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High-resolution 3D model of urban civil structures using integrated UAV and TLS point clouds: Case study in quangninh province, Vietnam)

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Abstract
High-resolution three-dimensional (3D) reconstruction of urban buildings plays a crucial role in infrastructure management, urban planning, cultural heritage preservation, and the development of smart cities. Unmanned Aerial Vehicle (UAV)-based photogrammetry and Terrestrial Laser Scanning (TLS) are two of the most representative geospatial technologies, both of which have made significant contributions to geospatial data acquisition. However, each data acquisition technique has inherent limitations in terms of observation coverage and the ability to capture information in occluded areas, resulting in 3D models generated from a single data source that often fail to represent the complete geometric characteristics of a building. This study focuses on the integration of UAV- and TLS-derived point clouds to develop an effective approach for high-resolution 3D reconstruction of urban buildings. The proposed approach is validated through a case study conducted on an urban building located in Quang Ninh Province, Vietnam. The proposed workflow consists of the following steps: (i). data acquisition using an Unmanned Aerial Vehicle (UAV) and a Terrestrial Laser Scanning (TLS) system; (ii). Point cloud preprocessing, including noise filtering, point cloud decimation, and selection of overlapping regions; (iii). Registration of the two point cloud datasets using the Iterative Closest Point (ICP) algorithm implemented in Cloud Compare; (iv). Point cloud fusion; and (v). High-resolution 3D reconstruction of the building. Experimental results demonstrate that the integration of UAV and TLS point clouds effectively compensates for missing data over roof surfaces, building façades, and occluded areas. Compared with models generated from a single data source, the integrated approach significantly improves both the geometric completeness and the level of detail of the reconstructed 3D model. The experimental results demonstrate that the geometric accuracy of the integrated UAV-TLS point cloud is location-dependent. Specifically, millimeter-level accuracy is achieved for objects located at the base of the building, whereas objects in the roof area are reconstructed with centimeter-level accuracy. The experimental results demonstrate the feasibility and effectiveness of integrating UAV and TLS point cloud data for high-resolution 3D reconstruction of urban buildings. Furthermore, the proposed approach provides a scientific and technical foundation for the implementation of urban spatial digitalization applications in Vietnam.

Keywords: 3D model, point cloud data, Unmanned Aerial Vehicle (UAV), Terrestrial Laser Scanning (TLS), point cloud registration, Iterative Closest Point (ICP) algorithm, Cloud Compare, urban buildings, Quang Ninh Province

1. Introduction

In recent years, rapid urbanization, together with the continuous development of urban infrastructure and smart city initiatives, has substantially increased the demand for high-accuracy, high-resolution three-dimensional (3D) models to support urban management, urban planning, infrastructure asset management, structural deformation monitoring, and the development of three-dimensional Geographic Information Systems (3D GIS). Beyond providing realistic representations of architectural geometry, 3D models constitute fundamental geospatial datasets for a broad range of applications, including urban digitalization, Building Information Modeling (BIM), Digital Twins, environmental simulation, and disaster risk management. Consequently, the development of advanced techniques for the acquisition and processing of high-precision 3D geospatial data has become a major research focus in the fields of surveying, photogrammetry, remote sensing, and geographic information science [1-4].

Among the currently available technologies for 3D geospatial data acquisition, Terrestrial Laser Scanning (TLS) has been widely recognized as one of the most effective techniques for acquiring high-density, high-accuracy point cloud data, typically achieving millimeter- to centimeter-level accuracy. TLS enables the rapid capture of detailed geometric information on building façades, complex architectural features, and irregularly shaped objects with a high level of precision. However, due to limitations imposed by scanner locations and line-of-sight occlusions, TLS often encounters difficulties in acquiring complete data over roof structures and other areas that are not directly visible from the scanning positions. As a result, point clouds generated solely from TLS commonly exhibit incomplete coverage in occluded regions and on elevated building components, thereby limiting the completeness of the reconstructed 3D model [3-5].

In parallel, the rapid advancement of Unmanned Aerial Vehicle (UAV) technology, combined with Structure from Motion-Multi-View Stereo (SfM-MVS) photogrammetric techniques, has significantly enhanced the capability for generating high-resolution 3D models from digital imagery. UAV-based photogrammetry offers several advantages, including operational flexibility, relatively low deployment costs, rapid data acquisition over large areas, and an exceptional capability to capture roof structures, terrain surfaces, and urban landscapes. Consequently, UAV systems have become an efficient and cost-effective solution for large-scale 3D geospatial data acquisition. Nevertheless, point clouds generated from UAV imagery generally exhibit lower geometric accuracy than those acquired using Terrestrial Laser Scanning (TLS), particularly for building façades and other vertical structures. In addition, the quality of UAV-derived point clouds may deteriorate in regions characterized by insufficient image texture, repetitive surface patterns, or severe occlusions, resulting in incomplete or less reliable reconstruction of complex architectural features. These limitations make the integration of UAV and TLS datasets a promising approach for achieving both high geometric accuracy and comprehensive spatial coverage in urban 3D reconstruction [1, 2] [6, 7].

To overcome the limitations associated with individual data sources, numerous studies have focused on integrating UAV- and TLS-derived point clouds to produce more complete and geometrically consistent 3D models. Such integration workflows generally comprise four main stages: point cloud preprocessing, registration, fusion, and surface reconstruction. Among the available registration techniques, the Iterative Closest Point (ICP) algorithm proposed by Besl and McKay [8] remains one of the most widely adopted methods due to its ability to iteratively minimize the distances between corresponding points and achieve high registration accuracy when sufficient overlap exists between the two datasets. Building upon the original ICP framework, numerous variants have subsequently been developed to improve convergence speed, robustness against noise and outliers, and registration performance for heterogeneous point clouds acquired from different sensing platforms [8-10]. These advances have significantly enhanced the reliability of multi-sensor point cloud integration and have facilitated the generation of high-quality 3D models for complex urban environments.

In the field of urban 3D modeling, the integration of UAV and TLS data has been widely demonstrated to enhance the geometric completeness of reconstructed models, reduce data gaps, and improve the geometric accuracy of building surfaces. UAV-derived point clouds provide comprehensive information on roof structures and the overall geometry of buildings, whereas TLS data capture highly detailed representations of building façades and other areas affected by occlusions. The complementary characteristics of these two data sources enable the generation of more complete and reliable 3D models, particularly for buildings with complex architectural geometries or those located in densely built urban environments. Consequently, the integration of UAV and TLS point clouds has become an effective solution for high-resolution urban 3D reconstruction and digital city modeling [2-4].

In recent years, Unmanned Aerial Vehicle (UAV) photogrammetry and Terrestrial Laser Scanning (TLS) technologies have been increasingly adopted in Vietnam for a wide range of geospatial applications, including Digital Terrain Model (DTM) generation, as-built surveying, cultural heritage documentation, deformation monitoring, infrastructure asset management, and the development of three-dimensional (3D) geospatial databases. A growing number of studies conducted by Vietnamese universities and research institutions have explored the application of UAV or TLS data for 3D reconstruction in support of surveying, infrastructure management, and urban planning [12-15]. However, existing studies in Vietnam have predominantly focused on the independent processing and analysis of individual data sources or on conventional registration approaches based on ground control points (GCPs) and artificial targets. In contrast, research on the direct integration of UAV- and TLS-derived point clouds for high-resolution 3D reconstruction of urban buildings remains relatively limited. Furthermore, systematic investigations into standardized workflows for multi-sensor point cloud registration using advanced optimization techniques, such as the Point-to-Plane Iterative Closest Point (Point-to-Plane ICP) algorithm, as well as comprehensive evaluations of the influence of registration parameters on the geometric accuracy of reconstructed 3D models, are still scarce. Addressing these research gaps is essential for improving the reliability and applicability of integrated UAV-TLS approaches in urban 3D modeling [8-11].

Motivated by the aforementioned challenges, this study proposes an integrated workflow for high-resolution 3D reconstruction of urban buildings through the fusion of point clouds acquired from Unmanned Aerial Vehicle (UAV) photogrammetry and Terrestrial Laser Scanning (TLS). The proposed workflow consists of the following steps: (i) UAV and TLS data acquisition; (ii) preprocessing of the UAV- and TLS-derived point clouds; (iii) noise and outlier removal; (iv) point cloud downsampling to reduce data density while preserving geometric features; (v) point cloud registration using the Iterative Closest Point (ICP) algorithm implemented in CloudCompare; (vi) point cloud fusion; and (vii) reconstruction of the final high-resolution three-dimensional (3D) model. The proposed methodology is validated through a case study conducted in Quang Ninh Province, Vietnam. The results contribute to the development of a systematic technical framework for multi-source point cloud integration and provide a scientific basis for applications in 3D mapping, infrastructure asset management, urban planning, and the development of three-dimensional geospatial databases in Vietnam.

2. Study Site and Data Acquisition

2.1 Study Site

The experimental study was conducted at Ha Long New Day 2 Hotel, located in Hung Thang Ward, Ha Long City, Quang Ninh Province, Vietnam (Fig.1). The building comprises five stories and has a building footprint of approximately 70 m². It is situated within a relatively densely built urban area. The boundary of the study site is delineated by the yellow polygon shown in Fig. 1.

Fig 1: Experimental building in Ha Long City, Quang Ninh Province, Vietnam

The area surrounding the building is relatively open, providing favorable conditions for data acquisition using an Unmanned Aerial Vehicle (UAV). However, the immediate vicinity of the building is characterized by numerous tall trees with broad and dense canopies, which introduce localized occlusions for both UAV photogrammetric surveys, particularly at low viewing angles, and Terrestrial Laser Scanning (TLS) observations. From an architectural perspective, the building has a relatively simple geometric configuration and is representative of small-scale hotels commonly found in coastal urban areas. The building is topped by a flat roof, which provides favorable conditions for UAV-based data acquisition.

Considering its location, surrounding environmental conditions, and architectural characteristics, the selected building provides a representative test site for evaluating the integration of UAV- and TLS-derived point cloud data in high-resolution 3D reconstruction.

2.2 Workflow of UAV and Terrestrial Laser Scanning (TLS) Field Data Acquisition

The data acquisition workflow adopted in this study is illustrated in Figure 2. To ensure the consistency and geometric accuracy of the input datasets for subsequent point cloud integration, the field survey was organized into two primary components: (i) aerial image acquisition using an Unmanned Aerial Vehicle (UAV) and (ii) point cloud acquisition using Terrestrial Laser Scanning (TLS)**.** These two components were implemented within a unified survey framework consisting of four sequential stages: (1) survey planning and preparation of the data acquisition strategy; (2) establishment of the geodetic control network to support positioning and dataset georeferencing; (3) design of the UAV flight mission and configuration of TLS scan stations to ensure sufficient spatial coverage, adequate overlap, and minimization of occluded areas; and (4) field data acquisition according to the predefined survey plan.

This integrated workflow ensures that the UAV and TLS datasets are acquired within a common reference coordinate system, provide sufficient spatial coverage, and satisfy the geometric accuracy requirements necessary for subsequent point cloud registration, data fusion, and high-resolution three-dimensional (3D) reconstruction.

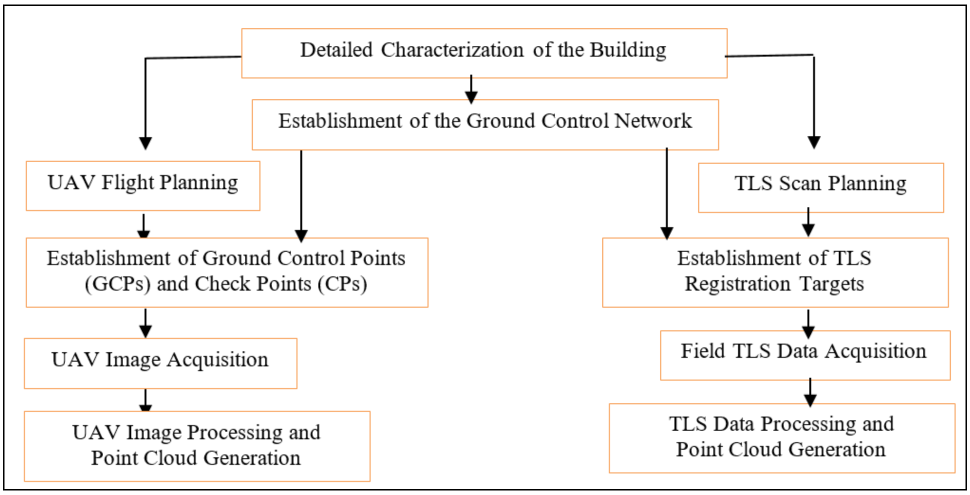


Fig 2: Workflow of UAV and Terrestrial Laser Scanning (TLS) Field Data Acquisition

3. Research Methodology

3.1. UAV and TLS Data Processing Methodology

The UAV imagery and Terrestrial Laser Scanning (TLS) datasets were processed independently using two dedicated software packages: Agisoft Metashape Professional for UAV photogrammetric processing and FARO SCENE for TLS data processing. For the UAV dataset, photogrammetric processing followed a Structure-from-Motion (SfM) and Multi-View Stereo (MVS) workflow to reconstruct a high-density three-dimensional (3D) point cloud. The SfM workflow comprised four principal stages: (i) detection and extraction of scale-invariant image features from individual images using the Scale-Invariant Feature Transform (SIFT) algorithm [16]; (ii) feature matching between overlapping image pairs to establish image correspondences; (iii) bundle adjustment to simultaneously estimate the camera interior orientation parameters, exterior orientation parameters, and three-dimensional coordinates of the matched feature points; and (iv) dense point cloud reconstruction using a Multi-View Stereo (MVS) algorithm based on the optimized image orientation parameters obtained from the bundle adjustment process [16-19].

3.2 The ICP algorithm

To integrate the point clouds generated from UAV imagery and Terrestrial Laser Scanning (TLS) data, this study employed the Iterative Closest Point (ICP) algorithm originally proposed by Besl and McKay [8]), one of the most established and widely used algorithms for three-dimensional (3D) point cloud registration. The ICP algorithm estimates a rigid-body transformation, consisting of a rotation matrix and a translation vector, to align the source point cloud (UAV) with the reference point cloud (TLS). The optimization is performed iteratively. During each iteration, the algorithm identifies the closest corresponding point pairs between the two point clouds and subsequently solves a least-squares optimization problem to estimate the transformation parameters that minimize the registration error. This iterative process continues until the Root Mean Square Error (RMSE) between the corresponding point pairs satisfies a predefined convergence criterion or the maximum number of iterations is reached [8, 20-22].

The Point-to-Point Iterative Closest Point (Point-to-Point ICP) algorithm minimizes the sum of squared Euclidean distances between corresponding point pairs:

$$E(\mathbf{R},\mathbf{t}) = \sum_{i=1}^{N} \left\| \mathbf{R}\mathbf{p}_i + \mathbf{t} - \mathbf{q}_i \right\|^2 \quad (1)$$

The corresponding optimization problem can be formulated as follows:

$$(\mathbf{R},\mathbf{t}) = \arg\min E(\mathbf{R},\mathbf{t}) \quad (2)$$

where:

- pi denotes the *i*-th point in the source point cloud derived from the UAV data;
- qi denotes the corresponding nearest point in the reference point cloud acquired from the TLS data;
- R is the rotation matrix;
- t is the translation vector;
- N is the total number of corresponding point pairs.

3.3 Flowchart of the Point-to-Point ICP Registration Workflow for UAV and TLS Point Clouds in Cloud Compare

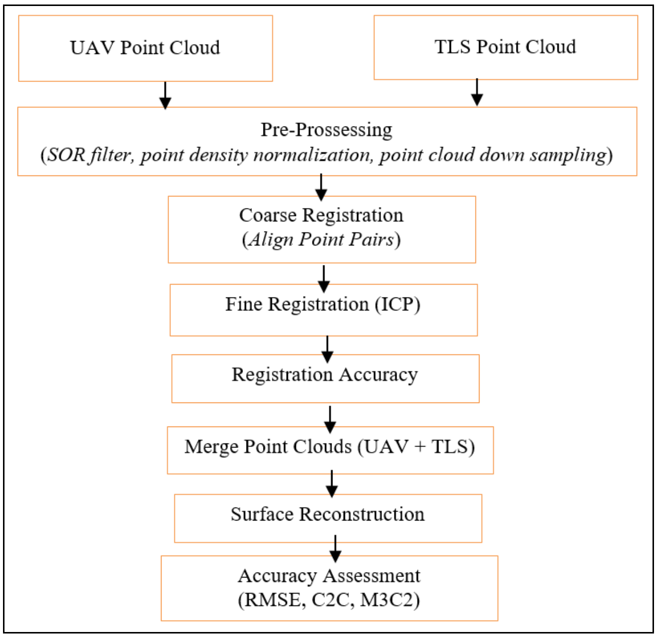


Fig 3: Flowchart of the Point-to-Point ICP Registration Workflow for UAV and TLS Point Clouds

4. Results and Discussion

4.1. Results of UAV and TLS Data Processing

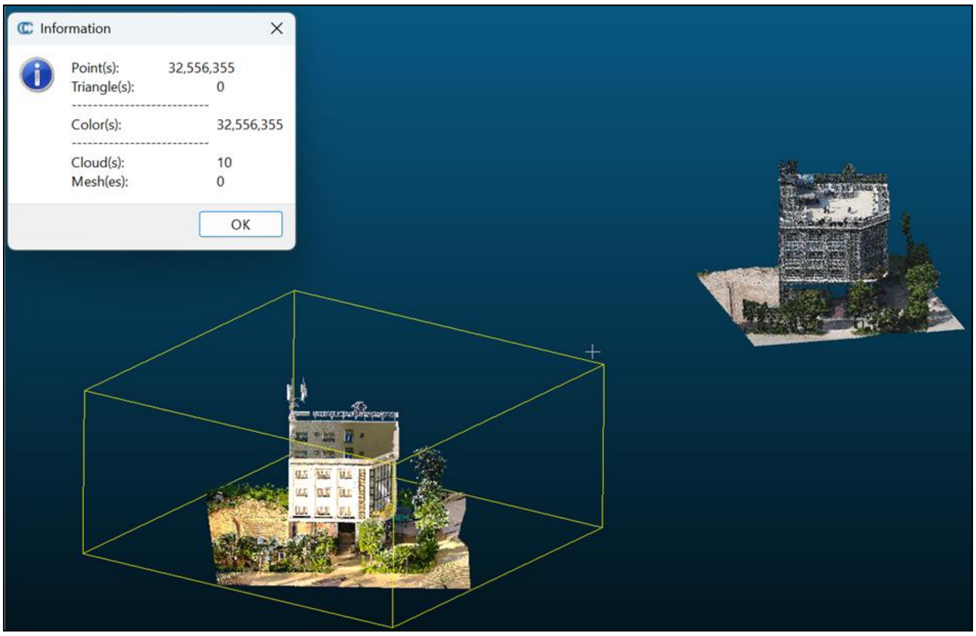
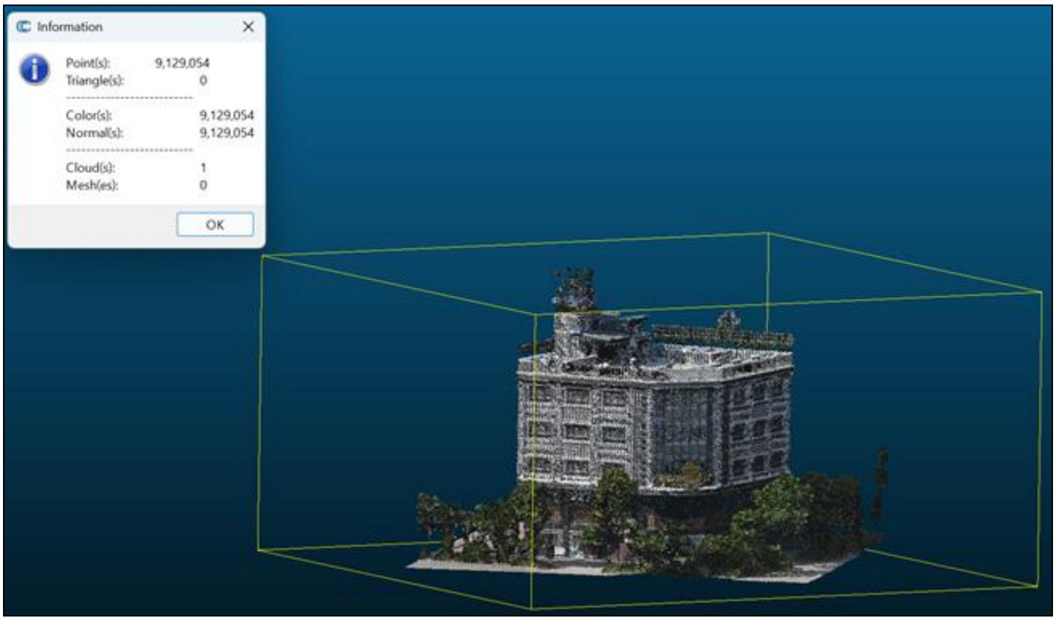
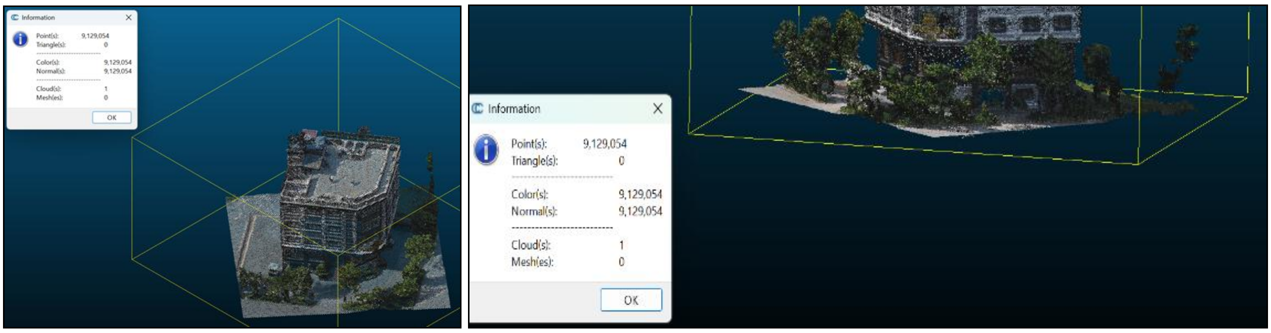


Fig 4: UAV- and TLS-derived point clouds before alignment to a common coordinate system

Following the completion of the field survey, the UAV imagery and Terrestrial Laser Scanning (TLS) datasets were processed independently using Agisoft Metashape Professional and FARO SCENE, respectively. For the UAV dataset, the Structure-from-Motion (SfM) and Multi-View Stereo (MVS) workflow reconstructed a dense point cloud comprising 9,129,054 points (fig.5), providing a comprehensive representation of the geometric characteristics of the roof, building façades, surrounding paved areas, and adjacent objects. In contrast, the TLS dataset was registered using spherical targets and checkerboard targets to generate a unified point cloud containing 29,269,808 points (fig.6). The resulting TLS point cloud exhibits a substantially higher point density on the building façades, windows, balconies, and other architectural features located at the lower levels of the structure.



(a)



(b) (c)

Fig 5: Dense Point clouds from UAV data (a), the roof portion of the UAV-derived point cloud (b), the lower portion of the building represented in the UAV-derived point cloud (c)

The comparative analysis of the geometric characteristics of the two datasets demonstrates that the UAV-derived and Terrestrial Laser Scanning (TLS) point clouds are highly complementary, reflecting the inherent differences in the data acquisition principles of the two sensing technologies. The UAV-derived point cloud provides superior spatial coverage through nadir and oblique image acquisition, enabling a relatively complete reconstruction of roof surfaces, rooftop structures, and other areas that are difficult to access using ground-based surveying techniques. However, because the point cloud is reconstructed from optical imagery using the Structure-from-Motion (SfM) and Multi-View Stereo (MVS) workflow, its point density on building façades is generally lower than that of the TLS dataset. Furthermore, occlusions caused by the building geometry, surrounding vegetation, and other obstacles in the urban environment reduce the visibility of UAV imagery, resulting in incomplete geometric information at the lower portions of the building, recessed openings, balconies, and other line-of-sight-obstructed areas.

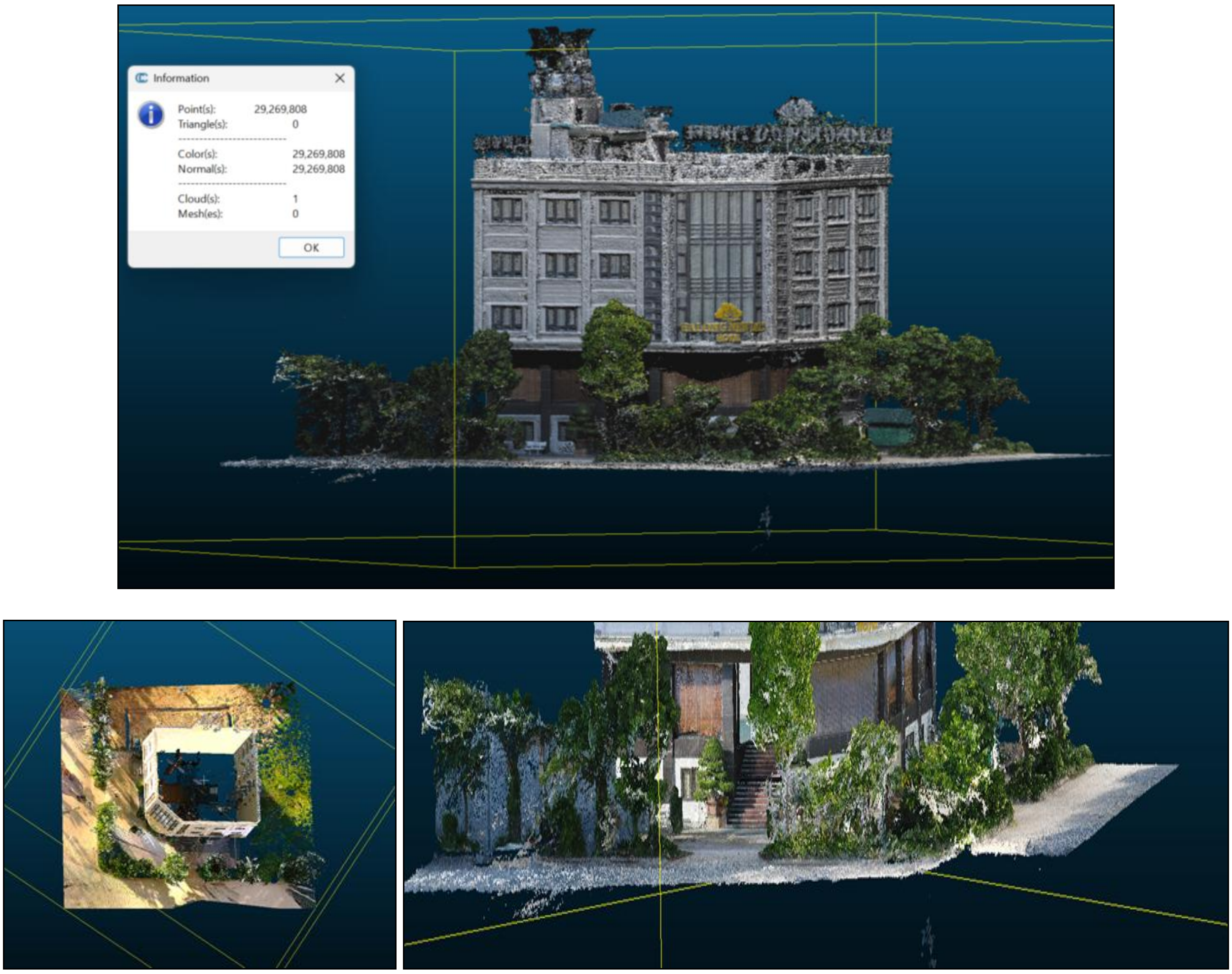


Fig 6: Dense Point clouds from TLS data (a), the roof portion of the TLS -derived point cloud (b), the lower portion of the building represented in the TLS -derived point cloud (c)

The comparative analysis of the geometric characteristics of the two datasets demonstrates that the UAV-derived and Terrestrial Laser Scanning (TLS) point clouds are highly complementary, reflecting the inherent differences in the data acquisition principles of the two sensing technologies. The UAV-derived point cloud provides superior spatial coverage through nadir and oblique image acquisition, enabling a relatively complete reconstruction of roof surfaces, rooftop structures, and other areas that are difficult to access using ground-based surveying techniques. However, because the point cloud is reconstructed from optical imagery using the Structure-from-Motion (SfM) and Multi-View Stereo (MVS) workflow, its point density on building façades is generally lower than that of the TLS dataset. Furthermore, occlusions caused by the building geometry, surrounding vegetation, and other obstacles in the urban environment reduce the visibility of UAV imagery, resulting in incomplete geometric information at the lower portions of the building, recessed openings, balconies, and other line-of-sight-obstructed areas.

The above results demonstrate that the two datasets are highly complementary in terms of both spatial coverage and geometric level of detail. Integrating the UAV- and TLS-derived point clouds not only compensates for the data gaps inherent in each individual dataset but also enhances the completeness, continuity, and spatial resolution of the reconstructed three-dimensional (3D) model. This complementary integration provides a robust foundation for generating geometrically accurate and high-resolution 3D models of urban buildings, thereby meeting the requirements of a wide range of applications, including Building Information Modeling (BIM), infrastructure asset management, heritage documentation and conservation, and the development of Digital Twins for smart urban environments.

4.2. Results of UAV-TLS Point Cloud Registration and Integration

Prior to point cloud registration and integration, the UAV- and TLS-derived point clouds were subjected to a preprocessing stage to improve the quality of the input data and ensure the stability of the optimization process. The preprocessing workflow comprised three main steps: (i) removal of noise and outlier points generated during data acquisition; (ii) elimination of objects irrelevant to the objectives of the study, such as vegetation, vehicles, and other temporary objects, in order to reduce the effects of occlusions and incorrect point correspondences; and (iii) normalization of point density through spatial subsampling, thereby reducing the density discrepancy between the two datasets and improving the computational efficiency of the subsequent registration process

Fig 7: The TLS and UAV-derived point clouds after noise filtering, vegetation removal, and point cloud down sampling

Following the preprocessing stage, point cloud integration was performed using CloudCompare v2.6.3. In this study, the TLS-derived point cloud was selected as the reference point cloud because of its superior geometric accuracy and high point density over building surfaces. In contrast, the UAV-derived point cloud was designated as the source point cloud and was transformed to align with the coordinate system of the TLS dataset. This strategy exploits the superior geometric fidelity of the TLS data to estimate the optimal rigid-body transformation, thereby improving the accuracy and robustness of the point cloud registration process.

Fig 8: Fused UAV-TLS point cloud

The integrated point cloud clearly demonstrates the advantages of combining UAV- and TLS-derived datasets. Roof structures, rooftop areas, and other surfaces observable from elevated viewpoints are comprehensively reconstructed using the UAV data, whereas building façades, entrances, windows, columns, railings, and other architectural features are represented with high geometric detail by the TLS data**.** Compared with the 3D model reconstructed solely from the UAV dataset, the integrated model substantially reduces data gaps along the building façades and significantly improves the sharpness and geometric fidelity of architectural details. Conversely, compared with the model generated exclusively from the TLS dataset, the integrated model effectively overcomes the lack of data over roof structures and other surfaces located outside the scanner's field of view. These findings confirm the complementary characteristics of the two sensing technologies and demonstrate that multi-sensor point cloud integration is an effective approach for improving the completeness, continuity, and reliability of three-dimensional (3D) building models.

4.4 Accuracy assessment

The geometric accuracy of the integrated point cloud generated from the UAV and Terrestrial Laser Scanning (TLS) datasets was evaluated by comparing geometric parameters extracted from the reconstructed 3D model with independent field measurements. The reference data were acquired using a total station, together with direct measurements of representative building dimensions, including the widths of the main entrance and windows, distances between architectural features, and other geometric dimensions that could be clearly identified in the integrated point cloud. The registration accuracy was quantified using the Root Mean Square Error (RMSE), calculated from the differences between the measurements derived from the integrated point cloud and the corresponding reference measurements obtained in the field. The RMSE provides a quantitative measure of the geometric agreement between the reconstructed 3D model and the actual structure; a lower RMSE indicates higher geometric accuracy and a greater capability of the model to faithfully represent the building geometry. The computed RMSE values and other relevant statistical metrics are summarized in the corresponding tables to provide a quantitative assessment of the quality of the 3D model after the integration of the UAV and TLS datasets.

Fig 9: Measurement of Building Features on the Point Cloud and in the Field

To evaluate the geometric accuracy of the integrated UAV-TLS point cloud, characteristic building dimensions were extracted from the point cloud and compared with corresponding in situ measurements acquired through conventional field surveying. The field measurements served as reference data for the quantitative assessment of the geometric consistency and accuracy of the three-dimensional (3D) model generated after point cloud registration and fusion.

Table 1: Accuracy evaluation results for the fused UAV-TLS point cloud

Points	Error in the X Direction (cm)	Error in the Y Direction (cm)	Mp (cm)	Error in the Z Direction (cm)	Point location
599	-0,36006	-1,08958	1,14753	-2,3491	Window
107	0,187597	0,561629	0,592132	0,46285	Ground
105	-0,26855	0,225359	0,350582	0,238866	Ground
549	-1,3453	-2,81343	3,118529	-0,76773	Roof
RMSE	0,715331	1,53857	**1,69673**	1,26283	

5. Conclusion

The primary objective of this study was to develop a high-accuracy three-dimensional (3D) point cloud database through the integration of two complementary spatial data acquisition technologies, namely UAV photogrammetry and terrestrial laser scanning (TLS). The proposed methodology focused on the registration and integration of UAV- and TLS-derived point clouds, in which the TLS point cloud was adopted as the reference dataset, while the UAV-derived point cloud served as the source dataset to be registered. Based on the experimental results, the following conclusions can be drawn:

The experimental results obtained in Ha Long City, Quang Ninh Province, demonstrate that the proposed high-resolution 3D reconstruction workflow based on the integration of unmanned aerial vehicle (UAV) and terrestrial laser scanning (TLS) point cloud data is capable of generating a 3D model with high spatial resolution, a high level of geometric detail, and superior geometric completeness. The integration effectively exploits the complementary characteristics of the two datasets: the UAV-derived point cloud provides comprehensive geometric information for the building roof and other elevated structures, whereas the TLS point cloud contributes highly detailed and accurate representations of the building façades, lower structural components, and areas that are occluded or beyond the field of view of the UAV. Consequently, the integrated 3D model provides a more complete representation of the building geometry, substantially reduces data gaps, and improves the overall reliability of the reconstructed model. These results demonstrate the effectiveness of the proposed UAV-TLS data integration approach for high-resolution 3D building reconstruction and highlight its potential for applications such as 3D mapping, Building Information Modeling (BIM), infrastructure asset management, and Digital Twin development.

The reconstructed 3D model achieved a high level of geometric accuracy, with a root mean square (RMS) error of approximately 1.7 cm. The results indicate that 3D reconstruction based on the integration of UAV- and TLS-derived point clouds is particularly well suited for individual buildings and other small-scale objects, including residential buildings, urban civil structures, cultural heritage sites, and historical architectural monuments. However, for large-scale applications, such as city-wide 3D mapping, the proposed approach remains relatively costly and time-consuming due to the extensive data acquisition and processing requirements.

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