Geoid
Journal of Geodesy and Geomatics

Geoid Vol. 21, No. 2, 2026, 11-29

P-ISSN: 1858-2281; E-ISSN: 2442-3998

# Evaluation of the Accuracy of a 3D Temple Model Based on Simultaneous Localization and Mapping Technology (Case Study: Pura Agung Wira Loka Natha, Cimahi)

**Shelli Rahmawati, Gusti Ayu Jessy Kartini***
Department of Geodetic Engineering, Faculty of Civil Engineering and Planning, Institut Teknologi Nasional, Bandung, 40124, Indonesia
*Corresponding author: ayujessy@itenas.ac.id

Received: 14 July 2026; Revised: 30 August 2026; Accepted: 2 November 2026; Published: 2 November 2026

**Abstract:** Simultaneous Localization and Mapping (SLAM) technology rapidly generate 3D point cloud models of complex structures. This study evaluates the accuracy and efficiency of the 3D model of Pura Agung Wira Loka Natha generated using two SLAM scanning approaches: single-session closed-loop and multi-session scanning. The resulting point clouds were processed and validated using field measurements obtained from a total station, a measuring tape, and a laser distance meter. To assess dimensional accuracy, 18 building elements were distributed across Nista, Madya, and Utama Mandala zones. Positional and dimensional evaluations were performed using Root Mean Square Error (RMSE), Circular Error 90% (CE90), Linear Error 90% (LE90), and Paired t-Tests. The results show that the single-session approach achieved an aggregate dimensional RMSE of 0.00284 m, while the multi-session approach yielded 0.00364 m. The Paired t-Test produced a p-value of 0.671, indicating no statistically significant difference in dimensional accuracy between the two approaches. However, the multi-session approach produced a denser point cloud (74,008 points/m² vs 52,317 points/m²) due to its longer scan duration and high trajectory overlap, while achieving better horizontal positional accuracy (CE90 of 0.043 m vs 0.053 m) because dividing the survey into shorter, independent trajectories restricted horizontal odometry drift propagation. Conversely, the single-session approach achieved better vertical positional accuracy (LE90 of 0.013 m vs 0.074 m) by leveraging continuous loop-closure to globally optimize vertical drift and avoid sub-map merging residuals. In terms of efficiency, single-session scanning took 26 minutes and 11 seconds, whereas multi-session scanning required 40 minutes and 22 seconds. This study demonstrates that for time-constrained and vertical-accuracy-critical heritage documentation, the single-session approach is highly preferable due to its unified loop-closure stability, conversely, for documentation applications prioritizing dense point clouds and superior horizontal positional consistency for highly detailed ornamental representations, the multi-session strategy is recommended.

Keywords : SLAM; Point Cloud; 3D Modeling; Accuracy Assessment

How to cite: Rahmawati, S., & Kartini, G. A. J. (2026). Evaluation of the Accuracy of a 3D Temple Model Based on Simultaneous Localization and Mapping Technology (Case Study: Pura Agung Wira Loka Natha, Cimahi). *Geoid, 21* (2), 11-29.

## Introduction

Digital geometric documentation and 3D modeling play a crucial role in the preservation, structural analysis, and inventory of traditional architectural assets, even before these assets are officially designated as cultural heritage sites (Remondino, 2011). In many cases, an accurate digital twin serves as a baseline for the identification and evaluation of historic properties. For several decades, standard methods such as static Terrestrial Laser Scanning (TLS) and Structure-from-Motion (SfM) photogrammetry have been widely used to generate high-precision 3D models (Westoby et al., 2012). However, although TLS provides sub-centimeter accuracy, its high capital costs, complex setup, and lengthy data acquisition times pose significant logistical challenges when documenting sites with highly complex layouts (Westoby et al., 2012), such as temples.

Advances in three-dimensional (3D) technology have increased the need for spatial data acquisition methods that are fast, efficient, and capable of producing detailed geometric representations of objects. One technology widely used for this purpose is Light Detection and Ranging (LiDAR), which generates three-dimensional point cloud data with a high level of detail. In recent years, Simultaneous Localization and Mapping (SLAM)-

based LiDAR technology has advanced rapidly due to its ability to simultaneously map and determine the sensor's position during the data acquisition process (Durrant-Whyte & Bailey, 2006; Liu et al., 2024). The fundamental principle of SLAM requires the system to solve the localization and mapping problems simultaneously, where the model's success depends heavily on the sensor's ability to track previously observed terrain features in order to minimize the accumulation of position errors (Durrant-Whyte & Bailey, 2006).

Compared to static terrestrial scanning methods, SLAM technology offers the advantages of operational flexibility and shorter acquisition times, as operators can move along a specific path without requiring many observation points. Lehtola et al. (2017) demonstrated that SLAM-based mobile mapping systems can significantly reduce data acquisition time in the field and offer much higher operational efficiency compared to static Terrestrial Laser Scanning (TLS). Similar findings were also reported by Grešla (2025) regarding the scanning of multi-story buildings using various 3D scanning technologies. These advantages have led to the widespread use of SLAM for building documentation, asset inventory, and surveys of objects with complex spatial configurations, including cultural heritage buildings (Bonora & Colapietro, 2026; Tanduo et al., 2023) as well as the development of digital twins for building documentation and asset management (Shimoda et al., 2025). In this context, mobile LiDAR and SLAM technologies offer significant advantages in mapping complex environments with narrow corridors and intricate structural layouts, where conventional static surveying methods often face severe data obstruction issues and logistical challenges (Di Stefano et al., 2021). In the context of cultural heritage documentation, Bonora and Colapietro (2026) demonstrate that portable SLAM systems are capable of achieving median residual values ranging from 6 mm to 17 mm, with RMSE values ranging from 12 mm to 15 mm for the local georeferencing accuracy of specific SLAM devices in interior environments, which already meets the standards for modeling information on historic buildings.

However, the quality of the resulting point cloud and 3D model is greatly influenced by the acquisition strategy used during the scanning process. Lehtola et al. (2017) and Chen et al. (2018) highlights that the main weakness of the SLAM system is the accumulation of errors (drift) that occurs when the loop closure frequency is not maintained, causing the 3D model to undergo structural distortion. The design of the sensor's trajectory determines the level of data overlap, the loop closure frequency, the distribution of observations, the point cloud density, and the efficiency of the data acquisition process. Merkle and Reiterer (2023) specifically demonstrates that a track design that induces high geometric overlap effectively reduces the RMSE of the trajectory, given that the loop closure mechanism is key to error correction in SLAM systems.

The geometry of the trajectory design applied in the field also determines the success of the SLAM system in achieving that level of accuracy. For indoor objects or enclosed spaces, previous studies generally used a single circular path that was completed in a single scanning session, requiring the operator to return to the starting point to trigger loop closure (Grešla, 2025; Tanduo et al., 2023). This design has proven to be reliable because there are many walls and room corners that help the SLAM algorithm correct positional errors along the path (Di Stefano et al., 2021; Lehtola et al., 2017). However, at large-scale cultural heritage sites with semi-open spaces, loop closure at the endpoints alone is insufficient, because long, single trajectories in open areas cause errors to accumulate erratically, especially when the sensor must traverse complex spatial transitions or landscapes with few distinct vertical planar geometric boundaries (Sammartano & Spanò, 2018). To address this issue, several studies on large horizontal sites have begun to adopt a multi-session approach, which involves dividing the scanning area into several overlapping sub-areas and then merging them through a registration process once all the data has been collected (Shimoda et al., 2025; Bonora & Colapietro, 2026). The transition from a continuous single-session approach to a multi-session scanning approach inherently poses complex computational challenges related to data association and map consistency, as SLAM algorithms must reliably match spatial features across temporally distinct sessions to establish a unified coordinate frame (Bailey & Durrant-Whyte, 2006). Nevertheless, research that directly compares the effects of these two trajectory schemes on the geometric accuracy of traditional architectural objects remains very limited.

Upon further examination, the objects in the aforementioned previous studies generally consist of enclosed buildings or sites characterized by relatively homogeneous single spaces. Bonora and Colapietro (2026) and Tanduo et al. (2023) tested the SLAM system inside a historic building using a closed single-session trajectory, while Grešla (2025) applied a similar scheme to multi-story buildings with vertical pathways between floors. On the other hand, studies of large-scale objects, such as that by Shimoda et al. (2025), have begun to use

multi-session trajectories because the objects are open, horizontal sites that prevent data collection in a single continuous session. Furthermore, the integration of portable mobile mapping technology in the outdoor areas of traditional temple sites, such as the Roman Temple of Bziza, generally focuses on combining multi-sensor data with photogrammetry to supplement visual documentation (Maset et al., 2022). However, no research has yet been found that tests both of these trajectory schemes on traditional architectural objects with spatial zoning and configuration transitions from enclosed to semi-open within the same site, as is commonly found in temple complexes in Indonesia. This gap in the literature formed the basis for selecting Pura Agung Wira Loka Natha as the research subject, as this temple complex features three zones with varying degrees of openness and geometric density, making it representative for testing the performance consistency of the two SLAM trajectory strategies on a single object. Thus, comparative studies specifically evaluating single-session vs. multi-session SLAM accuracy for cultural heritage remain limited, which this study addresses.

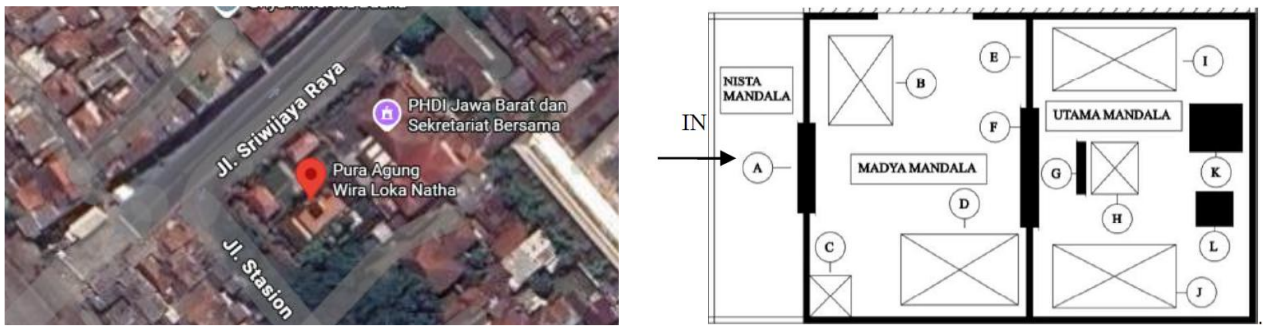
Pura Agung Wira Loka Natha in Cimahi is a place of worship consisting of three main zones, Nista Mandala, Madya Mandala, and Utama Mandala. Maharlika (2018) documented that the Utama Mandala zone of this temple features ornamental configurations and architectural elements with highly dense and complex geometries, making this site representative for testing the limits of SLAM systems' ability to capture the spatial details of complex structures. The presence of various buildings, pavilions, gateways, and differences between zones gives this location a level of geometric complexity suitable for evaluating the impact of acquisition strategies on the quality of the resulting 3D models.

This study aims to evaluate the accuracy and efficiency of the 3D model of Pura Agung Wira Loka Natha generated using SLAM technology through single-session and multi-session closed-loop scanning approaches. The evaluation was conducted by comparing the model's dimensions with field measurements taken using a total station, measuring tape, and laser distance meter. In addition, this study analyzes positional accuracy using the RMSE, CE90, and LE90 parameters, as well as the Paired t-Test statistical test, to evaluate the significance of accuracy differences between the two approaches and to assess the impact of scanning strategies on point cloud density and data acquisition duration. The results of this study are expected to provide recommendations for an optimal SLAM acquisition method for documenting buildings with complex architectural characteristics.

## Methodology

### *Study Area*

The research was conducted at Pura Agung Wira Loka Natha, located in the city of Cimahi, West Java Province, Indonesia. Astronomically, this temple is situated at Latitude -6.88393 and Longitude 107.53550. The temple complex consists of three main zones, Nista Mandala, Madya Mandala, and Utama Mandala (Figure 1). These three zones have distinct architectural characteristics, featuring gateways, pavilions, staircases, pillars, and architectural ornaments that create a high degree of geometric complexity. These conditions make the research site suitable for evaluating the performance of Simultaneous Localization and Mapping (SLAM) technology in generating three-dimensional point clouds of objects with complex spatial configurations.




(a) (b)

Figure 1. (a) Location of Pura Agung Wira Loka Natha (Google Maps, 2026) and (b) main research area (Maharlika, 2018)

### *Research Workflow*

The research stages are presented in Figure 2. The research began with a literature review and a preliminary survey to determine data requirements, measurement methods, and acquisition strategies. Next, a benchmark (BM) was established using GNSS observations as the basis for georeferencing the SLAM data. Validation point measurements were taken using an Electronic Total Station (ETS) to obtain reference coordinates used in evaluating positional accuracy. Additionally, object dimensions were measured using a measuring tape and a laser distance meter to serve as reference data for validating the model's dimensions.

SLAM data acquisition was performed using two closed-loop approaches, single-session and multi-session. The utilization of closed-loop trajectories is a well-established practice in heritage laser scanning, where starting and ending the scanning path at the same physical location is essential to trigger loop closures, thereby constraining the accumulation of systematic sensor drift (Bailey & Durrant-Whyte, 2006; Sammartano & Spanò, 2018; Bonora & Colapietro, 2026). Furthermore, dividing complex sites into overlapping multi-session trajectories has been successfully utilized to preserve local horizontal consistency in large archaeological campaigns (Bitelli et al., 2026). The acquired point cloud data was then processed through georeferencing, noise filtering, and area cropping before being used in the evaluation process. The final analysis involved validation of dimensional accuracy, validation of positional accuracy, evaluation of point cloud density, and analysis of acquisition time efficiency.

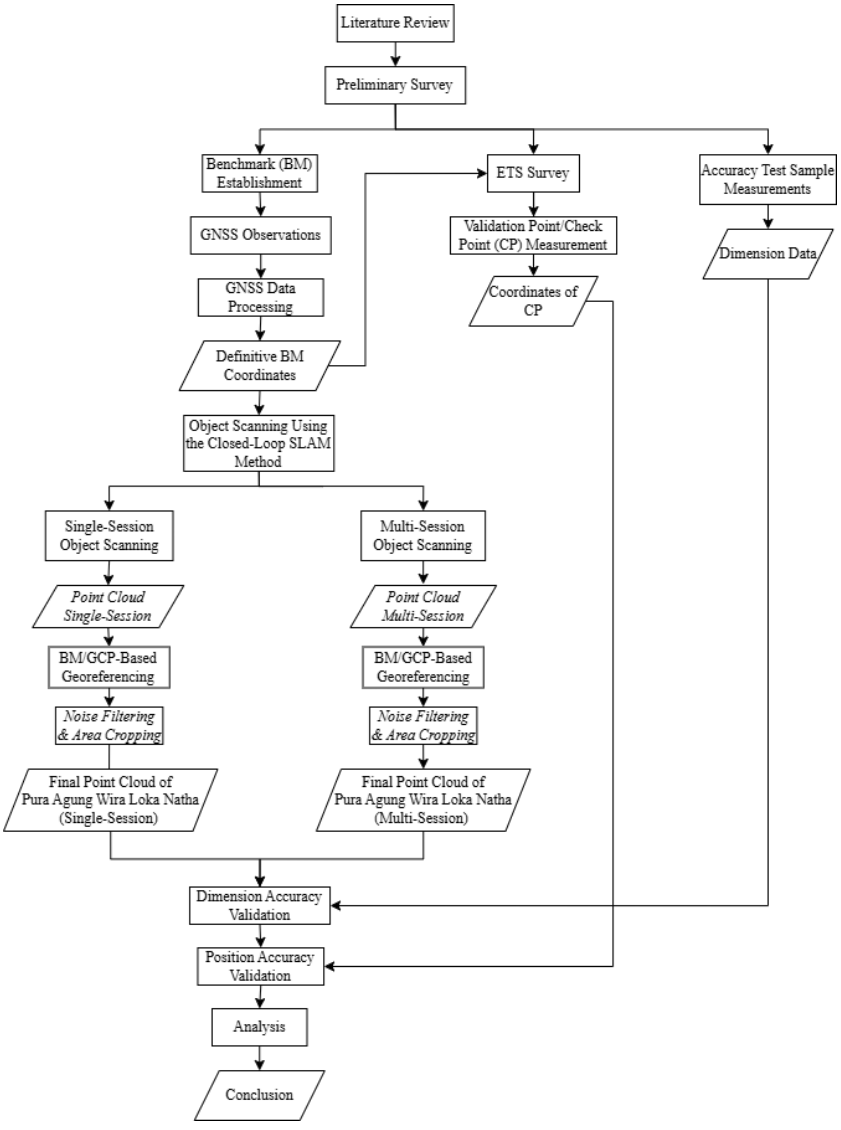



Figure 2. Research workflow

### *Data and Equipment*

The primary research data consists of point clouds generated from scans using the Hi-Target V700S SLAM RTK device. Supporting data consists of field measurements taken using a total station, a measuring tape, and a laser distance meter, which were used as reference data to validate the three-dimensional point cloud.
The software used includes Hi-LiDAR for initial SLAM data processing, CloudCompare for point cloud processing and point density analysis, and Microsoft Excel for statistical calculations. The resulting data consists of trajectory data, scanned point clouds, Ground Control Points (GCPs), dimensional data, and checkpoint coordinates.

### *Benchmark Establishment and Control Survey*

Benchmark establishment was carried out to serve as control points for the georeferencing process of the SLAM scan data. GNSS observations were conducted at the benchmark points to obtain definitive coordinates in the coordinate system used. The benchmark coordinates were then used as a reference in the point cloud georeferencing process.

In addition to the benchmarks, validation points were measured using an Electronic Total Station (ETS). A total of ten validation points (checkpoints) were selected and measured to obtain reference coordinates used in evaluating the positional accuracy of the point cloud from the SLAM scan.

### *Dimensional Reference Measurement*

Dimensional measurements were taken on 18 building elements located in the Nista Mandala, Madya Mandala, and Utama Mandala zones. Field measurements were conducted using a measuring tape and a laser distance meter. The reference dimensional values were obtained from the average of the measurements taken with both instruments for each building element.

### *SLAM Data Acquisition*

Data acquisition was performed using two scanning approaches, closed-loop single-session and closed-loop multi-session. In the closed-loop single-session approach, the entire area of Pura Agung Wira Loka Natha was scanned in a single closed path that continuously covered the Nista Mandala, Madya Mandala, and Utama Mandala zones. This approach produces a single main trajectory with a single loop closure process. In the closed-loop multi-session approach, scanning is performed separately for each zone. The Nista Mandala, Madya Mandala, and Utama Mandala zones are scanned as three independent sessions, each forming a closed path. The scan results from all three sessions are then combined into a single integrated point cloud model.

The scan duration for the single-session approach was 26 minutes and 11 seconds, while the multi-session approach took a total of 40 minutes and 22 seconds, consisting of 7 minutes and 50 seconds in the Nista Mandala zone, 9 minutes and 21 seconds in the Madya Mandala zone, and 23 minutes and 11 seconds in the Utama Mandala zone.

### *Point Cloud Processing*

The SLAM scan data was processed using Hi-LiDAR software. The processing began with creating a new project and importing the acquired data from the Hi-Target V700S device. Next, the SLAM processing was performed by entering the GCPs that had been marked in the field to georeference the point cloud.

The control point coordinates in Northing, Easting, and Elevation (NEZ) format were imported into Hi-LiDAR and used as a reference in the mapping result optimization process. The coordinate system was then adjusted to the study location before the processing was carried out.

In the multi-session approach, the scan data from the Nista Mandala, Madya Mandala, and Utama Mandala zones were processed separately, resulting in three independent point cloud datasets that were subsequently merged into a single dataset. Meanwhile, in the single-session approach, the entire study area was processed as a single dataset covering all zones within a single closed trajectory.

The processing results consist of a georeferenced point cloud, scan trajectory data, and an Accuracy Quality Report (AQR). While the single-session approach was processed as a single continuous trajectory in a single

computing run, the multi-session approach required separate SLAM processing runs in Hi-LiDAR for each of the three independent temple zones, producing three georeferenced sub-maps. Thanks to the highly consistent geodetic framework established by the RTK-GNSS module and the Ground Control Points (GCPs), these sub-maps automatically unified into a single integrated coordinate system upon import without requiring manual cloud-to-cloud registration or Iterative Closest Point (ICP) alignment. However, this required the operator to repeat the project setup, GCP ingestion, and trajectory optimization steps three times. Evaluation of the AQR was performed using GCPs that had been marked during the SLAM acquisition process to assess the internal georeferencing constraint quality of each trajectory in the Hi-LiDAR software.

The processed point cloud is then exported for further analysis. The number of points in the point cloud from each approach is used to calculate point density, while the point coordinates obtained from the Total Station observations serve as independent reference data in the positional accuracy evaluation.

***Field Reference Measurements***

The three-dimensional point cloud model was validated using field measurement data obtained through observations with a total station, a measuring tape, and a laser distance meter. A total of 18 building elements were selected as dimensional test samples, and 10 sample points were selected for positional evaluation, distributed across the three study zones.

Each sample was measured three times using a measuring tape and a laser distance meter. The reference value was determined based on the average of the measurements from both instruments. Total Station measurements were used to obtain the three-dimensional coordinates of the control points used in the positional accuracy evaluation.

***Dimensional Accuracy Assessment***

Dimensional accuracy was determined by comparing the measurement results of building elements in the point cloud with field measurement results used as reference data. A total of 18 building elements distributed across the Nista Mandala, Madya Mandala, and Utama Mandala zones were used as test samples. To address the statistical assumption of independent observations, the dataset consists of distinct cardinal dimensions (e.g., horizontal lengths, widths, and vertical heights). Although some complex architectural structures contributed more than one dimensional measurement to the dataset (e.g., both width and height of a single staircase), these measurements are considered geometrically independent. In SLAM coordinate estimation, planimetric errors (along the X and Y axes) and altimetric errors (along the Z axis) are governed by separate physical and algorithmic drift processes; therefore, orthogonal dimensional errors on the same physical object do not exhibit geometric autocorrelation (Liu et al., 2024; Sammartano & Spanò, 2018; Grešla, 2025).

To ensure reference reliability and minimize hand-held instrument noise, each of the 18 dimensional features was measured three times using a measuring tape and three times using a laser distance meter in the field. The average of these six readings established the single ground-truth reference value ($d_{ref}$) for each paired observation. Consequently, the Paired t-Test was executed with a total sample size of $n = 18$ paired dimensional observations (degrees of freedom, $d_f = 17$).

Dimensional deviations were calculated as the difference between the measurement results in the point cloud and the field reference values. Next, the level of dimensional accuracy was evaluated using the Root Mean Square Error (RMSE) for each scanning approach. The smaller the RMSE value, the higher the level of dimensional conformity of the point cloud with the existing conditions.

To determine whether there is a significant difference in dimensional accuracy between the single-session closed-loop approach and the multi-session closed-loop approach, a paired t-test was conducted. This test was chosen because the two approaches were compared using the same sample of building elements. The hypotheses used were:

$H_0$ : There is no difference in the mean dimensional error between the single-session and multi-session approaches.

$H_1$ : There is a difference in the mean dimensional error between the single-session and multi-session approaches.

Testing decisions were made using a significance level of 5% (α = 0.05). If p-value > 0.05, $H_0$ is accepted, if the p-value ≤ 0.05, $H_0$ is rejected.

### *Positional Accuracy Assessment*

Position accuracy was evaluated using the coordinates of points obtained from Total Station observations as independent reference data. The point coordinates extracted from the point cloud were compared with the coordinates from the Total Station observations to obtain the coordinate differences in the X, Y, and Z components. These coordinate differences were used to calculate RMSEx, RMSEy, RMSEz, RMSEr, CE90, and LE90 in accordance with the National Standard for Spatial Data Accuracy developed by the Federal Geographic Data Committee (FGDC, 1998).

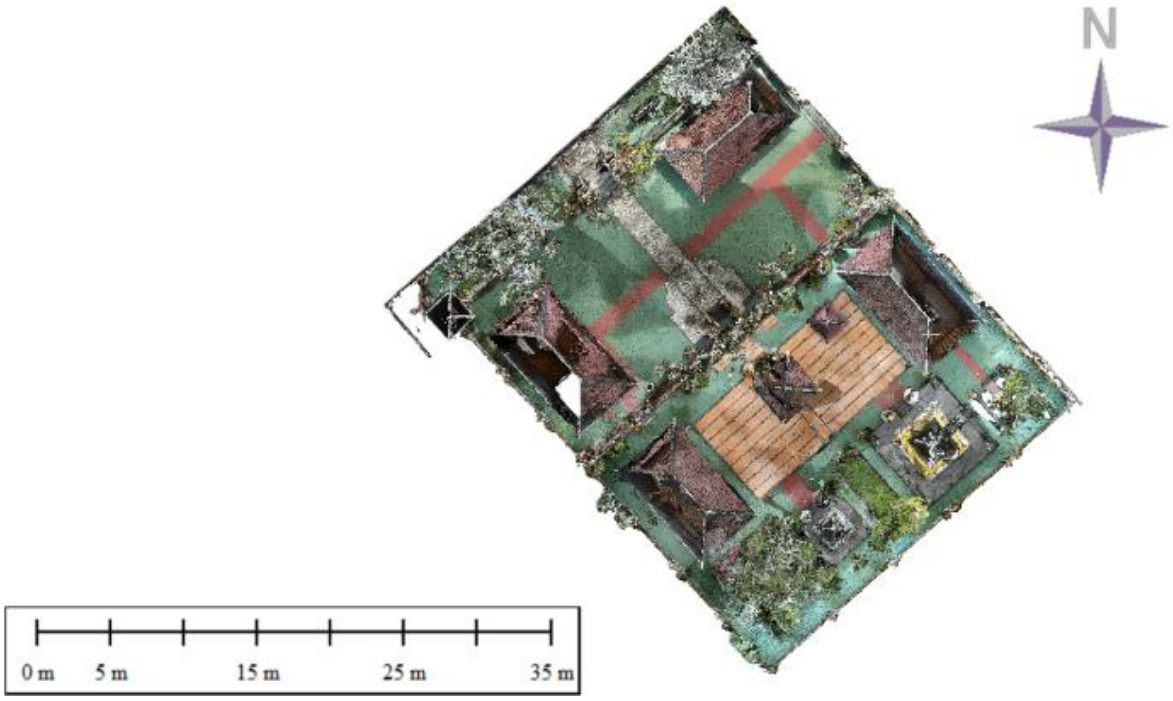
### *Density and Efficiency Analysis*

Scanning efficiency was evaluated based on the total acquisition time required by each approach. Meanwhile, point cloud quality was analyzed using the point density parameter, calculated as the number of points per unit area of the data coverage. Point cloud density analysis was conducted to evaluate the level of data density produced by each acquisition method. Point cloud density was calculated by dividing the total number of points by the area covered by the scan. The results of the evaluations of dimensional accuracy, positional accuracy, point cloud density, and acquisition time were then compared to determine the characteristics and advantages of each SLAM scanning approach.

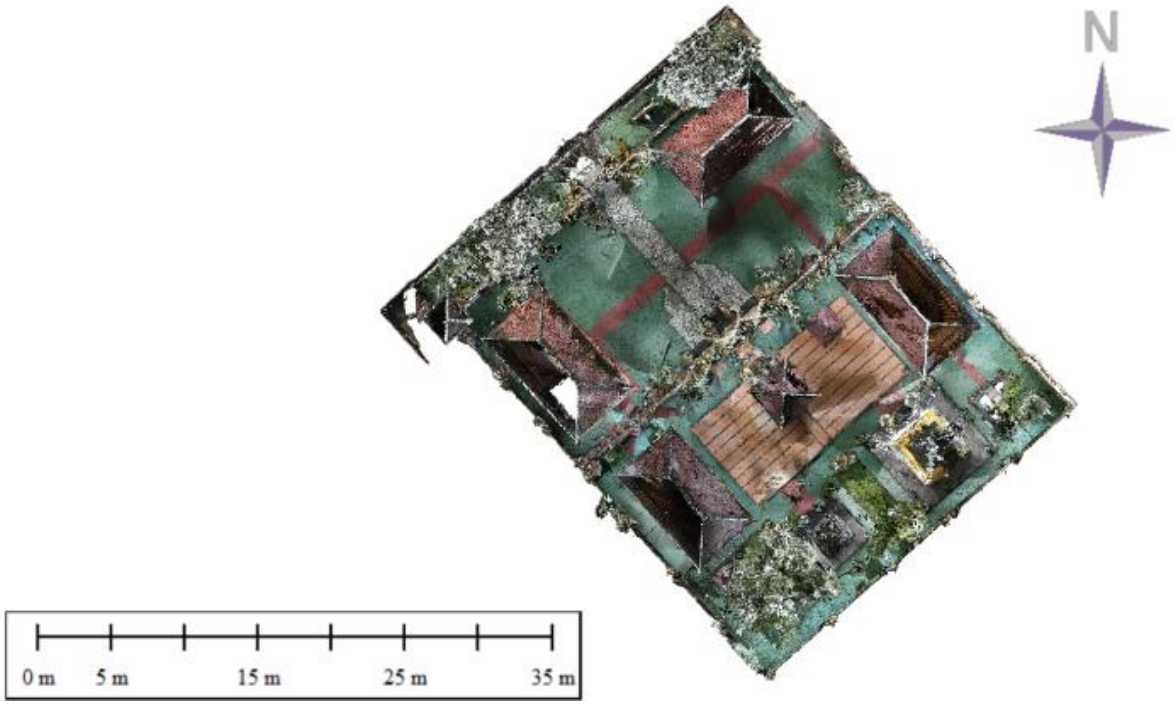
## Results and Discussion

### *Point Cloud Results*

Visually, after noise filtering (Figure 3), both methods successfully represented the geometry of Pura Agung Wira Loka Natha in its entirety. However, there were differences in the characteristics of the resulting point clouds. The multi-session point cloud exhibits a higher point density compared to the single-session point cloud, resulting in some parts of the objects and vegetation being captured with a denser point distribution. Nevertheless, this increase in density does not always result in a better visual representation, as there are still some areas that are not optimally rendered and relatively sparse sections appear on certain objects.




(a)



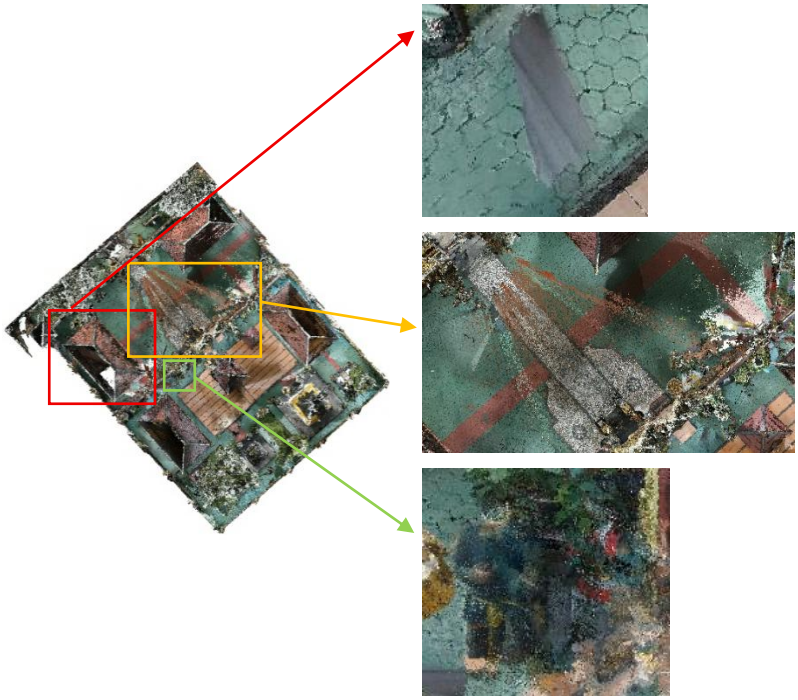

(b)

Figure 3. Visual comparison of point clouds (a) single-session and (b) multi-session

On the other hand, the raw data from the multi-session scan also showed the presence of noise and visual inconsistencies in the form of transient objects captured during the acquisition process, dark areas in some parts of the point cloud, and color variations on certain surfaces (Figure 4). These conditions are believed to be influenced by differences in acquisition times between sessions, which caused changes in lighting conditions and the presence of moving objects during the scanning process. In contrast, the single-session point cloud produces a more homogeneous visual appearance with a relatively consistent color distribution and less noise, since the entire area was scanned in a single, continuous acquisition session.

To evaluate these quality differences objectively beyond qualitative visual descriptions, the noise filtering and cleaning process for each session was quantitatively analyzed. Traditional automated statistical filters, such as the Statistical Outlier Removal (SOR), were found to cause unacceptable data omission and geometric hole, particularly on the upper roof structures. This degradation is a well-known limitation of terrestrial mobile SLAM, where the point density decreases proportionally with the scanning distance to higher elevations (Bonora & Colapietro, 2026), and the lack of high-altitude acquisition platforms leads to self-occlusions on the roof surfaces (Remondino, 2011). Consequently, when global SOR filters are applied, the naturally sparse points representing the roof structures are misidentified as statistical outliers and deleted.

To prevent this loss of critical geometric data, a manually-driven interactive cleaning and cropping workflow was adopted in CloudCompare, following the best-practice guidelines of Bitelli et al. (2026) and Westoby et al. (2012). This approach allowed for the targeted removal of transient dynamic features (e.g., visitors, operators) and surrounding peripheral vegetation while preserving the geometric completeness of the temple roofs and intricate carvings.



Dark areas and color variations on the surface due to differences in lighting conditions between sessions.

A temporary object (two people) was captured in the Utama Mandala, causing noise.

Figure 4. Examples of visual inconsistencies and noise observed in the raw multi-session point cloud

For the multi-session approach, the manual cleaning step reduced the point cloud from an initial raw count of 173,790,720 points to a final cleaned count of 165,643,829 points, representing the removal of 8,146,891 points (or 4.69% of the dataset) as dynamic noise and peripheral features. In comparison, the single-session raw dataset required the removal of 8,782,196 points out of 125,598,195 points (representing a 6.99% removal ratio) to yield a final cleaned point cloud of 116,815,999 points. The slightly higher percentage of points removed in the single-session scan is attributed to its continuous loop-closure trajectory over the entire temple perimeter, which inevitably captured a broader extent of surrounding background vegetation and peripheral terrain that had to be cropped to isolate the main temple structures.

The results of the visual evaluation show that higher point cloud density does not always correlate directly with improved visual quality of the model, given that noise and inconsistencies are actually more prevalent in multi-session results despite the larger number of points in the point cloud. This finding is consistent with Bonora and Colapietro (2026), who state that point cloud density does not always guarantee a more effective representation because it is still influenced by noise and the quality of the supporting data. Therefore, the assessment of SLAM scan quality must consider not only point density and geometric accuracy but also the level of noise, visual consistency, and the completeness of the resulting object representation.

***Accuracy Quality Report***

The Accuracy Quality Report (AQR) is used to evaluate the georeferencing quality of an internal point cloud based on the residuals between the coordinates of control points obtained from field observations and the coordinates of control points identified during the SLAM processing. The metric used in this study is the Root Mean Square Error in Plane, which describes the horizontal accuracy of the georeferencing results.

Table 1 shows that the single-session approach yielded a RMSE in Plane of 0.0037 m, while the multi-session approach yielded an average value of 0.0043 m. Both values are at the millimeter level of accuracy and indicate that the georeferencing process for both approaches produced good alignment with the GCPs used.

Table 1. Summary of the Accuracy Quality Report

| Scanning Approach | RMSE in Plane (m) | Number of GCPs | Spatial Distribution |
|---|---|---|---|
| Single-session | 0.0037 | 6 | 2 (Nista Mandala), 2 (Madya Mandala), 2 (Utama Mandala) |
| Multi-session | 0.0043 | 9 | 3 (Nista Mandala), 3 (Madya Mandala), 3 (Utama Mandala) |

The superior planar accuracy of the single-session approach (0.0037 m) compared to the multi-session approach (0.0043 m), despite utilizing fewer total control points, aligns with SLAM optimization principles. The single-session scheme operates on a continuous, unified closed-loop trajectory, allowing the backend factor graph to execute a single global loop-closure optimization that smoothly distributes odometric drift across a geometrically rigid model (Durrant-Whyte & Bailey, 2006). Conversely, the multi-session approach requires merging three independent sub-maps. This merging process is highly susceptible to local, non-linear co-registration residuals and seam alignment errors at narrow transition gateways, propagating errors through the merged dataset and elevating the planar residuals (Bailey & Durrant-Whyte, 2006; Bonora & Colapietro, 2026).

The difference in AQR values between the two methods is relatively small, so it can be concluded that both the single-session and multi-session approaches are capable of producing comparable internal georeferencing quality. This is closely related to the physical characteristics of Pura Agung Wira Loka Natha, which is dominated by outdoor and semi-outdoor areas, as well as the hybrid sensor features of the Hi-Target V700S SLAM RTK. This differs from previous studies that tested SLAM in enclosed indoor spaces or the interiors of historic buildings without satellite signals (Bonora & Colapietro, 2026; Tanduo et al., 2023) where pure SLAM systems rely on loop closure and the density of geometric features to correct their position (Di Stefano et al., 2021; Grešla, 2025; Lehtola et al., 2017). The open area around the temple allows the V700S's GNSS RTK/PPK module to achieve optimal satellite signal lock. The integration of LiDAR, IMU, and GNSS data into SLAM optimization helps stabilize the trajectory and limit global drift, although GNSS corrections essentially serve as a geodetic orientation constraint after local reconstruction, so they cannot yet fully compensate for locally accumulated errors, particularly on long outdoor trajectories or those with few features (Bitelli et al., 2026).

During acquisition, GCPs were marked directly on the SLAM device to lock the horizontal spatial orientation at millimeter-level accuracy. The discrepancy in control point density was strictly dictated by operational requirements, the multi-session approach processed the temple as three independent runs, requiring at least 3 GCPs per session (9 GCPs cumulatively) to resolve local 3D coordinate transformations. In contrast, the continuous single-session path was georeferenced using a subset of 6 GCPs coincident with the exact physical benchmarks of the multi-session, ensuring that both schemes were evaluated against an identical geodetic reference frame.

Importantly, during optimization, the single-session backend was constrained by a higher number of simultaneous local GCPs (6 GCPs) compared to the multi-session approach (3 GCPs per session), preventing any bias in favor of the multi-session scheme. To ensure an unbiased comparative analysis, absolute positional accuracies (RMSE, CE90, and LE90) were validated using an identical, independent set of ten checkpoints measured via Total Station. These checkpoints were strictly excluded from the georeferencing pipeline, ensuring that the results reflect the intrinsic geometric stability of the scanning trajectories rather than control point density.

However, these comparable AQR values do not yet reflect the consistency of the internal geometry along the actual trajectory. In open environments with varying spatial zoning, local nonlinear deviations may still occur when the sensor moves out of range of the GCP or passes through areas with dense ornamentation and few vertical surfaces (Sammartano & Spanò, 2018). Therefore, the accuracy evaluation will be independently tested using checkboard validation points measured with ETS, since differences in visual quality, density, and point cloud noise are ultimately more influenced by trajectory characteristics, temporal variations in acquisition, and observation distribution than by the initial georeferencing quality in AQR.

### *Dimensional Accuracy Assessment*

A dimensional accuracy evaluation was conducted on 18 building elements distributed across the Nista Mandala, Madya Mandala, and Utama Mandala zones, an example of the field measurement process and dimensional extraction from the point cloud is shown in Figure 5. Reference values were obtained from the average of measurements taken with a tape measure and a laser distance meter, and were then compared with the measurement results from the point cloud generated using both single-session and multi-session approaches.

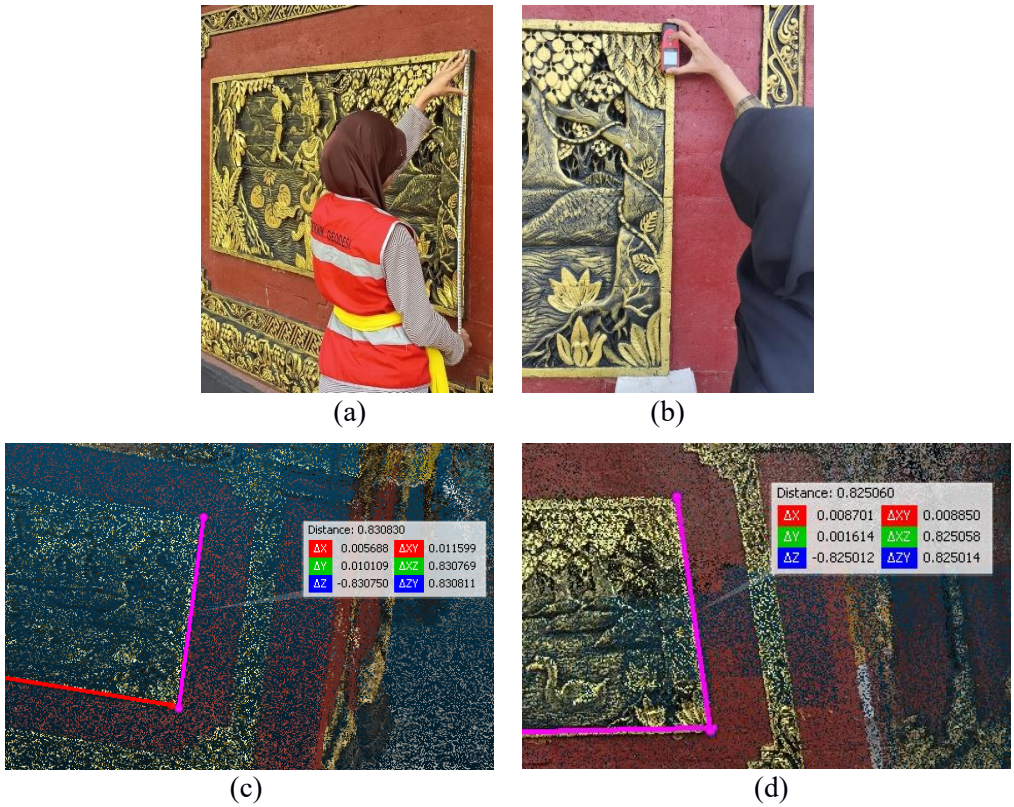



Figure 5. Examples of dimensional measurements used for accuracy assessment, (a) field measurement using a measuring tape, (b) field measurement using a laser distance meter, (c) dimension extraction from the single-session point cloud, and (d) dimension extraction from the multi-session point cloud

Next, the dimensional differences, Mean Absolute Error (MAE) and standard deviation (Table 2), and Root Mean Square Error (RMSE) values were calculated for each scanning approach, both as a single aggregate value and broken down across the three temple zones to evaluate the impact of local geometric complexity (Table 3). In this study, we intentionally utilized the absolute values of dimensional errors to evaluate the overall magnitude of geometric discrepancies without considering directions, which is a well-established and standard approach in LiDAR and mobile mapping system (MMS) accuracy assessments (Gharineiat et al., 2024). Both approaches yielded dimensional errors on the order of millimeters, demonstrating that both scanning strategies are highly capable of accurately representing the object's physical dimensions.

Table 2. MAE and standard deviation results by dimension

| Scanning Approach | MAE (m) | Standard Deviation (m) |
|---|---|---|
| Single-session | 0.00241 | 0.00154 |
| Multi-session | 0.00276 | 0.00245 |

Since the absolute difference in aggregate dimensional MAE between the single-session and multi-session approaches is remarkably small, amounting to only 0.35 mm (2.41 mm vs 2.76 mm), and both methods exhibit highly precise, millimeter-level random error dispersion (SD of 1.54 mm and 2.45 mm, respectively), the two models are shown to be practically equivalent. This is consistent with portable SLAM performance

benchmarks in built heritage, where residual errors of several millimeters are well within acceptable architectural representation tolerances (Bonora & Colapietro, 2026; Tanduo et al., 2023)

Table 3. RMSE results by dimension

| Temple Zone | Number of Elements | Single-session RMSE (m) | Multi-session RMSE (m) |
|---|---|---|---|
| Nista Mandala | 6 | 0.00142 | 0.00336 |
| Madya Mandala | 8 | 0.00322 | 0.00286 |
| Utama Mandala | 4 | 0.00354 | 0.00515 |
| Overall | 18 | 0.00284 | 0.00364 |

However, the relatively small sample size (n = 18 elements) and its specific distribution, 6 in the Nista Mandala, 8 in the Madya Mandala, and 4 in the Utama Mandala, must be acknowledged as an inherent limitation. In this study, the sample size, particularly in the Utama Mandala (n = 4), was strictly dictated by the sacred nature of the site. As the innermost, most sacred zone of Pura Agung Wira Loka Natha used for primary religious worship, prohibited physical markings or the placement of physical checkerboard targets directly on sacred ornaments.

Because the absolute difference in aggregate dimensional RMSE between the single-session and multi-session approaches is remarkably small, amounting to only 0.8 mm (0.00284 m versus 0.00364 m), any statistically undetected difference remains practically negligible for the scale of heritage architectural documentation and restoration. This is consistent with portable SLAM performance benchmarks in built heritage, where residual errors of several millimeters are well within acceptable architectural representation tolerances (Bonora & Colapietro, 2026; Tanduo et al., 2023).

Looking at the zone-specific results in Table 3, both methods achieved highly precise results. In the Nista Mandala, the single-session achieved an exceptionally low RMSE of 1.42 mm, while the multi-session yielded 3.36 mm. However, as geometric complexity and the density of traditional ornaments increased, a slight degradation in dimensional accuracy was observed for both strategies in the Utama Mandala, where the Single-session approach yielded an RMSE of 3.54 mm and the Multi-session approach exhibited an RMSE of 5.15 mm. This localized accuracy reduction for the multi-session approach in Utama Mandala is primarily attributed to minor sub-map co-registration residuals and local thickness artifacts that propagate when merging independent trajectories at narrow gateway transitions, a phenomenon well-documented in sub-mapping SLAM optimization (Bailey & Durrant-Whyte, 2006). Conversely, the continuous, unified closed-loop path of the single-session approach successfully bypassed these merging errors, maintaining tighter dimensional control even in highly complex spaces.

Although the single-session approach yielded a slightly smaller RMSE than the multi-session approach, the difference was relatively small. To determine the significance of the difference in accuracy between the two methods, a paired t-test was conducted on the difference in dimensional measurements (Table 4). The test results yielded a p-value of 0.671, which is greater than the significance level of 0.05. Thus, the null hypothesis ($H_0$) is accepted, indicating that there is no statistically significant difference between the dimensional accuracies produced by the single-session and multi-session approaches. Geometric alignment analysis showed that the multi-session approach exhibited a slightly larger dimensional RMSE error. This finding is consistent with the fundamental theory of SLAM, which states that the fusion of multi-session maps is inherently prone to local nonlinear drift and inter-session alignment errors during the sub-map merging stage (Bailey & Durrant-Whyte, 2006).

Table 4. Paired t-Test

| Statistic | Value |
|---|---|
| p-value | 0.671 |
| α | 0.05 |
| Decision | There is no significant difference |

However, the relatively small sample size (n = 18 elements) evaluated in this study must be acknowledged as a limitation. In statistical hypothesis testing, a small sample size can diminish the statistical power of the test, thereby raising the risk of a Type II error (the failure to detect a statistically significant difference when a real difference actually exists) (Oka & Suci, 2026). In this study, the sample size was strictly dictated by the limited number of discrete, accessible, and well-defined architectural elements across the temple's zones, as well as strict non-destructive cultural heritage preservation guidelines that prohibited physical markings or target placements directly on temple ornaments.

Nonetheless, the paired-sample design used in this test inherently mitigates this limitation by controlling for the high geometric variability of different architectural components, making the t-test highly sensitive to systematic scale discrepancies. Furthermore, because the absolute difference in dimensional RMSE between the single-session and multi-session approaches is remarkably small, amounting to only 0.8 mm (0.00284 m versus 0.00365 m), any statistically undetected difference remains practically negligible for the scale of heritage architectural documentation and restoration. This is consistent with portable SLAM performance benchmarks in built heritage, where residual errors of several millimeters are well within acceptable architectural representation tolerances (Bonora & Colapietro, 2026; Tanduo et al., 2023). This reinforces the validity of the conclusion that both acquisition strategies are practically equivalent in capturing dimensions.

These results indicate that dividing the trajectory into multiple sessions does not yield a significant improvement in dimensional accuracy. The primary factors influencing dimensional accuracy are likely more closely related to the quality of georeferencing, sensor characteristics, and the process of extracting dimensions from the point cloud than to the acquisition strategy used.

This finding is consistent with the research by Chen et al. (2018), which showed that SLAM systems are capable of producing geometric representations of objects with a relatively consistent level of accuracy as long as the loop closure mechanism is properly maintained.

***Positional Accuracy Assessment***

Position accuracy was evaluated using ten validation points measured with a total station and compared with the coordinates extracted from the point cloud. The calculated values of RMSEx, RMSEy, RMSEz, RMSEr, CE90, and LE90 for both methods are presented in Table 5.

Table 5. Comparison of positioning accuracy between single-session and multi-session

| Parameter | Single-session (m) | Multi-session (m) |
|---|---|---|
| RMSE X | 0.01649 | 0.01467 |
| RMSE Y | 0.03079 | 0.02440 |
| RMSE Z | 0.00815 | 0.04490 |
| RMSEr | 0.03493 | 0.02847 |
| CE90 | 0.05301 | 0.04320 |
| LE90 | 0.01345 | 0.07408 |

The results show that the multi-session approach has better horizontal accuracy than the single-session approach, as indicated by lower RMSEr and CE90 values. The resulting CE90 values of 0.053 m for the single-session approach and 0.043 m for the multi-session approach are consistent with the accuracy range commonly reported for outdoor SLAM applications, which typically varies between 10 mm and 60 mm depending on site conditions and acquisition factors (Gharineiat et al., 2024). This difference indicates that dividing the scan area into multiple sessions results in a denser distribution of observations and increases the frequency of overlap and loop closure in each zone.

In the vertical component, the single-session approach produces an RMSEz of 0.00815 m and an LE90 of 0.01345 m, while the multi-session approach produces an RMSEz of 0.04490 m and an LE90 of 0.07408 m. In contrast to the horizontal component, vertical accuracy in this study was actually better in the single-session approach compared to the multi-session approach.

To investigate the driver of this discrepancy, a spatial distribution analysis of the vertical residuals (dZ) was conducted across the ten validation points (Table 6). In the single-session approach, the vertical residuals

remained exceptionally low and highly uniform across all mandala zones, ranging tightly between 5.0 mm and 11.0 mm. This is likely related to the characteristics of the single-session trajectory which covers the entire research area in one continuous closed trajectory, thereby minimizing the accumulation of vertical drift throughout the acquisition process (Gharineiat et al., 2024).

Table 6. Distribution of actual vertical residuals (|dZ|) by Temple Zone

| Validation Points | Temple Zone | Vertical Residuals Single-Session (\|dZ\|) | Vertical Residuals Multi-Session (\|dZ\|) |
|---|---|---|---|
| CK6 | Nista Mandala | 0.002 m | 0.002 m |
| CK18 | Nista Mandala | 0.009 m | 0.020 m |
| CK27 | Nista Mandala | 0.001 m | 0.006 m |
| CK8 | Madya Mandala | 0.002 m | 0.046 m |
| CK9 | Gateway Madya to Utama Mandala | 0.018 m | 0.046 m |
| CK11 | Madya Mandala | 0.013 m | 0.034 m |
| CK21 | Madya Mandala | 0.005 m | 0.055 m |
| CK3 | Utama Mandala | 0.001 m | 0.088 m |
| CK5 | Utama Mandala | 0.003 m | 0.006 m |
| CK20 | Utama Mandala | 0.006 m | 0.059 m |

Conversely, the vertical errors in the multi-session point cloud were highly localized and indicative of systematic sub-map vertical shift. Validation points located within the Nista Mandala, such as CK6 (0.002 m) and CK27 (0.006 mm) maintained excellent vertical alignment. However, within the Utama Mandala, the vertical residuals spiked significantly, reaching 0.059 m at CK20 and peaking at 0.088 m at CK3. Furthermore, at the transition zones, the vertical residuals spiked to 0.020 m at CK18 and 0.046 m at both CK8 and CK9, with CK9 being situated directly at the narrow transition gateway connecting the Madya and Utama Mandala.

This distinct spatial clustering of errors empirically proves that systematic vertical shift within the independent Utama Mandala sub-map and inter-session coordinate alignment residuals during merging, rather than raw IMU sensor drift generally, are the primary drivers of vertical accuracy degradation in the multi-session model. When separate, temporally disconnected trajectories are merged at narrow gateways, minor pitch and roll angular tilts in the local coordinate systems propagate, manifesting as vertical 'double-floor' or 'stepped' thickness artifacts at the overlapping margins, a phenomenon consistent with multi-session SLAM optimization limits (Lehtola et al., 2017; Sammartano & Spanò, 2018; Bailey & Durrant-Whyte, 2006).

***Point Cloud Density Analysis***

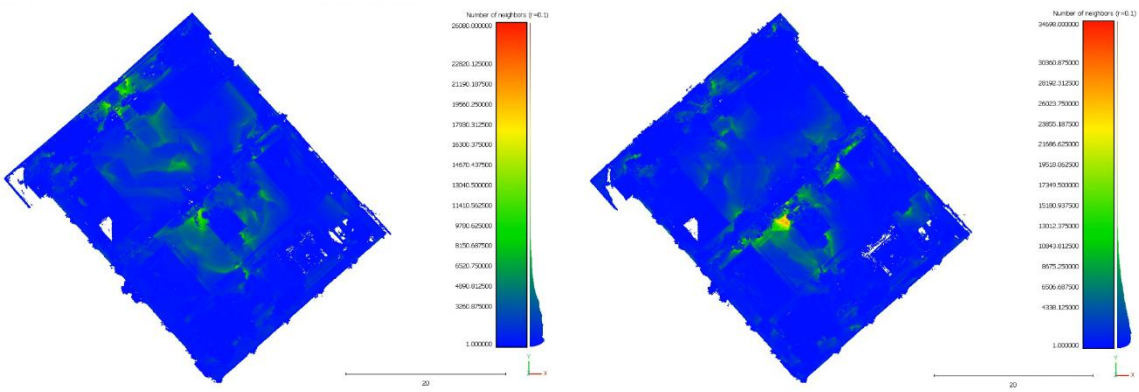
In addition to accuracy, the quality of the point cloud is also evaluated based on the point density generated by each approach.

Table 7. Comparison of point cloud densities

| Parameter | Single-session | Multi-session |
|---|---|---|
| Number of point clouds | 116,815,999 | 165,643,829 |
| Density (point/$m^2$) | 52,317 | 74,008 |

Based on Table 7, the multi-session approach yielded a larger number of points than the single-session approach. Based on the scanned area, the point cloud density for the single-session approach was 52,317 points/$m^2$, while the multi-session approach reached 74,008 points/$m^2$. The higher point cloud density in the multi-session approach is likely due to increased observation overlap resulting from scanning along several separate trajectories.

The spatial distribution of density was visualized using a scalar field of “number of neighbors” with a search radius of 0.1 meter in CloudCompare (Figure 6). Blue indicates areas with low density, while green through red indicate areas with higher density.



(a) (b)

Figure 6. Spatial distribution of point cloud density derived from the number of neighbors analysis (r = 0.1 m) for (a) single-session and (b) multi-session approaches

The visualization in Figure 6 also shows that the multi-session approach has more areas with medium to high density compared to the single-session approach. This is likely due to increased observation overlap resulting from scanning along several separate trajectories, thereby increasing the frequency of observations in specific areas.

Although the multi-session approach produces a higher point cloud density, the previous visual results show an increase in noise in some parts of the point cloud. This indicates that an increase in density is not always accompanied by an improvement in the model's visual quality.

***Scanning Efficiency Analysis***

The efficiency of the methods was evaluated based on the time required to complete the data acquisition process in the field. According to Table 8, the single-session approach took 26 minutes and 11 seconds to complete data acquisition, while the multi-session approach took a total of 40 minutes and 22 seconds. Thus, the multi-session approach took approximately 54% longer than the single-session approach.

Table 8. Detailed comparison of scanning and processing efficiency

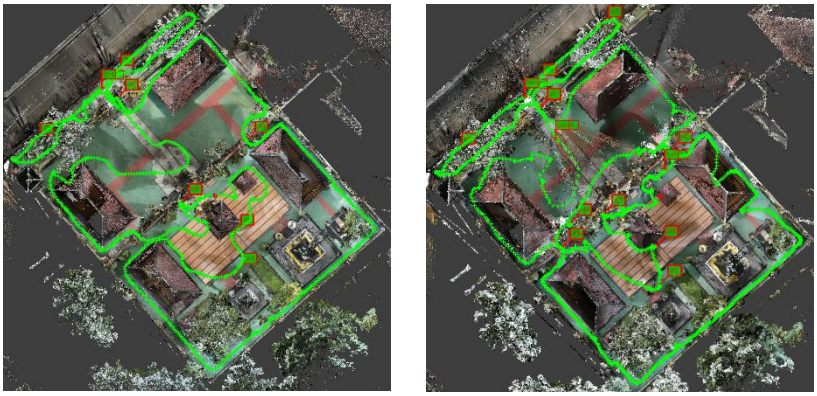
| Method | Field Acquisition Time | SLAM Processing Time | Cleaning, Cropping & Export | Total Time Effort |
|---|---|---|---|---|
| Single-session | 26 minutes 11 seconds | ~60 minutes | ~15 minutes | ~101 minutes |
| Multi-session | 40 minutes 22 seconds | ~180 minutes | ~45 minutes | ~265 minutes |

This difference in duration is due to the need to scan each zone separately, as well as the additional time required for movement and track preparation during each scanning session. From an operational efficiency standpoint, the single-session approach is more advantageous because it covers the entire study area in a single closed track without the need to repeat the scanning process.

As presented in Table 8, although the multi-session sub-maps automatically unified based on their shared georeferenced coordinate system, the total operational effort was still doubled (265 minutes vs 101 minutes). This is because the multi-session workflow required repeating the SLAM trajectory optimization three times in Hi-LiDAR and performing manual noise filtering, cleaning, and cropping across three individual datasets in CloudCompare instead of just one continuous point cloud.

***Trajectory Analysis***

Figure 7 shows the differences in trajectory patterns between the single-session and multi-session approaches. In the single-session approach, the entire study area is scanned in a single closed trajectory that continuously covers the Nista Mandala, Madya Mandala, and Utama Mandala zones. In contrast, the multi-session approach divides the study area into several shorter closed trajectories within each zone. As a result, the multi-session trajectories have a denser distribution compared to the single-session approach.

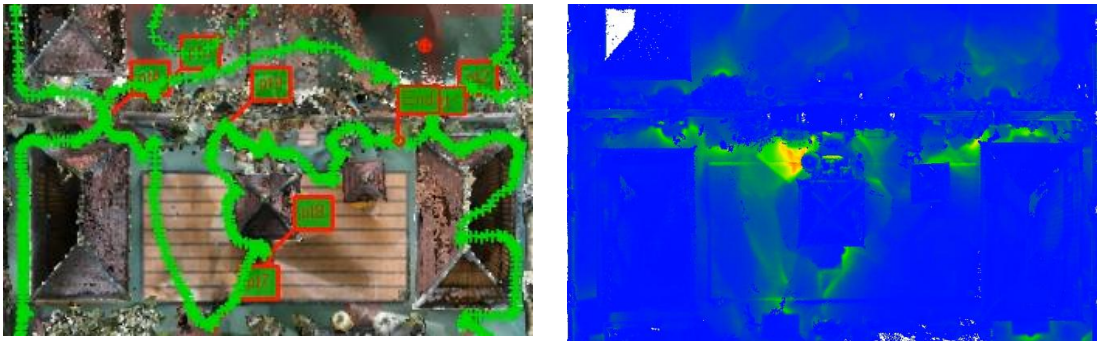


(a) (b)

Figure 7. Closed-loop scanning trajectories for the (a) single-session and (b) multi-session approaches

These differences in trajectory patterns affect the distribution of observations during the data acquisition process. Multi-session trajectories result in greater overlap between paths and increase the frequency of observations in specific areas. Gharineiat et al. (2024) explain that sufficient overlap plays a crucial role in reducing SLAM drift during the mapping process. Furthermore, Ress et al. (2024) emphasize that the quality of trajectory estimates plays a vital role in generating a dense 3D map. Meanwhile, Merkle and Reiterer (2023) specifically highlight trajectory design as a key component in evaluating SLAM system performance.

To clarify the influence of trajectory patterns on scanning results, Figure 8 shows an area with high trajectory overlap in the multi-session approach. The greatest overlap occurs in the transition area between the Madya Mandala and Utama Mandala zones, where several trajectories intersect. This condition increases the observation frequency, resulting in a point cloud with higher density in that area.



(a) (b)

Figure 8. Example of high-overlap trajectory areas in the multi-session approach and their corresponding dense point cloud regions

The results of this study show that the multi-session approach produces a point cloud with higher density and better horizontal positional accuracy compared to the single-session approach. This improvement is believed to be influenced by the higher frequency of loop closure in each scanning zone, thereby reducing the accumulation of horizontal errors. Conversely, in the single-session approach, the longer scan path has the potential to increase the accumulation of drift before the loop closure process is performed.

Nevertheless, the results of the Paired t-Test indicate that the increased point cloud density and horizontal accuracy in the multi-session approach do not result in a significant difference in object dimensional accuracy. Therefore, the choice of acquisition strategy must be tailored to the survey objectives. If the primary priority is acquisition time efficiency while maintaining good dimensional accuracy, the single-session approach is more suitable. Conversely, if a denser point cloud and higher horizontal positional accuracy are required, the multi-session approach is the more appropriate choice. Recommendations for applying each approach based on the results of this study are presented in Table 9.

Table 9. Recommendations for the application of SLAM scanning strategies

| Purpose of the survey | Recommended approach | Considerations |
|---|---|---|
| Fast data acquisition with good dimensional accuracy | Single-session | Offers more efficient acquisition times, a more uniform visual appearance, and dimensional accuracy comparable to multi-session scanning |
| Surveys with time constraints in the field | Single-session | The entire area can be scanned in a single continuous pass without requiring multiple scanning sessions |
| Surveys that prioritize vertical positional accuracy | Single-session | Achieves lower RMSEz and LE90 values, resulting in better vertical positional consistency |
| Acquisitions requiring high point cloud density | Multi-session | Produces a denser point cloud due to higher overlap and loop closure frequency |
| Surveys that prioritize horizontal positional accuracy | Multi-session | Has lower RMSEr and CE90 values, resulting in better horizontal positional consistency |
| Detailed documentation of buildings with complex geometries | Multi-session | Is better able to produce a dense spatial representation, although it requires a longer acquisition time |

## Conclusions

This study evaluates the effect of a closed-loop scanning strategy based on Simultaneous Localization and Mapping (SLAM) on the quality of the 3D point cloud of Pura Agung Wira Loka Natha using both single-session and multi-session approaches. The results of this study show that both methods produce well-georeferenced point clouds, as evidenced by the Accuracy Quality Report (AQR), and both demonstrate comparable dimensional accuracy based on the results of a paired t-test. These findings indicate that dividing the scanning path into multiple sessions does not necessarily contribute to an increase in the dimensional accuracy of the resulting objects.

However, the acquisition strategy still influences the characteristics of the resulting point cloud. The multi-session approach yields higher point density and better horizontal positional accuracy compared to the single-session approach. This is likely due to greater observation overlap resulting from the division into multiple sessions, which in turn improves the geometric quality of the point cloud and its horizontal positional accuracy. Conversely, the single-session approach achieves better vertical positional accuracy, with lower RMSEz and LE90 values than the multi-session approach, which may be attributed to its continuous, single closed-loop trajectory that minimizes vertical drift accumulation compared to the sub-map merging process required in the multi-session approach. Visually, the point cloud obtained through the multi-session approach also provides a more comprehensive representation of objects, although it contains more noise and color inconsistencies due to varying acquisition conditions across sessions. In contrast, the single-session approach produces a more homogeneous and cleaner point cloud, with a faster acquisition time.

Overall, the results of this study contribute to the evaluation of SLAM acquisition strategies for documenting buildings with complex architectural designs. In particular, this study demonstrates that increasing point cloud density and horizontal positional accuracy does not always coincide with improved dimensional or vertical accuracy. Therefore, the choice of scanning strategy must be tailored to the survey's objectives. The single-session approach is more suitable for activities requiring time efficiency combined with good dimensional and vertical accuracy, while the multi-session approach is more appropriate for needs requiring high point cloud density, broader object coverage, and improved horizontal positional accuracy.

Further research is recommended to investigate the effects of various trajectory designs and scan overlap levels on positional accuracy, point density, and the visual quality of the point cloud. Additionally, the analysis could be expanded to evaluate the quality of object representation in subsequent modeling stages, such as mesh generation, to gain a deeper understanding of how acquisition strategies impact the overall 3D documentation process.

## Author Contributions

Conceptualization, S.R. and G.A.J.K.; methodology, S.R. and G.A.J.K.; software, S.R.; validation, S.R.; formal analysis, S.R.; investigation, S.R.; resources, S.R.; data curation, S.R.; writing—original draft preparation, S.R.; writing—review and editing, G.A.J.K.; visualization, S.R.; supervision, G.A.J.K.; project administration, S.R. and G.A.J.K.; funding acquisition, G.A.J.K. All authors have read and agreed to the published version of the manuscript.

## Declaration of Generative AI Usage

Artificial intelligence (AI) tools were used to assist in the preparation of this manuscript. The authors used Claude and ChatGPT for language editing (including translation and grammatical refinement) and technical formatting assistance. The authors used NotebookLM solely as a personal comprehension aid to help interpret reference literature during the preparation of the literature review; no text generated by NotebookLM was incorporated into the manuscript, and the literature review was written independently by the authors based on their own understanding of the source materials. All AI-generated outputs were reviewed, edited, and verified by the authors. AI tools were not used for data collection, data analysis, result interpretation, or scientific decision-making, and were not involved in fabricating data, generating falsified results, or manipulating research findings. The authors take full responsibility for the accuracy, originality, and integrity of the content presented in this publication.

## Acknowledgment

The authors would like to express their sincere gratitude to the management of Pura Agung Wira Loka Natha for granting permission and providing support during the field survey and data acquisition activities. The authors also gratefully acknowledge the Surveying and Mapping Laboratory and the Photogrammetry Laboratory, Institut Teknologi Nasional Bandung, for providing the equipment and facilities used throughout this research. Their support and assistance greatly contributed to the successful completion of this study.

## References

Bailey, T., & Durrant-Whyte, H. (2006). *Simultaneous Localization and Mapping (SLAM): Part II*. https://doi.org/10.1109/MRA.2006.1678144

Bitelli, G., Forte, A., & Mandanici, E. (2026). SLAM mobile mapping for complex archaeological environments: Integrated above–below-ground surveying. *Geomatics*, *6*(2). https://doi.org/10.3390/geomatics6020031

Bonora, V., & Colapietro, M. (2026). Performance assessment of portable SLAM-Based systems for 3D documentation of historic built heritage. *Sensors*, *26*(2), 657. https://doi.org/10.3390/s26020657

Chen, Y., Tang, J., Jiang, C., Zhu, L., Lehtomäki, M., Kaartinen, H., Kaijaluoto, R., Wang, Y., Hyyppä, J., Hyyppä, H., Zhou, H., Pei, L., & Chen, R. (2018). The accuracy comparison of three Simultaneous Localization and Mapping (SLAM)-Based indoor mapping technologies. *Sensors*, *18*(10), 3228. https://doi.org/10.3390/s18103228

Di Stefano, F., Torresani, A., Farella, E. M., Pierdicca, R., Menna, F., & Remondino, F. (2021). 3D surveying of underground built heritage: Opportunities and challenges of mobile technologies. *Sustainability (Switzerland)*, *13*(23). https://doi.org/10.3390/su132313289

Durrant-Whyte, H., & Bailey, T. (2006). Simultaneous localization and mapping: Part I. *IEEE Robotics & Automation Magazine*, *13*(2), 99–110. https://doi.org/10.1109/MRA.2006.1638022

Federal Geographic Data Committee. (1998). *Geospatial positioning accuracy standards part 3: National standard for spatial data accuracy (FGDC-STD-007.3-1998)*. https://www.fgdc.gov/standards/projects/FGDC-standards-projects/accuracy/part3/chapter3

Gharineiat, Z., Tarsha Kurdi, F., Henny, K., Gray, H., Jamieson, A., & Reeves, N. (2024). Assessment of NavVis VLX and BLK2GO SLAM Scanner accuracy for outdoor and indoor surveying tasks. *Remote Sensing*, *16*(17). https://doi.org/10.3390/rs16173256

Grešla, O. (2025). From old-school to high-tech: 3D scanning a multi-storey building with everything we've got. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, *XLVIII-5/W3-2025*, 23–28. https://doi.org/10.5194/isprs-archives-xlviii-5-w3-2025-23-2025

Lehtola, V. V., Kaartinen, H., Nüchter, A., Kaijaluoto, R., Kukko, A., Litkey, P., Honkavaara, E., Rosnell, T., Vaaja, M. T., Virtanen, J. P., Kurkela, M., El Issaoui, A., Zhu, L., Jaakkola, A., & Hyyppä, J. (2017). Comparison of the selected state-of-the-art 3D indoor scanning and point cloud generation methods. *Remote Sensing*, *9*(8). https://doi.org/10.3390/rs9080796

Liu, Y., Wang, C., Wu, H., & Wei, Y. (2024). An effective LiDAR-Inertial SLAM-Based map construction method for outdoor environments. *Remote Sensing*, *16*(16). https://doi.org/10.3390/rs16163099

Maharlika, F. (2018). Ornaments as an Element to Forming Interiority in Utama Mandala Pura Agung Wiralokanatha. *Proceedings of the International Conference on Business, Economic, Social Science and Humanities (ICOBEST 2018)*. https://doi.org/10.2991/icobest-18.2018.44

Maset, E., Valente, R., Iamoni, M., Haider, M., & Fusiello, A. (2022). Integration of photogrammetry and portable mobile mapping technology for 3D modeling of cultural heritage sites: The case study of the Bziza Temple. *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences - ISPRS Archives*, *43*(B2-2022), 831–837. https://doi.org/10.5194/isprs-archives-XLIII-B2-2022-831-2022

Merkle, D., & Reiterer, A. (2023). Automated method for SLAM evaluation in GNSS-Denied areas. *Remote Sensing*, *15*(21), 5141. https://doi.org/10.3390/rs15215141

Oka, N. W. A., & Suci, N. M. (2026). Reaksi Pasar Saham Terhadap Skandal Tata Kelola ESG PT Timah Tbk (TINS). *RIGGS: Journal of Artificial Intelligence and Digital Business*, *5*(2), 4742–4750. https://doi.org/10.31004/riggs.v5i2.9090

Remondino, F. (2011). Heritage recording and 3D modeling with photogrammetry and 3D scanning. *Remote Sensing*, *3*(6), 1104–1138. https://doi.org/10.3390/rs3061104

Ress, V., Zhang, W., Skuddis, D., Haala, N., & Soergel, U. (2024). SLAM for indoor mapping of wide area construction environments. *ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, *10*(2), 209–216. https://doi.org/10.5194/isprs-annals-X-2-2024-209-2024

Sammartano, G., & Spanò, A. (2018). Point clouds by SLAM-Based mobile mapping systems: Accuracy and geometric content validation in multisensor survey and stand-alone acquisition. *Applied Geomatics*, *10*(4), 317–339. https://doi.org/10.1007/s12518-018-0221-7

Shimoda, I., Im, S., Oishi, T., Nakamura, R., Kajiwara, L., & Chen, W. (2025). Safeguarding Banteay Chhmar through Digital Twins: Integrated approaches for research, management, and conservation. *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences - ISPRS Archives*, *48*(M-9–2025), 1357–1364. https://doi.org/10.5194/isprs-archives-XLVIII-M-9-2025-1357-2025

Tanduo, B., Teppati Losè, L., & Chiabrando, F. (2023). Documentation of complex environments in cultural heritage sites. A SLAM-Based survey in the Castello Del Valentino basement. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, *XLVIII-1/W1-2023*, 489–496. https://doi.org/10.5194/isprs-archives-XLVIII-1-W1-2023-489-2023

Westoby, M. J., Brasington, J., Glasser, N. F., Hambrey, M. J., & Reynolds, J. M. (2012). "Structure-from-Motion" photogrammetry: A low-cost, effective tool for geoscience applications. *Geomorphology*, *179*, 300–314. https://doi.org/10.1016/j.geomorph.2012.08.021



This article is licensed under a Creative Commons Attribution-ShareAlike 4.0 International License.