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Accuracy Assessment of UAV–LiDAR Integrated LOD 3 Housing Models: A Case Study in Darul Hana, Kuching

Full Paper

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Che Ku Ahmad Fuad Che Ku Abdullah[1]*, Mohd Fadhli Che Adenan[1], Bong Siaw Wee[2]

[1]Department of Civil Engineering, Politeknik Kuching Sarawak, M 22, Jalan Matang, Petra Jaya, 93050 Kuching, Sarawak, Malaysia
[2]Department of Electrical Engineering, Politeknik Kuching Sarawak, M 22, Jalan Matang, Petra Jaya, 93050 Kuching, Sarawak, Malaysia

*Corresponding author: ahmad_fuad@poliku.edu.my
Please provide an **official organisation email** of the corresponding author

Abstract

This study evaluates the accuracy of a 3D housing model (LOD 3) developed for the Darul Hana residential area in Kuching, Sarawak, using an integrated approach of UAV photogrammetry and Mobile LiDAR scanning. The primary objective is to assess the reliability of digital measurements extracted from the model by comparing them with field measurements obtained using a distometer. The 3D model was generated through structure-from-motion and LiDAR data integration. The comparison results indicate a Root Mean Square Error (RMSE) of ±1.33 m, influenced by several outliers. While this level of accuracy may not meet the requirements for high-precision surveying applications, it is acceptable for visualization, documentation, and preliminary planning at the housing scale. The results demonstrate an effective workflow for housing-scale 3D modelling, with digital measurements extracted using ACUTE software.

Keywords: UAV, LiDAR, ACUTE software, 3D modelling, spatial accuracy, housing survey

1. Introduction

The quick development of 3D modelling technologies has brought formidable changes to surveying and mapping, which is a typical field of geomatics. Traditional building surveys (based on manual measurements made by used measuring tapes, distometers or total stations) are often time-consuming and labour-intensive processes limited by safety and accessibility considerations in dense residential areas (Rahman, 2023). In the context of urban development, a growing request for more effective and reliable solutions for spatial data acquisition and building documentation is evident.

In recent years, Unmanned Aerial Vehicle (UAV) photogrammetry and laser scanning have been combined as a viable solution to meet the needs of rapid and high-resolution data acquisition. On the other hand, UAV mapping retrieves detailed aerial image from different angles and point cloud data about houses based on laser scanning technology for high density, which are conducive to information extraction. It has been proved that point cloud data fusion from different sensors, e.g., airborne and terrestrial laser scanning, contribute to enhancement of the completeness and geometric accuracy of 3D building models (Abdullah et al., 2017 & Remondino & Fraser, 2019). Recent research has also shown that hybrid photogrammetry–LiDAR strategies enhance model completeness and reduce occlusion, specifically in housing and urban contexts (Habib et al., 2016 & Nex & Remondino, 2014).

Level of Detail (LOD), determining geometric and visual representation of a building, has been an important concept in 3D building modelling. LOD 1 as simplified block models, LOD 2 in the form of building footprints with its height information, LOD 3 for realistic representation in 3D including façade geometry, roof structures and detailed building elements (Biljecki et al., 2013 & Chen & Wu, 2020). In such categories, LOD 3 is especially conducive to accuracy verification applications as it is capable of direct dimensional measurement and comparison with field data (Li & Zhang, 2021). Previous studies have also shown that LOD 3 models are increasingly used in urban documentation and digital twin development because they offer a good trade-off between geometric complexity and data manipulation (Gröger & Plümer, 2012).

The use of terrestrial laser scanning (TLS) technologies to three-dimensional as-built building modelling has also been reported that can be used for accurate dimension analysis and realistic structure representation of building components, which is an essential component in scaling accuracies at the building scale (Abdullah et al., 2017). Nevertheless, although new systems are developed using UAV and TLS based modelling methodology, the reliability of digital data extracted from three-dimensional (3D) models is still under discussion. Measurement variance may still exist because of limited number of observations, irregular point cloud registration inaccuracy, modulation workflow instructions and unpredictable environmental conditions especially at the housing scale (Tan & Ahmad, 2022 & Zhou et al., 2023).

Despite the rapid development of UAV and LiDAR integration for 3D building modelling, previous studies have primarily focused on model generation and visual quality, with limited emphasis on validating the reliability of extracted dimensional measurements at the housing scale. Furthermore, there is a lack of empirical assessment comparing digital measurements from LOD 3 models with ground-based observations. Therefore, this study aims to address this gap by quantitatively evaluating the accuracy of digital measurements derived from an integrated UAV–LiDAR workflow using field measurements as ground truth.

2. Methodology

In this study, a workflow comprising UAV-based photogrammetry, Mobile LiDAR scanning and 3D modelling was utilized to validate the positional accuracy of a LOD 3 model at residential scale. The method was developed to make field observations and digital measurements consistent with one another for a comparison of measurement accuracies. The general workflow for data collection, processing, model building and accuracy estimation can be seen in Fig. 1.

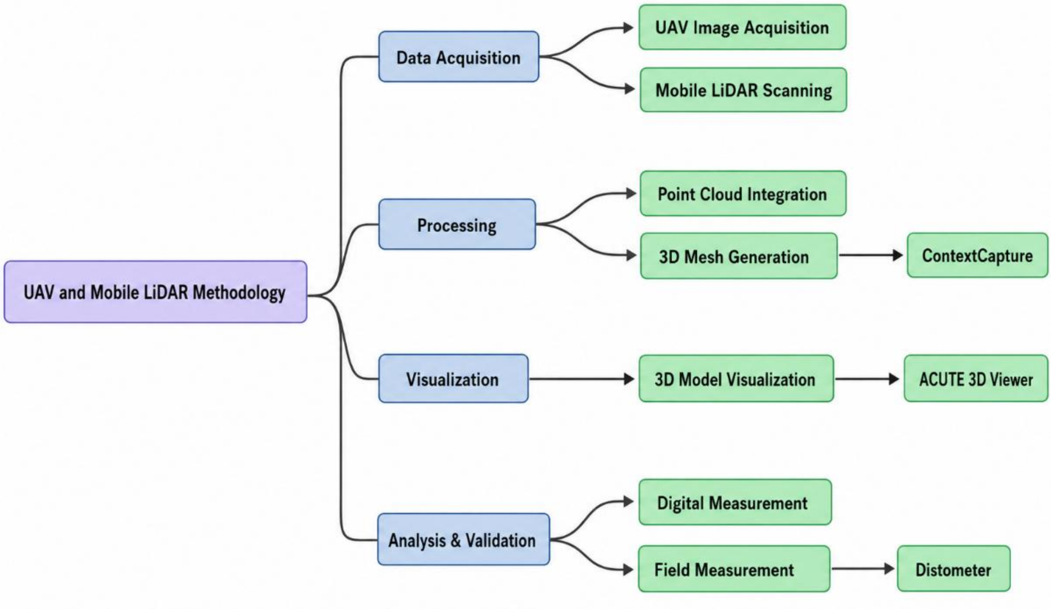

Fig. 1: UAV and Mobile LiDAR data acquisition workflow, 3D model generation, digital and field measurement, accuracy analysis

2.1 Study Area

This study was carried out in the residential area of Darul Hana, Petra Jaya, Kuching, Sarawak. The area consists of uniformly aligned single-storey terrace houses which provide for a controlled accuracy assessment in the context of 3D building modelling. A typical single-story terrace house was chosen as the subject of analysis because of its architectural simplicity, 3 well-determined building dimension and ease for digital data collection along with field measurements.

The regularity of the building design helped to avoid possible errors due to architectural complexity and allowed measurement differences to be mainly affected by different acquisition and modelling strategies rather than structural heterogeneity.

2.2 Data Acquisition

Data acquisition was conducted using UAV photogrammetry and Mobile LiDAR scanning. The UAV survey was performed using a DJI Phantom 4 RTK quadcopter, a mapping-grade UAV equipped with a high-resolution RGB camera (20 MP) and RTK positioning capability. The RTK functionality enhances georeferencing accuracy, which is essential for improving the reliability of spatial measurements derived from the 3D model. The flight was conducted at an approximate altitude of 40 m above ground level, with 80% forward overlap and 70% side overlap to ensure sufficient image coverage and reliable feature matching. Multiple flight passes were carried out to capture all building perspectives, including the front, rear, sides, and roof.

The Mobile LiDAR system was used to capture dense point cloud data of the building geometry, particularly for vertical structures and areas with limited visibility from aerial imagery. The LiDAR data achieved an estimated point density of approximately 200–400 points/m², providing sufficient detail for housing-scale modelling.

The datasets obtained from UAV and LiDAR were georeferenced using onboard GNSS positioning and further aligned during processing. Data registration between the photogrammetric model and LiDAR point cloud was performed using a cloud-to-cloud registration approach within ContextCapture software to ensure geometric consistency and minimize misalignment errors.

2.3 Data Processing and Model Development

The UAV images and Mobile LiDAR point cloud data were co-processed using ContextCapture software according to the workflow illustrated in Fig. 1. The processing steps included image registration, point cloud integration, and 3D mesh generation. The fusion of airborne and terrestrial datasets improved the geometric accuracy and surface representation of the model. Multi-source spatial data were integrated following established photogrammetric and laser scanning procedures for building-scale modelling (Luhmann et al., 2023).

The resulting 3D mesh was exported in 3MX format and visualized using ACUTE 3D Viewer (ACUTE, 2023), where digital measurements were extracted for accuracy assessment. SketchUp was additionally used to enhance model visualization for presentation purposes. The model represents the roof geometry, façades, and building height in accordance with LOD 3. This detailed 3D model enabled a quantitative comparison between digital and field measurements.

The integration approach adopted in this study follows established multi-sensor data fusion techniques, where point clouds from different sources are registered and combined to improve model completeness and accuracy (Abdullah et al., 2017).

2.4 Digital and Field Measurement

Digital measurements were obtained from 3D model in ACUTE 3D Viewer, such as wall length, roof height, door size and window size. Field measurements for each treatment were simultaneously made by means of a distometer, along cruciform distances identical to those measured digitally and at the same locations.

All field measurements were conducted under near-identical settings to avoid introducing any sampling bias due to differences in lighting, shadows, or temporary blockages. The measuring points in the field were used as truth data to validate the accuracy of digital model.

2.5 Accuracy Assessment

The accuracy of the developed 3D model was evaluated by comparing digital measurements extracted from the model with corresponding field measurements obtained using a distometer. The comparison was carried out based on selected building elements, including wall lengths, window dimensions, door sizes, and building height.

The discrepancies between digital and field measurements were quantified using absolute error and Root Mean Square Error (RMSE). Absolute error represents the magnitude of difference between the two measurements, while RMSE provides an overall indicator of measurement accuracy across all sampled points.

A total of 12 measurement points were selected to represent different parts of the building geometry, ensuring a balanced and reliable assessment. These points were carefully chosen from both horizontal and vertical elements to capture variations in measurement accuracy.

To minimize measurement uncertainty, field data collection was conducted under consistent conditions, and measurement locations were carefully matched with their corresponding positions in the 3D model. Outlier values were identified during the analysis and considered in the interpretation of the RMSE results.

3. Results and Analysis

3.1 Comparison Results

Table 1 presents the comparison between digital measurements obtained from ACUTE software and field measurements collected using a distometer. The differences between building components are expressed as residual values, ranging from –3.81 m to +0.71 m.

Table 1: Comparison between digital measurements obtained from ACUTE 3D Viewer and field measurements using a Distometer, including residual values

Sample	Acute (m)	Distometer (m)	Residual (+-) m
Window height	1.17	1.17	0.00
Window width	1.02	1.17	-0.15
Door height	2.46	2.05	0.41
Door width	1.19	1.10	0.09
House height	4.00	5.31	-1.31
House pole height	3.31	2.60	0.71
House width side 1	11.09	14.90	-3.81
House width side 2	2.62	4.01	-1.30
House width side 3	3.40	3.41	-0.01
House width side 4	3.46	3.90	-0.44
House width side 5	1.61	1.60	0.01
House length (back)	6.36	7.90	-1.54

Most of the calculated parameters, including window height, window width, door size and multiple elements of house width had a reasonably small residual value that suggested good fit between the digital model and field measurements. Nonetheless, a number of measurements had substantial negative biases including House width side 1 (–3.81 m), House width side 2 (–1.30 m) and House length (back) (–1.54 m), which had significant effects on the overall accuracy statistics.

Based on all observed points of Table 1, the RMSE was calculated to be ±1.33 m showing moderate discrepancy between 3D digital model and ground measurements.

3.2 Results Summary

The residual measurements were dominated by those between − 0.50 and + 0.50 m (Table 1), indicating that the integrated UAV and Mobile LiDAR model captured most building elements with reasonable accuracy for housing-scale applications. Relatively larger residuals were accumulated in the measurements of longer spans of building and low visibility areas like side widths and rear length.

Visual inspection of the real building (UAV mapping) and 3D SketchUp model indicates that the roof structure, façade distribution of windows, and overall building geometry have some correspondence in geometrical terms between Fig. 2 (real value) and Fig. 3 (3D Model). This visual correspondence and the quantitative results validate that the generated model fulfils the LOD 3 requirements.

3.3 Discussion

The variation between the observed and estimated measurements was mainly caused by several outliers, particularly in the side width and rear length measurements. These areas are more prone to error due to occlusion effects during UAV image acquisition and limited visibility.

The RMSE value of ±1.33 m is influenced by these outliers as well as limitations in data acquisition. Variations in LiDAR point density and potential misalignment during dataset registration may have also contributed to the discrepancies. Compared to previous studies that achieved higher accuracy under controlled conditions (Che Ku Abdullah et al., 2017), the higher RMSE observed in this study may be attributed to differences in data acquisition environment, sensor configuration, and measurement scale.

While this level of accuracy may not be suitable for high-precision surveying applications, it is acceptable for visualization, documentation, and preliminary planning at the housing scale. This finding is consistent with recent studies that reported similar accuracy limitations in UAV-based 3D modelling for building measurements (Sun et al., 2022 & Jiang et al., 2021).

Measurements over larger spans and from partially occluded building areas are more susceptible to errors due to limitations in UAV image resolution, LiDAR point density, dataset registration accuracy, and environmental conditions during data acquisition (Remondino & Fraser, 2019). However, the integration of UAV photogrammetry and Mobile LiDAR provides a reliable workflow for housing-scale 3D modelling, with digital measurements extracted using ACUTE software. Field recalibration may still be required for applications demanding higher accuracy (Rahman, 2023).

using UAV mapping

Fig. 3: 3D SketchUp model of the same building created from combined UAV and mobile LiDAR data, meeting LOD 3

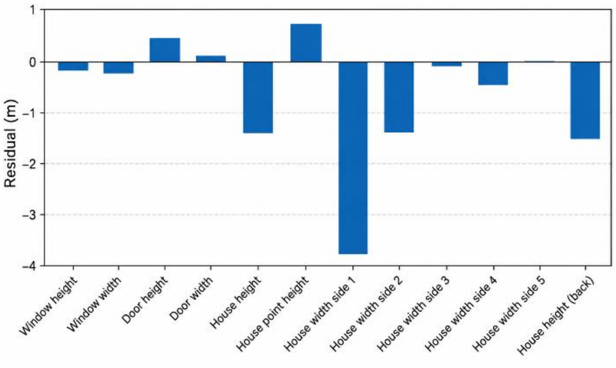

Fig. 4: The residual differences between digital measurements from the ACUTE 3D model and linear field measurements with a distometer

4. Conclusion

This research demonstrates that the integration of UAV photogrammetry and Mobile LiDAR scanning effectively produces a Level of Detail 3 (LOD 3) 3D housing model for the Darul Hana residential area. The accuracy assessment yielded a Root Mean Square Error (RMSE) of ±1.33 m, influenced by several outliers. While this level of accuracy may not meet the requirements for high-precision surveying, it is acceptable for visualization, documentation, and preliminary planning at the housing scale. The findings highlight the potential of integrated 3D modelling approaches in improving survey efficiency, while emphasizing the importance of field validation for applications requiring higher accuracy.

Author Contributions: The study was conducted successfully with contributions from all authors.

Conflicts of Interest: The authors declare no conflict of interest.

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