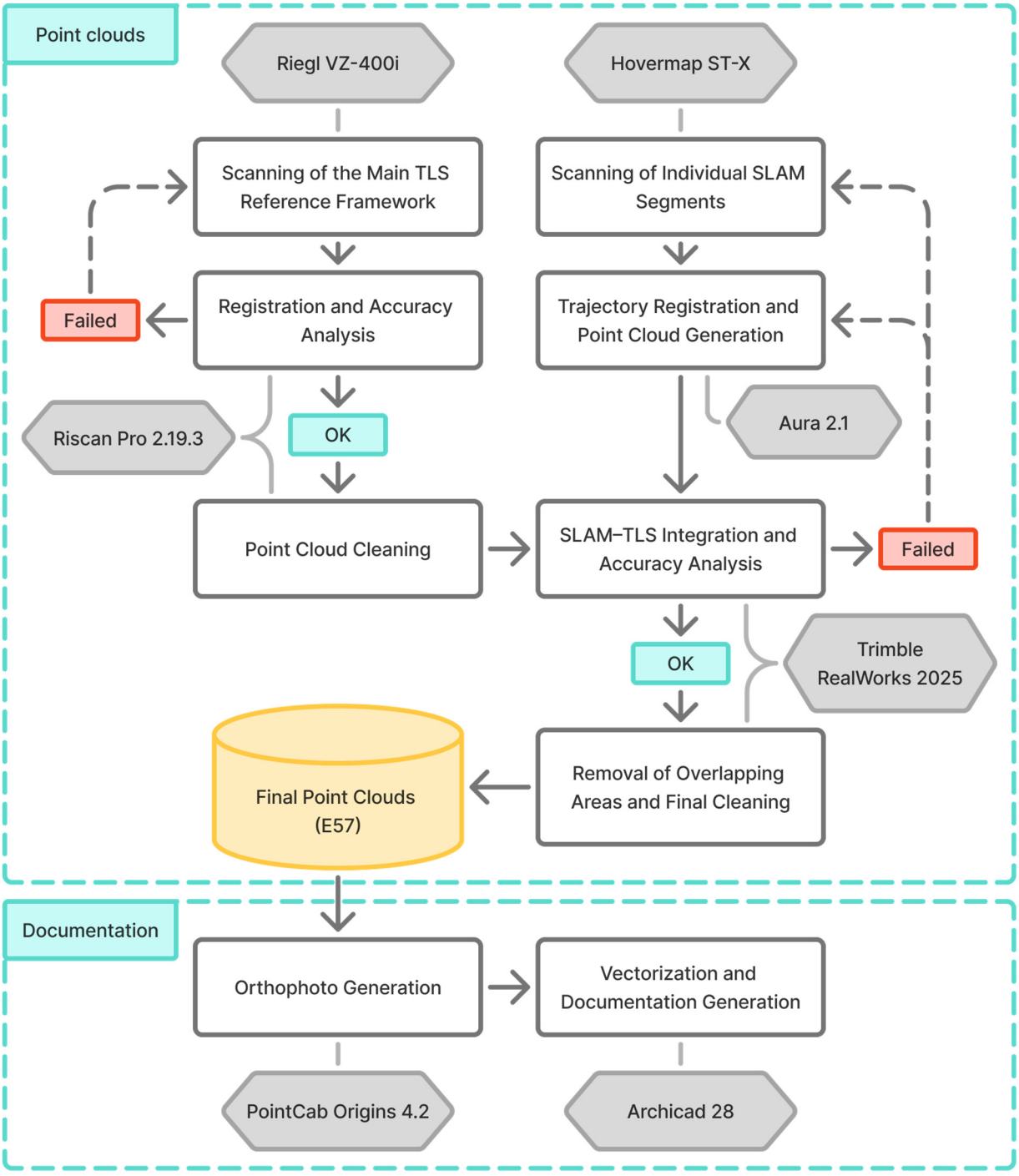
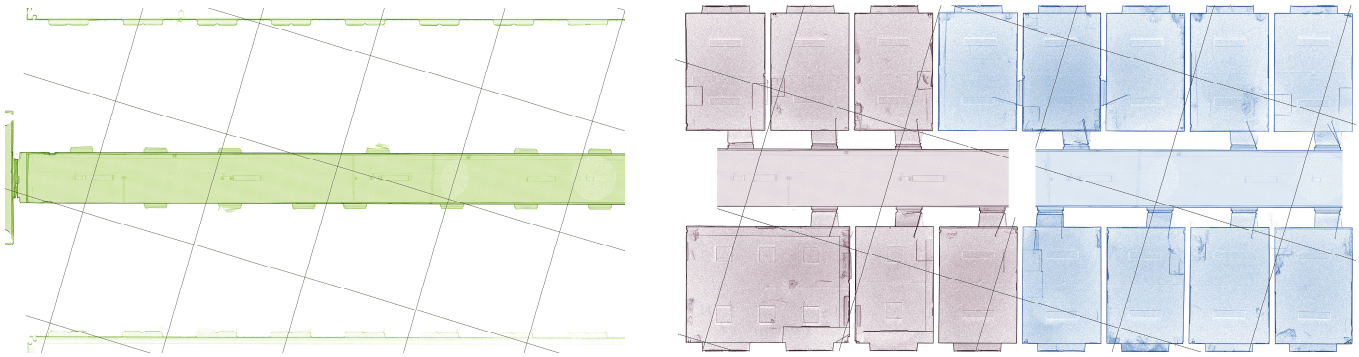


Figure 3. Schematic representation of the proposed TLS+SLAM spatial data acquisition framework, including the verification loops and the specific tools used in the research presented in this article.

Table 1. Survey equipment and the corresponding number of scan positions and trajectories.

Survey Equipment	Acquired Data
RIEGL VZ-400i	2073 TLS scan positions
HOVERMAP ST-X	351 SLAM trajectories

Mobile data acquisition was performed using the Emesent Hovermap ST-X system, which combines LiDAR (Light Detection and Ranging) sensing with SLAM-based trajectory estimation. Following the framework assumptions, the building was divided into a series of independent acquisition segments, each comprising groups of adjacent rooms connected to the main TLS reference framework (Figure 4a). Every segment included a shared area with the TLS dataset (Figure 4b), enabling subsequent registration and validation procedures. A total of 351 SLAM-based mobile scanning trajectories were acquired (Table 1).



(**a**) (**b**)

Figure 4. Point cloud segments used for TLS–SLAM integration: (**a**) TLS scan of corridor and exterior façade (green); (**b**) two SLAM scans of rooms including corridor sections used for registration (pink and blue).

2.2.2. Data Processing, Validation and Integration

TLS data were initially processed in RiSCAN PRO 2.19.3. The processing and validation procedure was organized into three consecutive stages: (1) TLS data acquisition and single-point measurement accuracy, (2) registration of individual TLS scan positions within separate projects, and (3) integration of the registered TLS projects with the main reference framework.

The survey was performed using a RIEGL VZ-400i terrestrial laser scanner. According to the manufacturer's specifications, the scanner provides a single-point measurement accuracy of ± 3 mm at a distance of 45 m when operating at a pulse repetition rate of 1200 kHz, and ± 3 mm at a distance of 100 m at 100 kHz. For the specific instrument used in this study, the manufacturer's calibration and performance verification report indicated a measured accuracy of 1.2 mm. This measurement accuracy constitutes the initial geometric basis for the subsequent registration and integration of the TLS datasets.

The registration of individual TLS scan positions was performed using automated algorithms implemented in RiSCAN PRO 2.19.3. The initial point clouds were first combined using the scanner-based registration procedures and subsequently refined in RiSCAN PRO using the built-in Automatic Registration 2 and Multi Station Adjustment 2 algorithms. These procedures use voxel-based processing; the Indoor Small scenario was applied with a voxel size of 0.05 m. At this stage, the geometry of the individual scan positions may be adjusted as part of the registration process. The resulting project-level point clouds were subsequently used as rigid datasets in the integration with the main reference framework. During this stage, the point clouds were also subjected to initial cleaning, including reflectance filtering within the range of -18 to 15 dB, retention of a single laser return, automated removal of moving objects using the built-in Mark Moving Objects tool, and manual removal of reflections and artifacts. For moving-object filtering, the maximum number of neighboring scan positions was set to 5 and the maximum distance of neighboring scan positions to 25 m. To optimize the point cloud data, an octree structure with a step size of

0.005 m was applied in RiSCAN PRO, resulting in a uniform and balanced point density across the dataset.

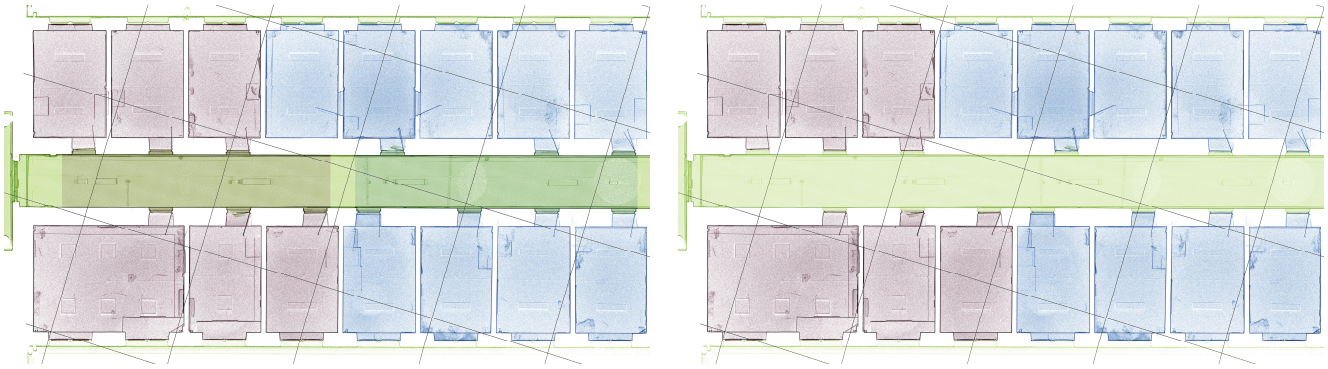
The integration of the registered point clouds corresponding to individual building sections and floors with the main TLS reference framework was performed in RiSCAN PRO 2.19.3 using the built-in semi-automatic Multi Station Adjustment algorithm. The registration was based on plane patches generated from the point clouds. Horizontal and vertical TLS reference loops were used to provide a geometrically redundant reference framework. Both loops were established within the project containing the base floor. During the integration of the individual projects with the reference framework, the mean Standard Deviation of the registration was approximately 0.004 m.

At this stage, the individual project-level point clouds were not geometrically deformed; instead, the already registered datasets were positioned relative to the common reference framework. Consequently, visual inspection of the integrated point cloud over long distances, reaching approximately 100 m, was considered an essential component of the final validation. In the context of architectural documentation, such visual assessment is particularly important because geometric consistency must be evaluated not only through numerical registration indicators but also through the spatial continuity and architectural coherence of the resulting point cloud. This complementary visual verification is especially relevant in increasingly algorithm-driven data-processing workflows, where numerical registration results should be interpreted together with the actual geometric configuration of the surveyed environment.

The SLAM data were processed in Aura 2.1, where automated reconstruction of the scanning trajectory, loop-closure detection, and trajectory optimization were performed. During this processing, the built-in moving-object filter was applied to remove elements detected as moving during the acquisition. To optimize the size of the point cloud files prior to integration with the TLS dataset, random subsampling at a rate of 20% was performed in Trimble RealWorks 2025. An octree-based reduction was intentionally not applied in order to preserve higher point density in areas considered critical for architectural inventory. The resulting point clouds were then prepared for integration with the reference spatial dataset acquired using TLS.

The final registration and integration of the TLS and SLAM data were performed in Trimble RealWorks 2025 using the built-in semi-automatic cloud-to-cloud registration algorithm. Individual SLAM segments were aligned with the TLS reference point cloud using overlapping corridor sections common to both datasets (Figure 5a). During registration, temporary point cloud segmentation was used to isolate the circulation spaces, which constituted the key registration area for the cloud-to-cloud alignment. A Refine Error (error during model cloud assembly refinement—cloud to cloud procedure) of 0.006–0.008 m was obtained in the Quality Check, calculated for the overlapping TLS and SLAM data, with a target value of approximately 0.006 m adopted for the integration process. The higher registration error compared with the TLS data was attributed to the lower geometric quality of the SLAM point clouds.

Additional partial TLS scans acquired inside rooms with open doors during the terrestrial laser scanning survey were intentionally retained and used as independent control datasets to validate the registration accuracy of the integrated point clouds. Their contribution to the alignment process was not essential and, in some cases, introduced errors and shifts during the integration of the SLAM point clouds with the TLS dataset. In the vast majority of cases, limiting the reference area exclusively to the circulation zone proved to be the most effective solution.



(**a**) (**b**)

Figure 5. Integrated TLS (green) and SLAM (pink, blue) point clouds: (**a**) with overlapping corridor regions prior to cleaning; (**b**) final cleaned dataset after removal of redundant points.

Despite the positive numerical registration indicators, visual inspection was considered necessary for the final validation of the integrated TLS–SLAM point clouds. This was particularly important over longer distances and in the context of architectural documentation, where geometric continuity and consistency of the surveyed space cannot always be fully assessed using numerical registration indicators alone.

Following registration, overlapping SLAM data located within the main TLS reference loop were selectively removed in accordance with the framework assumptions (Figure 5b). This approach preserved the geometric reliability of the TLS backbone while maintaining the efficient spatial coverage provided by SLAM acquisition.

2.2.3. Preparation of Spatial Documentation

The integrated point clouds were processed to generate orthophoto representations using PointCab Origins 4.2 software. These outputs were then exported and used as a reference for subsequent architectural drafting in Archicad 28, including the preparation of floor plans and DWG-format deliverables. In the present study, vector floor plans were produced through manual interpretation of the point cloud and orthophoto data to ensure high geometric reliability and to avoid potential errors associated with automated vectorization methods. This stage represents the final phase of the proposed process, transforming the integrated point-cloud-based spatial dataset into standardized documentation outputs commonly used in architectural practice and BIM-based environments.

3. Results

The primary outcome of the proposed framework was an integrated point cloud representing the entire building, generated through the combination of TLS and SLAM data. The mean Standard Deviation obtained during the integration of the TLS datasets with the reference framework was approximately 0.004 m, while the Refine Error obtained during TLS–SLAM registration ranged from 0.006 to 0.008 m. Visual inspection of the integrated point cloud over distances of approximately 100 m revealed no visible systematic geometric discrepancies, discontinuities, or registration shifts. The additional TLS datasets used for independent control likewise revealed no significant discrepancies. The resulting integrated point cloud provided continuous spatial coverage while preserving the geometric reliability of the TLS reference framework and was subsequently used to generate orthophoto plans (Figure 6a) and vector floor plans (Figure 6b).

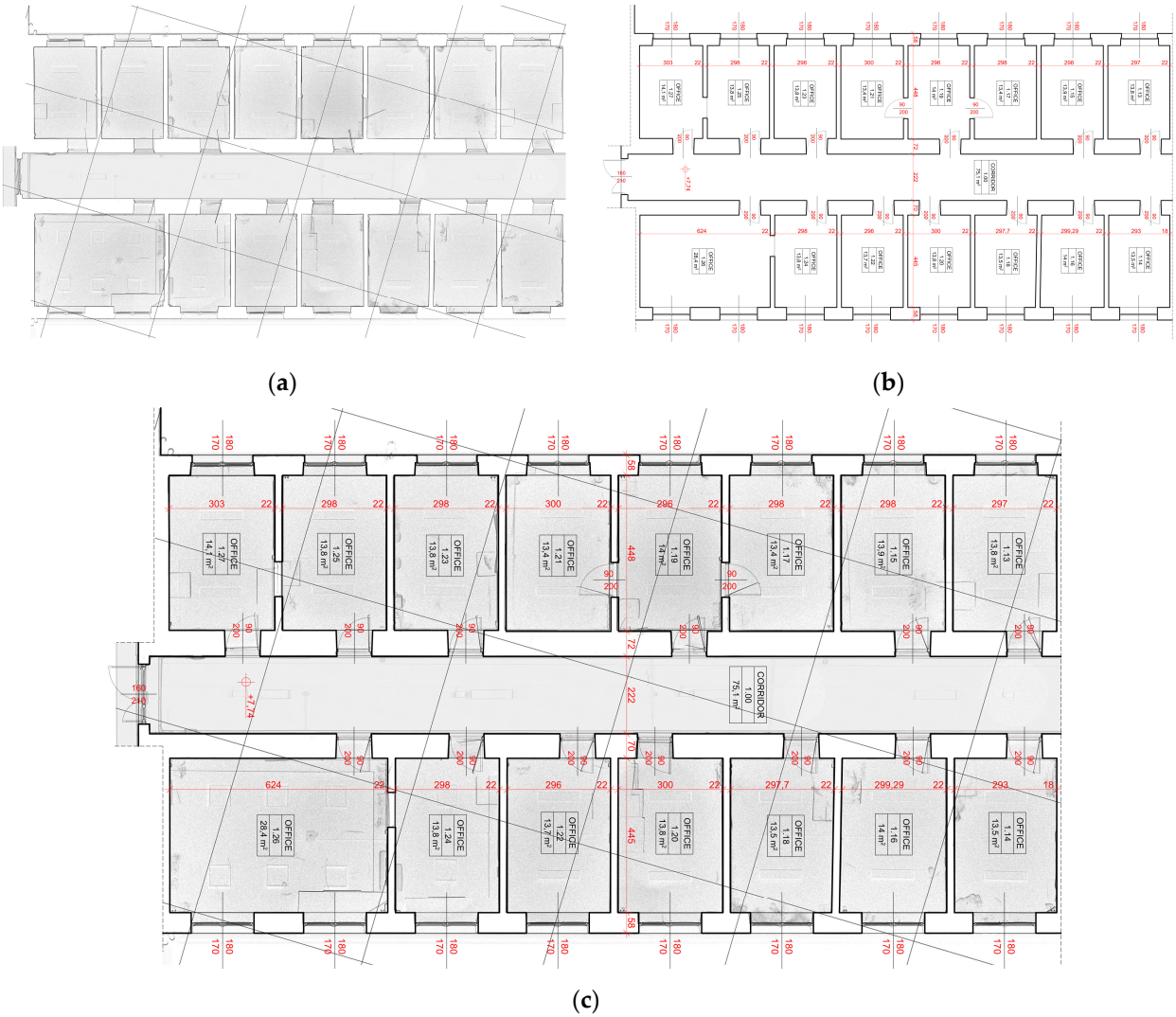


Figure 6. Excerpt from the final floor plan documentation derived from the integrated point clouds: (**a**) orthophoto plan; (**b**) vector floor plan created from the survey data; (**c**) overlay of the orthophoto plan and vector drawing. Numerical values follow the Polish number-format convention, in which commas are used as decimal separators, as the documentation was prepared for use in Poland.

4. Discussion

The practical application of the proposed hybrid TLS–SLAM system confirmed its effectiveness in enabling the efficient and reliable acquisition of high-quality spatial data. The proposed methodology enables the generation of geometrically consistent spatial datasets while significantly reducing field acquisition time. In the presented case study, the average survey efficiency was approximately one scan position per 15 m^2 of surveyed area, whereas in comparable projects conducted by the same research team using TLS-only technology, this ratio typically ranged from one scan position per 3–6 m^2. The time required to acquire data from a single TLS scan position and along a single SLAM trajectory was comparable, amounting to approximately 1–1.5 min. Therefore, the comparison was considered without differentiating between the two technologies. The results indicate a substantial improvement in field survey efficiency while maintaining the quality and usability of the resulting data.

A key aspect of the proposed methodology is its built-in self-validation mechanism. Spatial data acquisition using laser scanning technologies is inherently susceptible to various sources of error, including registration inaccuracies, sensor drift, and geometric

inconsistencies caused by dynamic environmental conditions. The proposed framework mitigates these issues through a dual-level validation strategy.

The first level of quality control is based on ensuring global data consistency through the closure of the TLS reference loop. Its verification is performed by analyzing the geometry of elements scanned from different positions that, for various reasons, could not be directly linked during the registration process. In the example shown in Figure 7, the comparison involves doors that remained closed during the scanning process. Due to the effective closure of the scanning loop in other areas, the overall geometry acquired sufficient rigidity that, over approximately 55 scan positions distributed along a distance of approximately 250 m, no significant discrepancies were observed between the initial and final points of contact of the two endpoint point clouds. The figure shows the parallelism of the door planes, the actual thickness of the door leaf, and the clearly defined geometry of the door frames. This comparison confirms the high stability and reliability of the established reference geometry. As the door could not be opened, this verification remained qualitative, and no direct numerical measurement of the loop-closure discrepancy was obtained.

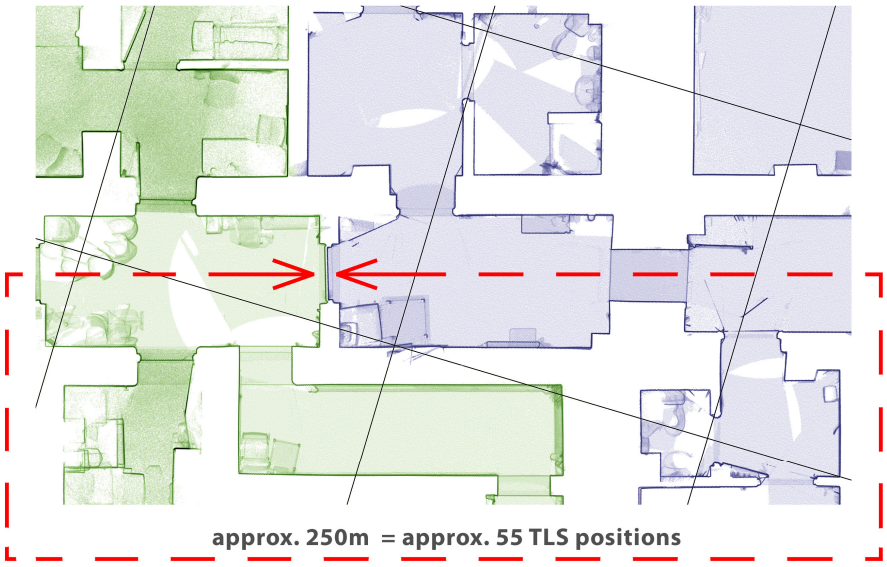


Figure 7. Excerpt from the orthophoto floor plan illustrating the geometric consistency of the main TLS reference loop. The junction of the loop closure (red dashed line) shows no detectable misalignment, confirming the robustness of the registration process. The green and purple colors represent the point clouds acquired at the beginning and end of the loop, respectively.

Second, local validation of SLAM-based datasets was performed through comparison with the TLS reference cloud (Figure 8). In the analysed case, the door geometry showed consistent alignment, with average offset 0.5 cm (Figure 8b). Across the project, the estimated average offset at the façade windows was 1.5 cm, with Figure 8a illustrating this comparison. The window comparison provided an additional local check for possible rotational misalignment of the SLAM segments registered using corridor overlaps. The segmentation of SLAM trajectories, as proposed in the framework, proved critical in maintaining geometric consistency, preventing error accumulation and drift propagation. This was further presented through a comparison with a similar case (Figure 9), where the absence of segmentation led to significant misalignment between TLS and SLAM datasets, despite the use of identical equipment.

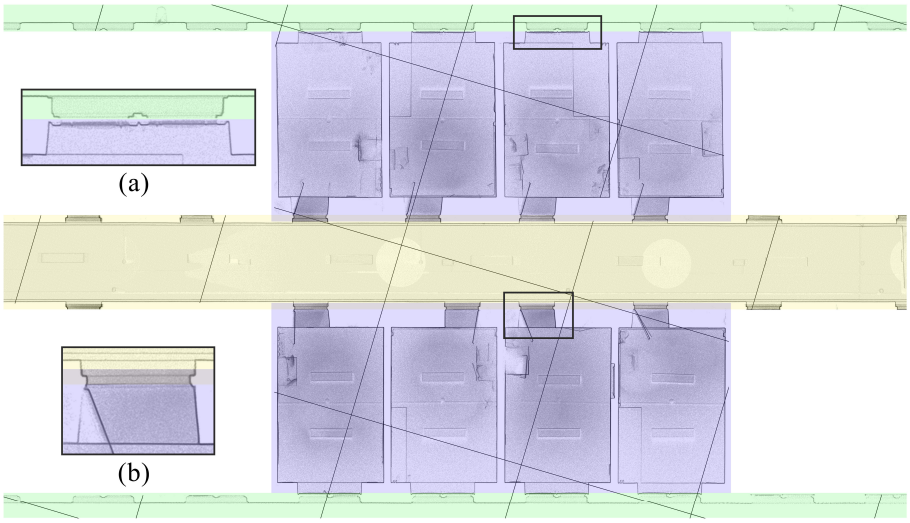


Figure 8. Comparison of TLS (corridor in yellow, façade in green) and SLAM (purple) point clouds showing alignment quality at key structural elements: (**a**) window areas; (**b**) door areas.

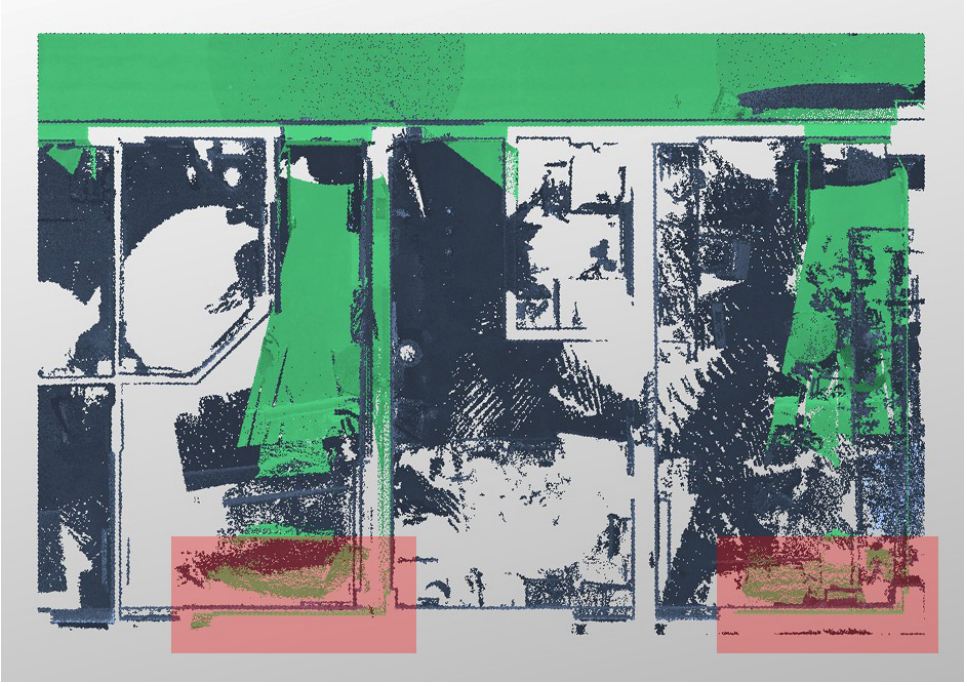


Figure 9. Excerpt from a hotel floor plan illustrating a separate case without SLAM trajectory segmentation, acquired using the same equipment, showing significant misalignment between TLS (green) and SLAM (dark blue) point clouds. Red rectangles indicate areas where discrepancies between the two point clouds are clearly visible.

From a methodological perspective, TLS provides highly accurate and reliable geometric data, but at the cost of extended survey times, increased organizational effort, and measurement occlusions in furnished interiors. This limitation becomes particularly relevant in continuously operating buildings, where survey activities should minimally interfere with users and daily functions. In this context, SLAM-based mobile scanning offers a substantial advantage in terms of speed and flexibility. However, its susceptibility to drift, sensitivity to dynamic objects such as people and moving doors, and reduced long-range stability limit its standalone applicability. Whereas Keitaanniemi et al. [29] subdivided a continuous SLAM dataset into sections for post-processing drift correction, the present workflow introduces segmentation at the acquisition stage and combines separate short

SLAM surveys with a TLS reference framework, verified through TLS loop-closure checks and local TLS–SLAM consistency assessment. The proposed hybrid approach addresses these complementary limitations [30,31] by combining TLS as a stable geometric reference with segmented SLAM acquisition to ensure both efficiency and accuracy.

Reliable spatial data constitute a fundamental basis for design and decision-making processes in architecture and urban planning. The results demonstrate that the proposed approach can efficiently generate high-quality spatial datasets suitable for the production of CAD and BIM documentation. Beyond documentation, such datasets can provide a reliable geometric basis for advanced design and analytical workflows, including algorithmic spatial optimization, AI-assisted development of urban scenarios, and the assessment of safety, environmental quality, and stakeholder preferences in public-space design [32–34]. Such applications require spatial information that is sufficiently accurate and consistent to support the evaluation of existing conditions, comparison of design alternatives, and informed decision-making. Although demonstrated at the building scale, the proposed approach could potentially be extended to urban environments using street- or block-level TLS reference networks, subject to further validation.

An important advantage of the proposed methodology is the reduction in the time required to complete the entire field survey, as described above. However, part of this time saving is transferred to the registration process, in which the SLAM segments were aligned with the TLS reference point cloud using semi-automated procedures available in Trimble RealWorks. The scale and degree of repetition of the surveyed building did not allow the fully automated functions to be used effectively. The registration therefore involved manually moving the mobile-scanning point cloud to the appropriate location within the reference cloud, followed by automated fine registration using the algorithm available in the software. In addition, the removal of overlapping TLS and SLAM areas constituted another time-consuming part of the data processing and optimization workflow. There is therefore considerable scope for further improving the proposed methodology through the automation of SLAM-to-TLS point-cloud alignment. Such automation could reduce not only the time required for data acquisition but also the time needed for subsequent data processing.

A limitation of the present study is the manual generation of vector documentation based on the processed point cloud data. Although automated vectorization methods using machine learning and artificial intelligence are currently under development [35–38], manual processing was intentionally adopted in this study to ensure maximum geometric reliability and to eliminate potential errors associated with automated interpretation. Nevertheless, the generated datasets may serve as input for automated processing pipelines, including AI-based extraction methods.

Finally, the proposed framework highlights the value of hybrid sensing strategies in the context of emerging geospatial technologies. While individual technologies such as TLS and SLAM continue to evolve, hybrid approaches provide a pragmatic pathway for leveraging their complementary strengths. Such systems not only improve current data acquisition workflows but also offer a transitional solution bridging the gap between experimental sensing technologies and fully automated, production-ready mapping systems.

5. Conclusions

This study presented a hybrid TLS–SLAM framework for efficient and reliable spatial data acquisition in operational building environments. The approach combines the high geometric accuracy of TLS with the speed and flexibility of SLAM, enabling consistent and practical reality-capture workflows.

The results confirm that the proposed segmentation strategy and dual-level validation (TLS loop closure and TLS–SLAM comparison) improve data acquisition efficiency while maintaining geometric reliability and controlling error propagation. A key finding is that, due to the potential occurrence of measurement errors in both TLS and SLAM systems, the integration of a built-in self-verification mechanism based on partial data redundancy is essential for ensuring the robustness and trustworthiness of the resulting dataset.

The conducted research demonstrated the effectiveness of the proposed methodology in continuously occupied buildings and confirmed its potential to support the generation of spatial documentation suitable for further use in CAD and BIM environments. Although the analyses were conducted at the scale of a single building, the proposed approach is potentially transferable to larger architectural and urban structures, as well as to other types of architectural objects.

Future work should focus on increasing automation in data processing and vector extraction, as well as further development of quantitative uncertainty assessment.

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