

Automatic Extraction 3D Building Models from UAV LiDAR Point Cloud Data: A Case Study of Tunjungan Street, Surabaya

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Abstract. High resolution 3D City Models are essential for the Smart City paradigm, yet acquiring accurate spatial data in dense tropical urban environments remains challenging due to the limitations of passive optical sensors. This study addresses these issues by validating a semi-automated workflow for generating Level of Detail 2 (LOD2) building models using UAV LiDAR data, specifically focusing on mitigating systematic strip misalignment errors. Using Surabaya's Tunjungan Street as a case study, the research implements a rigorous strip adjustment method followed by nDSM-based extrusion guided by 2D footprints. Results demonstrate that strip adjustment is indispensable, improving Z-axis consistency by nearly 50% (from 1.23 mm to 0.63 mm). Crucially, this improvement minimizes vertical discrepancies and outliers, ensuring the high data cohesion required for precise architectural reconstruction and preventing geometric misinterpretations. The final products achieved a Horizontal Accuracy (CE90) of 0.079 m and Vertical Accuracy (LE90) of 0.385 m, surpassing Indonesian Class 1 standards for 1:5,000 scale mapping. Furthermore, the LOD2 models exhibited a vertical RMSE of 0.268 m, confirming the workflow's reliability for precision critical urban planning.

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1 Introduction

The "Smart City" paradigm has emerged as a fundamental tenet of modern urban management, particularly in the 21st century, where rapid urbanization necessitates the adoption of advanced technologies to foster efficiency and sustainability [1]. A pivotal element within this framework is the 3D City Model, which serves as a digital twin of the physical environment. These models enable complex simulations and analyses unattainable through traditional 2D mapping. Traditional 2D maps fail to represent the volumetric density and vertical complexity of urban canyons, which are critical for simulating wind flow, solar potential, and thermal comfort [2], [3], [4]. In dense corridors like Tunjungan Street, 3D models provide a digital twin that allows for vertical-space management and precise heritage conservation analysis. High-resolution spatial data is indispensable, particularly in complex urban environments like Surabaya, where areas such as the Tunjungan Street corridor dominated by high-rise buildings and dense vertical infrastructure require highly accurate data for effective management.

Conventional methods for high-accuracy spatial data acquisition, such as Total Stations and Terrestrial Laser Scanning (TLS), have long served as the standard approach [5]. While these methods yield high geometric accuracy, they are frequently constrained by logistical inefficiencies, time-consuming data collection processes, and difficulties in accessing busy commercial districts, rendering them impractical for large-scale applications. Conversely, aerial photogrammetry utilizing passive optical sensors struggles within narrow "urban canyons," where severe shadowing and texture homogeneity hinder the accurate reconstruction of vertical structures.

UAV LiDAR technology offers a robust solution to these challenges [6], [7]. As an active sensor, UAV LiDAR is capable of acquiring high-density 3D point clouds in complex urban environments, independent of lighting conditions, and can penetrate vegetation canopies to detect underlying structures. This makes UAV LiDAR particularly well-suited for mapping dense urban corridors, especially in tropical environments like Indonesia. However, a primary challenge in deriving accurate 3D building models from UAV LiDAR is the geometric inconsistency between adjacent flight lines, commonly referred to as strip misalignment.

These systematic errors arise from the integration of the onboard GNSS and IMU systems, causing vertical and horizontal shifts in overlapping point clouds [8], [9]. If not adequately addressed, these misalignments can severely degrade the quality of the resulting 3D building models. Furthermore, extracting building geometries to meet Level of Detail (LOD) 2 standards specifically roof structures poses a significant computational challenge. Unlike LOD1, which merely represents buildings as prismatic blocks with flat tops based on average height, LOD2 requires the interpretation of complex roof slopes and tiered structures from noisy point clouds. A hybrid workflow capable of reducing noise while preserving architectural detail is required to ensure model accuracy and viability. Consequently, the implementation of strip adjustment methods becomes imperative within

the data processing workflow. This method functions by minimizing discrepancies between overlapping flight lines through mathematical transformations of the vehicle's trajectory [10], [11].

This study aims to: (1) evaluate the effectiveness of strip adjustment algorithms in minimizing systematic sensor errors within UAV LiDAR data, and (2) develop and validate a semi-automated workflow for generating LOD2 3D building models to ensure high-fidelity urban representation. To achieve these objectives, the research first implements geometric corrections to improve trajectory consistency, which is fundamental for assessing the accuracy of the resulting base map. Subsequently, LOD2 building models are constructed through an extrusion method based on a Normalized Digital Surface Model (nDSM), utilizing the 'Extract Roof Form Information' task in ArcGIS Pro and guided by 2D building footprints. Finally, the vertical accuracy of the generated models is validated against independent terrestrial measurements from a Total Station to confirm their reliability for precision-critical urban management.

2 Methods

2.1 Study Area

This research was conducted along the Tunjungan Corridor, located in Surabaya, East Java, Indonesia as shown in Fig 1. The study area is situated within the geographic coordinates of 7°15'30" S-7°16'00" S and 112°44'00" E-112°44'30" E. The corridor stretches approximately 0.7 km with an average road width of 20 meters. This location was selected due to its significance as a major commercial hub and the complex urban morphology it presents. The area is characterized by high-rise buildings, shopping centers, office buildings, and hotels, creating an "urban canyon" effect. This environment presents specific challenges for geospatial data acquisition, including the potential for GNSS signal multipath errors caused by reflections from glass buildings, as well as occlusion zones that block the sensor's line of sight to the ground surface. These conditions make the Tunjungan Corridor an ideal site for evaluating the limitations and accuracy of UAV LiDAR systems.

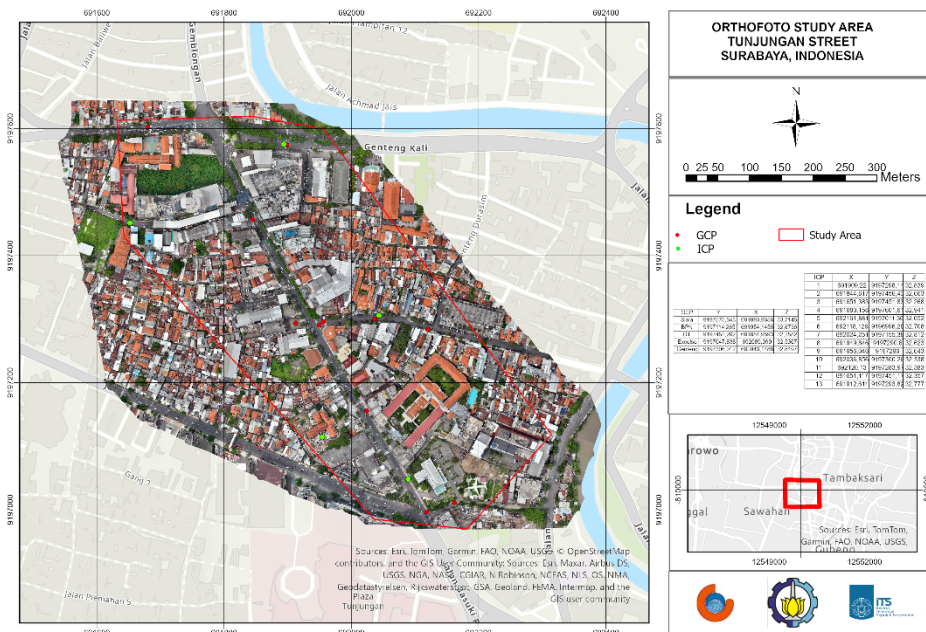


Fig. 1. Study Area

2.2 Dataset

The data utilized in this study comprises primary and secondary sources essential for obtaining precise geospatial information. The primary dataset consists of a UAV LiDAR point cloud collected using a Matrice 350 RTK platform equipped with a DJI L2 sensor, providing high-density 3D coordinates, reflectance intensity, and time-stamped trajectory data. For the building geometry, 2D building footprints were manually digitized from high-resolution orthophotos at a scale of 1:5,000. This vector data serves as the foundational geometry for the extrusion process. To ensure reliability, the positional consistency of these footprints was validated by cross-referencing them with the LiDAR-derived orthophoto, ensuring precise alignment with the physical roof extents. Furthermore, 5 Ground Control Points (GCPs) and 13 Independent Check Points (ICPs) were employed for georeferencing and accuracy assessment. The GCPs were strategically placed using a corridor-based distribution along Tunjungan Street to minimize potential model distortion in this narrow urban environment. Additional vertical validation was

conducted through field measurements using an Electronic Total Station (ETS) to serve as an independent ground truth for the generated 3D models.

2.3 Method

The workflow of this research follows a systematic approach that includes several stages: data acquisition, preprocessing (which involves trajectory processing and strip adjustment), point cloud classification, elevation model creation, and 3D building modeling.

The first stage of the process involves the acquisition and preprocessing of UAV flight data. Raw GNSS/IMU data is processed utilizing the Post-Processed Kinematic (PPK) method to generate a Smoothed Best Estimate of Trajectory (SBET). This method was selected for its robustness in maintaining high trajectory accuracy in dense urban environments. This SBET is then integrated with raw laser range data to perform georeferencing of the point cloud. The next step is strip adjustment, which addresses the inevitable errors in the IMU boresight. Flight paths in adjacent areas often exhibit mismatches due to these errors. To resolve this, the study uses an automatic algorithm, such as TerraMatch, to identify “cut lines” or “section lines” on both vertical surfaces, like building walls, and horizontal surfaces in overlapping regions[10]. By examining the geometric differences between these features, particularly in terms of vertical misalignment (Z-mismatch), correction parameters for the sensor's orientation (heading, roll, and pitch) are computed. These adjustments are then applied across the entire dataset. The use of thousands of section lines as internal observations ensures the robustness and accuracy of the adjustment process.

In the point cloud classification and elevation model creation stage, the ground and non-ground points were interpolated into a DTM and DSM using the Inverse Distance Weighting (IDW) algorithm with a grid resolution of 0.68 meters. These parameters were chosen to preserve fine architectural details in the resulting nDSM. The main goal of this step is to generate accurate surface models. To achieve this, the ground points are used to create a Digital Terrain Model (DTM), and the non-ground points are used to generate a Digital Surface Model (DSM). Once both the DSM and DTM are created, the Normalized Digital Surface Model (nDSM) is derived by subtracting the DTM from the DSM[12], [13] (eq.1).

$$nDSM = DSM - DTM \quad (1)$$

The resulting nDSM isolates the height of objects above the ground surface by removing the terrain's topography. The pixel values in the nDSM represent the absolute height of objects, effectively distinguishing between the terrain surface and the structures

above it, such as buildings. This model is critical for accurately capturing the heights of objects in a 3D space, which is essential for subsequent 3D building modeling.

For 3D building modeling, a hybrid approach based on classified data, known as Extrusion-Based Modeling, is employed. This technique combines the geometric accuracy of 2D cadastral building footprints with the vertical precision provided by LiDAR data. The main process starts with the Input Geometry step, where the 2D footprint provides the exact horizontal boundaries (X, Y) for the building. The next step involves Height Extraction, the LOD2 models were generated using the 'Extract Roof Form Information' method within the 'Create Buildings' task in ArcGIS Pro. This process utilizes procedural rules to analyze the nDSM and automatically differentiate between various roof types, such as flat, gabled, or hipped structures. Rather than relying on a single average height, the method performs zonal statistical analysis within each footprint to extract critical parameters: the maximum height is utilized to determine the ridge height (roof peak), while the median or mode height is used to estimate the eave height (wall top). This dual-parameter approach effectively captures the true volumetric shape of slanted or multi-tiered roofs while mitigating the influence of sensor noise and small rooftop outliers, such as chimneys or antennas.

Finally, the accuracy of the generated maps and models is rigorously assessed. According to Badan Informasi Geospasial (BIG) Regulation No. 15 of 2014, the base map accuracy is evaluated using 13 Independent Check Points (ICPs), as shown in Fig. 1. The Root Mean Square Error (RMSE) is calculated for both horizontal (X, Y) and vertical (Z) components, and these values are then converted into CE90 and LE90 to determine the map's accuracy scale[14]. For the 3D building model, the vertical accuracy is validated by comparing the extracted building heights from the model with independent field measurements taken using a Total Station. To confirm the reliability of the generated 3D models, a total of 13 buildings were used for validation. These buildings were selected to represent a wide range of vertical diversity, spanning from low-rise commercial shophouses (approx. 5-10 meters) to high-rise structures such as the Double Tree and Platinum Hotels (exceeding 50 meters). RMSE is calculated by comparing the heights from the model with the reference measurements, which provides an accurate assessment of the vertical performance of the 3D building model.

This multi-step methodology ensures high precision and accuracy in creating 3D building models, which are essential for urban planning, land management, and other applications that require detailed geospatial information.

3 Result and Discussion

3.1 Strip Adjustment

Initial point cloud inspections revealed visible vertical discrepancies between adjacent flight paths due to IMU boresight calibration errors. To resolve this, a strip adjustment process was implemented, which significantly enhanced geometric integrity by reducing the average Z-mismatch and RMSE by approximately 50%. Table 1 presents the comparative statistics, grounding the claim of improved data cohesion in quantitative results.

Table 1. Strip Adjustment Error Statistics

Parameter	Value Before Adjustment	Value After Adjustment (m)	Percentage Improvement
Average 3D Mismatch	0.00123	0.00063	48.78%
Average Z Mismatch (Vertical)	0.00063	0.00063	48.78%
RMSE (Sum Z)	0.002	0.001	50.00%
Maximum Mismatch	0.035	0.013	62.68%

The data in Table 1 indicates a substantial improvement in data cohesion after the strip adjustment process. The average vertical mismatch (Average Z Mismatch) decreased by nearly 50%, reaching a sub-millimeter level of 0.00063 meters, significantly enhancing the statistical quality of the dataset. More importantly, the maximum Z mismatch, which represents outliers, dropped dramatically from 3.5 cm to 1.3 cm. This reduction of outliers is crucial for applications requiring high precision, such as micro-drainage analysis, where such errors could lead to misinterpretations, such as incorrect identification of roof texture in the 3D model.

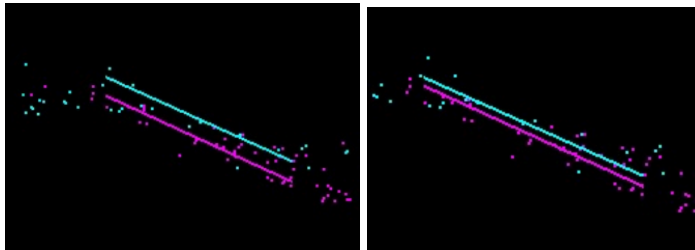


Fig. 2. Comparison of Point Cloud Alignment with Tie Line - Left: Before Strip Adjustment, Right: After Strip Adjustment

The strip adjustment process involved adjusting 6,034 section lines, providing a substantial internal observation dataset. The large number of observations ensures a robust

statistical basis, confirming that the global representation of sensor errors, especially those due to IMU calibration, was effectively corrected. As a result, the strip adjustment minimized the RMSE compared to the laser system's inherent noise floor, improving the overall geometric quality of the model. Visually, as shown in Fig. 2, this adjustment resulted in a smoother surface and a significant reduction in "step edges" the vertical offsets previously visible between overlapping flight strips. The clearer alignment of profile lines on roof surfaces and walls demonstrates the substantial improvement in vertical accuracy, enabling the generation of a more refined 3D surface model.

3.2 Geometric Accuracy

The accuracy of the geospatial product from the LiDAR campaign was evaluated based on several key metrics, as shown in the Table 2. The spatial resolution of the product was measured at 0.681 meters, indicating the level of detail captured by the LiDAR system and reflecting the precision with which features in the landscape can be distinguished. The horizontal accuracy, represented by the CE90 value, was 0.079 meters, which significantly surpasses the tolerance of 2.5 meters for a scale of 1:5,000 as set by the Geospatial Information Agency (BIG) standards. This value also meets the Class 1 requirement for horizontal accuracy at a scale of 1:1,000, where the acceptable CE90 is 0.2 meters. In terms of vertical accuracy, the LE90 value was 0.385 meters. This result meets the Class 1 requirement ($LE90 \leq 1$ meter) for a 1:5,000 scale but falls within the Class 3 standard ($LE90 \leq 5$ meters) for a 1:1,000 scale. This level of vertical precision is highly relevant for LOD2 building modeling, as it ensures that the extracted roof heights and structural geometries remain within the acceptable error margins for high-fidelity urban simulations and infrastructure management. Overall, these results demonstrate that the LiDAR system provides highly accurate spatial data, particularly in horizontal positioning, making it suitable for 3D building model generation. However, further refinement of vertical accuracy is necessary for producing highly precise 3D models that require the strictest level of detail, especially in urban planning and detailed building design.

Table 2. Geometric Accuracy Assessment Results

Aspect	Measurement Result (m)
Spatial Resolution	0.681
Horizontal Accuracy (CE90)	0.079
Vertical Accuracy (LE90)	0.385

3.3 3D Model Buildings

The core output of this study is the LOD2 3D building model, which is generated through an extraction process that utilizes the Normalized Digital Surface Model (nDSM) to determine the vertical dimensions of structures, defined by the 2D footprint. The use of the nDSM effectively filters out the influence of terrain topography variations, allowing the algorithm to focus solely on the height of objects relative to the ground. This technical approach is especially critical along the 0.7 km Tunjungan Street corridor, where the ground elevation exhibits notable variations. By quantifying and removing these terrain slopes through the nDSM, the workflow prevents topographical distortions from affecting the building height calculations, ensuring that the generated models align accurately with the actual vertical dimensions of the structures. As demonstrated in the Fig.3, the application of the nDSM ensures accurate building height extraction, highlighting the vertical dimensions of the structures and ensuring they are represented accurately, free from the influence of varying terrain.

The generated model successfully captures the roof shapes, distinguishing them from the simpler LOD1 block. By analyzing the point cloud distribution within each footprint, the algorithm reconstructs roof geometries, such as differentiating between the flat roofs of modern buildings and the gabled roofs of heritage structures. This approach significantly improves the dataset's utility, allowing applications like solar radiation simulations that depend on roof slope and orientation. The 3D model clearly illustrates these roof forms and accurately represents building features, making the model more suitable for advanced planning and analysis.

The extrusion method used in this study results in a clean and geometrically consistent model. The model aligns consistently with the cadastral footprint, resolving issues such as jagged building edges. However, it is important to acknowledge the limitations of extrusion-based modeling, particularly when dealing with highly complex or non-traditional roof geometries that may require more advanced reconstruction techniques. The resulting 3D model demonstrates a smoother, more accurate urban representation, enhancing the model's reliability for urban planning and other applications. This 3D building model, derived from the nDSM-based extraction process, showcases the effectiveness of this methodology in generating high-quality, detailed 3D models, making them ideal for further urban analysis and planning applications.

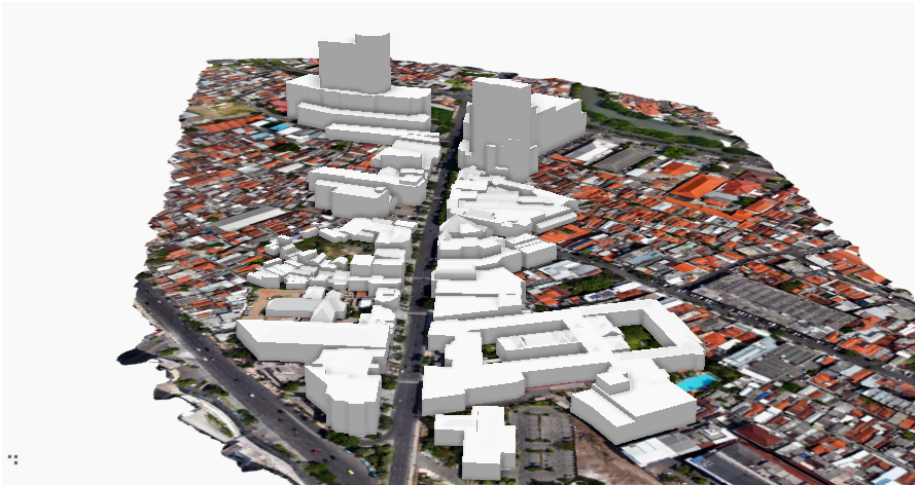


Fig. 3. Visualization of LOD2 Building Models generated from nDSM-based extrusion along Tunjungan Street

3.4 Validation Vertical Height Of Model 3D

To validate the absolute vertical accuracy and roof height consistency of the generated 3D models, a rigorous ground-truthing campaign was undertaken utilizing an Electronic Total Station (ETS). A sample set of thirteen buildings, exhibiting a wide range of elevations, was selected to ensure the validation process adequately represented the vertical diversity within the study area.

The selection of these samples was designed to capture a broad spectrum of the urban topography. This included high-rise structures, such as the Double Tree and Platinum Hotels, as well as low-rise commercial clusters like shophouses. Integrating this variety was crucial to verify the model's consistency across different vertical tiers.

The analysis yielded a Root Mean Square Error (RMSE) of 0.268 meters (approximately 27 cm). Notably, this performance metric surpasses the LE90 value recorded for the general ground surface (0.385 m), demonstrating that the model is well within the acceptable decimeter level thresholds for LOD2 building modeling and urban planning applications. This discrepancy is likely attributable to the physical properties of the building roofs; as hard, reflective surfaces, they provide cleaner and less ambiguous laser returns. In contrast, ground-level measurements are often complicated by vegetation, uneven terrain, or shadow occlusion, which tend to reduce accuracy in standard LE90 calculations.

4 Conclusion

This study establishes a validated, automated workflow for extracting LOD2 3D building models from UAV LiDAR data, utilizing the Tunjungan Street corridor in Surabaya as a representative urban case study. A pivotal component of this success was the integration of a rigorous strip adjustment method based on section lines, which proved indispensable for high-fidelity modeling—specifically in improving roof height accuracy and reducing systematic strip misalignment. This correction process effectively mitigated vertical mismatches by nearly 50%, tightening Z-axis consistency from 1.23 mm to 0.63 mm, thereby ensuring a robust foundation for subsequent modeling steps.

In terms of geospatial compliance and model reliability, the generated outputs demonstrated exceptional precision. With a Horizontal Accuracy (CE90) of 0.079 m and a Vertical Accuracy (LE90) of 0.385 m, the data comfortably exceeds the Class 1 standards for 1:5,000 scale mapping mandated by the Badan Informasi Geospasial (BIG), confirming its suitability for formal planning purposes. Furthermore, the extrusion-based technique successfully produced LOD2 geometries that accurately capture roof structures surpassing the limitations of standard LOD1 block models with a vertical RMSE of 0.268 m when corroborated against independent Total Station surveys. This level of precision explicitly confirms the model's suitability for LOD2 applications and complex urban planning tasks, meeting standard vertical tolerances for 3D building city development.

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