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Evaluating the Accuracy of 3D Point Cloud Data of Elevated Structures Using Terrestrial Laser Scanners at Various Distances

(Penilaian ketepatan data titik awan 3D terhadap struktur tinggi menggunakan pemindai laser daratan pada jarak yang berbeza)

Wan Mohamed Syafuan[a*], Neza Ismail[a], Muhammad Hakim Jazmee Rosmee[a]

[a]*Department of Civil Engineering, National Defense University of Malaysia, Kuala Lumpur,Malaysia*

**Corresponding author: wmsyafuan@upnm.edu.my*

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ABSTRACT

Terrestrial laser scanning (TLS) is a powerful tool for generating detailed 3D models of elevated structures such as bridges, towers, and buildings. However, the quality of the resulting models heavily depends on the setup configuration of the TLS system. This research evaluates the precision of 3D point cloud data of elevated structures acquired through TLS at different distances. The data processing was performed using Cyclone Register360 software. The study aimed to evaluate the accuracy of point cloud data obtained from various TLS setup locations and compare it with the measurements obtained from a Total Station. Four different distances were used to set the TLS to scan the three elevated structure piers. The acquired data was then processed using Cyclone Register360 software to eliminate noise, visually align, and precisely register the point clouds. The results indicated that shorter distances between TLS setups resulted in more accurate point cloud data, with reduced error rates, highlighting the need to locate the scanner effectively. The study also highlighted the capabilities of Cyclone Register360 in improving the precision of point cloud data through effective data processing techniques. The findings demonstrate the significance of precise scanning distance evaluation in TLS applications to ensure high-quality data capture. It is vital for comprehensive 3D modeling and analysis of elevated structures. These valuable insights apply to specialists in surveying, engineering, and architecture. It offers guidance on the best practices for TLS setups, which can improve the accuracy and reliability of measurements. Further studies should examine the influence of other factors, such as scanning angles and environmental conditions, on the precision of TLS data.

Keywords: TLS; point cloud; accuracy; elevated; structure

ABSTRAK

Pengimbasan laser daratan (TLS) ialah alat berkuasa untuk menjana model 3D terperinci bagi struktur yang tinggi seperti jambatan, menara dan bangunan. Walau bagaimanapun, kualiti model yang dihasilkan sangat bergantung pada konfigurasi penyediaan sistem TLS. Penyelidikan ini menilai ketepatan data titik awan 3D bagi struktur tinggi yang diperoleh melalui TLS pada jarak yang berbeza. Pemprosesan data dilakukan menggunakan perisian Cyclone Register360. Kajian ini bertujuan untuk menilai ketepatan data titik awan yang diperoleh daripada pelbagai lokasi pemasangan TLS dan membandingkannya dengan ukuran yang diperoleh daripada Total Station. Empat jarak berbeza digunakan untuk menetapkan TLS untuk mengimbas tiga tiang berstruktur tinggi. Data yang diperoleh kemudiannya diproses menggunakan perisian Cyclone Register360 untuk menghapuskan hingar, menjajarkan secara visual dan mendaftarkan titik awan dengan tepat. Keputusan menunjukkan bahawa jarak antara tiang dan TLS yang lebih pendek menghasilkan data titik awan yang lebih tepat, dengan kadar ralat yang berkurangan, menyerlahkan keperluan untuk mengesan pengimbas dengan berkesan. Kajian ini juga menyerlahkan keupayaan Cyclone Register360 dalam meningkatkan ketepatan data titik awan melalui teknik pemprosesan data yang berkesan. Penemuan menunjukkan kepentingan penilaian jarak pengimbasan yang tepat dalam aplikasi TLS untuk memastikan tangkapan data berkualiti tinggi. Ia adalah penting untuk pemodelan 3D yang komprehensif dan analisis struktur tinggi. Hasil ini boleh digunakan untuk pakar dalam ukur, kejuruteraan dan seni bina. Ia menawarkan panduan tentang amalan terbaik untuk persediaan

TLS, yang boleh meningkatkan ketepatan dan kebolehpercayaan pengukuran. Kajian lanjut perlu mengkaji pengaruh faktor lain, seperti sudut imbasan dan keadaan persekitaran, terhadap ketepatan data TLS.

Kata kunci: TLS; titik awan; ketepatan; tinggi; struktur

INTRODUCTION

Terrestrial laser scanning (TLS) is a modern technology that uses laser beams to precisely scan and measure the surfaces or surroundings of objects. The origins of this technology may be traced back to the 1960s, when the first laser scanners were developed for industrial automation and quality control (Wu et al., 2022). Due to advancements in computing and data processing, more advanced and portable laser scanners became available in the 1990s. Efficiently capturing huge building facade point clouds with improved time efficiency and data quality requires precise planning of a TLS observation network (Chen et.al, 2022).

TLS is widely used in various fields, such as surveying, engineering, architecture, and cultural heritage conservation. It is a method of measuring surfaces or features without physical contact. It uses lasers to capture topographic data points rapidly and accurately (Rashidi et.al, 2020). Technology has been utilized in surveying and civil engineering to generate complex three-dimensional representations of expansive and complicated structures such as bridges, buildings, and tunnels. Engineers, architects, and surveyors have utilized it to examine, measure, and manage the condition of structures. The main advantage of utilizing TLS is its ability to minimize expenses and time due to data collecting while still preserving high accuracy.

The accuracy of TLS can be affected by the angle of observation and the distance between the scanner and the object being scanned. Therefore, each approach has advantages and disadvantages regarding precision, time efficiency, labor, and costs (Syafuan et al., 2023). This study aims to acquire point cloud data of three different piers using TLS with varying distance setups and then compare it with the actual data measurements obtained through a Total Station.

LITERATURE REVIEW

Terrestrial Laser Scanning (TLS), as shown in Figure 1, is a technology that employs a laser beam to scan and measure the surface of an object or environment. It is extensively utilized in several fields, including surveying, architecture, engineering, forensics, and the conservation of cultural heritage. According to (Holst et al., 2016), TLS is now widely used in engineering for documentation and deformation monitoring with analyzing area-based deformations of built structures. TLS captures the target object's position and then forms a point cloud in Cartesian coordinates (XYZ) as a result. The point cloud is obtained by measuring the light pulses that are emitted and returned.

FIGURE 1. Terrestrial Laser Scanner Leica RTC360

The position and value of the target object is determined based on the position of laser scanner (Abbas et al., 2017). According to (Neza et al., 2022), TLS is gaining popularity for dimensional quality control because of its ability to quickly give as-built data in the form of dense and accurate 3D point clouds. It involves the accuracy ranging from sub-mm to mm. It allows engineers and architects to assess the condition of a structure, identify potential problems, and plan repairs or renovations quickly and accurately.

TLS technologies grant the acquisition and the merging of different point clouds of millions of points. The combination of models with the network of Global Navigation Satellite System (GNSS) targets ensures correct georeferencing with exact coordinates x, y, and z (Scianna et al., 2020). TLS technology allows a quick point cloud acquisition, but the visualization, management and processing are time-consuming. These elaborations also require a considerable amount of RAM and memory of the laptop or PC, depending on the data dimension of the considered point cloud.

Despite the accuracy and precision of a TLS, the point cloud generated by the scanner can have geometric and radiometric errors caused by mechanical errors of a scanner, scanning geometry, and target properties. For practical application of the TLS, performance evaluation is necessary to predict and quantify error sources, which significantly affect laser scanning data (Lee J et al., 2016)

According to Li et al. (2023), they proposed using intensity information from TLS data analysis to enhance the accuracy of the point cloud. The study showed that by modifying the surface properties of scanned objects, more precise point cloud data could be obtained. This method was particularly effective in improving the quality of data for complex surface reconstructions, as it emphasized the importance of surface characteristics and scanner range on data accuracy.

(Witzmann et al., 2022) conducted a study to examine the accuracy and precision of different modeling techniques in estimating the cross-sectional area of tree stems. The researchers specifically investigated the use of TLS-derived point clouds for this purpose. Through a comprehensive analysis, they found that spline models yielded the highest precision and accuracy compared to ellipse and circle fits. These findings underscored the importance of placing the TLS in an optimal position, as shorter distances between the scanner and the target object generally resulted in more precise point cloud data.

However, the accuracy of TLS data can be influenced by the scanning range. For instance, the precision of TLS measurements, specifically the range precision, heavily relies on the scanning conditions, including the scan configuration and the reflectivity of the object's surface (Schmitz et al., 2019). Furthermore, the accuracy of TLS data can be validated by conducting a comparative analysis with reference measurements derived from more precise instruments, such as Total Station (TS) surveys (Kuçak et al., 2020). In terms of specific accuracy metrics, various studies have reported Root Mean Square Error (RMSE) values for TLS data, which range from 0.003m to 0.021m.

The reported values depend on the specific application and the integration of TLS data with other data sources (Ruiz et al., 2021) (Zakiyon et al., 2023). Overall, while TLS provides high accuracy for 3D modeling, its effectiveness can be enhanced by integrating it with other methodologies and by carefully considering scanning conditions and object properties. This means that the relationship between the range of TLS and the accuracy of 3D modeling becomes a complex interaction of various factors that require proper management to achieve optimal results.

According to (Abdul Shukor et al., 2015), 3D modelling illustrates how the building will look to the owner and contractors before the construction starts. Contractors will use the same model to build the building, and later, building owners and managers can use the same model as the as-built drawings for maintenance purposes.

An elevated building is one where either portion of or entirety is situated above the ground on a structural system consisting of piers or stilts. Alternate building types exist that may also be classified as elevated buildings. These include residential buildings constructed with an underlying crawlspace and manufactured homes. It is also known as "mobile homes" on steel chassis systems or steel or concrete footers. (Kim et al., 2020).

METHODOLOGY

Study Area

The study area was at Jalan Langat, Bandar Botanik, Klang Selangor. The bridge piers of the LRT3 base, as shown in Figure 2, are beside the road, and no trees block TLS from scanning the structure and setup configuration planned. That location has an area between each side of the road that provides gaps for safety while setting up the instrument.

FIGURE 2. Bridge pier structure

Data Collection

In this study, the pier elements as an elevated structure are divided into six dimensions: A, B, C, D, and E, as shown in Figure 3. The features are classified as A, F, and E is horizontal, B and D is vertical, and C is slope.

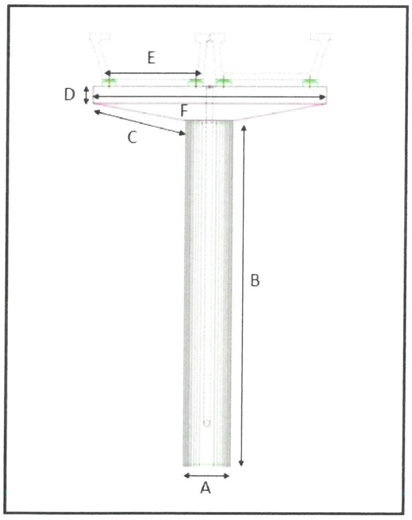

FIGURE 3. Pier elements

Four setup locations of TLS to cover the three piers were set with various distances, as shown in Figure 4. Table 1 represented the range distance of TLS between piers.

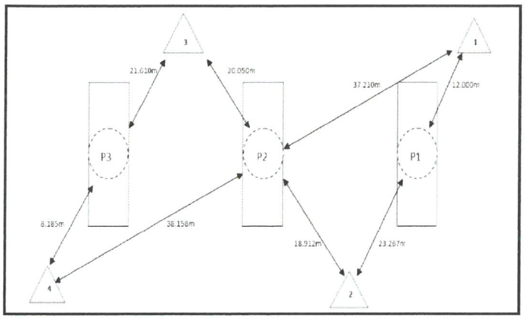

FIGURE 4. TLS setup locations

TABLE 1. Distance from setup to piers

From (Setup)	To (Piers)	Distance (m)
1	P1	12.000
2	P1	23.267
1	P2	37.210
2	P2	18.912
3	P2	20.050
4	P2	38.158
3	P3	21.610
4	P3	8.185

Data collection began with scanning the pier using TLS. The TLS setup configuration used is a single scan with high resolution, as shown in Figure 5. It takes only 2 minutes and 42 seconds to complete the scanning process for each location.

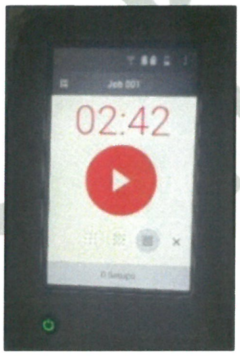

FIGURE 5. The duration of complete TLS scanning process of each setup.

After finishing the scanning process, the pier elements were measured using Total Station as shown in Figure 6 to get the actual measurement data. Using Total Station is indispensable for obtaining precise measurements between two points when a direct line of sight is obstructed or physically inaccessible, a common scenario in complex infrastructure.

FIGURE 6. Measuring actual data using Total Station

These measurements, along with the known angles and distances, allow for the application of trigonometric calculations to determine the lengths of the missing lines, thereby enabling the accurate determination of the pier's dimensions. It is achieved by constructing geometric shapes, typically triangles, using the measured angles and distances. The dimensions of the triangles, including the lengths of the sides of the missing lines, are then calculated using basic trigonometric formulas.

Data Processing

Post-processing points cloud data produced by TLS is crucial and complex. A thorough approach is required to ensure the accuracy of the digital model results. Cyclone Register360 was used as a prominent software solution with comprehensive tools for TLS data processing. This software provides a user-friendly interface and straightforward steps as shown in Figure 7, to process the raw data of the point cloud.

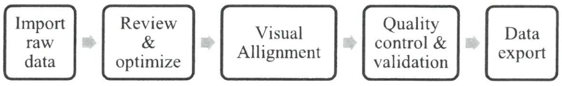

FIGURE 7. Cyclone Register360 processing steps

The initial step in processing points cloud data with Cyclone REGISTER 360 involves importing the raw scan data into the software, as shown in Figure 8. This step is to transfer the detailed scan data captured by TLS into the Cyclone REGISTER 360 environments.

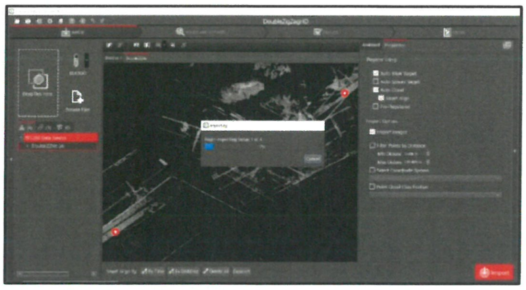

FIGURE 8. Import raw data to Cyclone Register360

This software supports a variety of file formats, providing a flexible import process that accommodates data from Leica scanners and other compatible formats. At this stage, users can connect their scanning devices to the software or import files stored on their computers or external storage devices. Figure 9 shows the result of raw data processing after import, with an inaccurate setup bundle link.

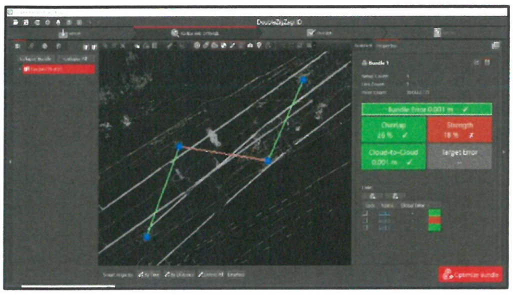

FIGURE 9. Output after importing raw data

Cyclone Register360 provides a range of functionalities for noise filtering and point cloud optimization. Users can choose to manually select and remove irrelevant points or utilize automated algorithms that identify and eliminate outliers based on intensity, color, or spatial location criteria. The cleanup procedure not only involves the removal of unnecessary data but also enhances the clarity and precision of the scans. This ensures that subsequent steps, such as the registration process, can be executed with the highest level of accuracy.

The visual alignment step in processing TLS data with Cyclone REGISTER 360 is utilized to establish a reliable and precise basis for point cloud registration. As depicted in Figure 10, the cyan point cloud signifies the data from station 1, whereas the orange point cloud signifies the data from station two. It is imperative to align the cyan point cloud with the orange point cloud, with either one being designated as the reference.

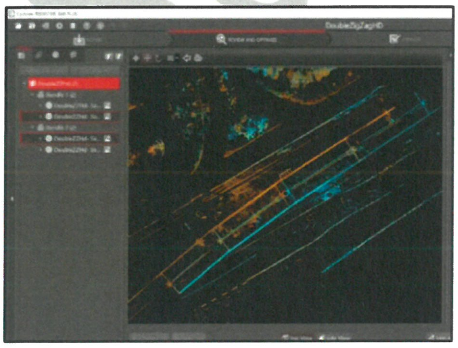

FIGURE 10. Visual alignment top view

Figure 11 illustrates the alignment process from a vertical perspective. Through the analysis of the scans' overall layout and orientation, Cyclone REGISTER360 can efficiently estimate their relative positions, resulting in a preliminary alignment that significantly reduces the manual workload in subsequent stages. However, it is important to acknowledge that automatic pre-alignment is not always perfect, especially in cases where there is minimal overlap between scans or when distinctive features are scarce.

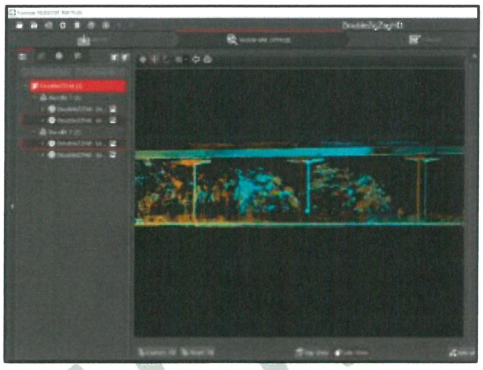

FIGURE 11. Visual alignment side view

The cloud-to-cloud registration techniques have been employed in visual alignment to accurately match millions of points from overlapping point clouds. This procedure entails generating a precise overlay of the scans to ensure that every detail in the environment is precisely captured and represented in the unified point cloud. Users are advised to undertake an iterative review, making necessary adjustments to parameters and re-aligning when required, to optimize the registration process.

Achieving a high level of accuracy in cloud registration, as demonstrated in Figure 12, enables users to establish a solid foundation for all subsequent analyses and applications. It ensures the reliability and effectiveness of the processed point cloud data.

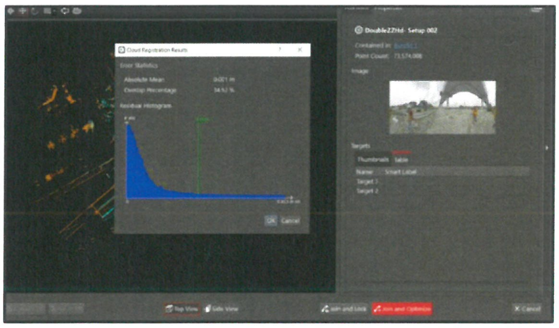

FIGURE 12. Cloud registration results

Cyclone REGISTER360 includes various tools specifically designed for this purpose, making it easier to carefully inspect the aligned scans for any errors or inconsistencies that might affect the accuracy of this research. During this phase, a thorough examination is conducted using the software's features to detect and correct any possible issues, ensuring the highest level of accuracy in the results.

Leica Cyclone REGISTER 360 provides a variety of distance measurement capabilities for numerous professional applications. With the support of the software's snap-to-feature functionality, users can achieve remarkable precision when measuring simple point-to-point distances. The software allows users to measure horizontal distances, which helps check ground-level distances and ensure level alignment between features. Vertical distance measurements help verify heights and clearances, which is crucial for ceiling height verification and vertical space assessment.

The sloped distance measurement mode also offers the precise measurement of distances along inclined surfaces, a critical feature for analyzing terrain, measuring roofs, or evaluating any sloped structures. These versatile measurement modes guarantee that users can acquire accurate and pertinent data tailored to their specific needs, thereby enhancing the precision and usability of the point cloud data. Figure 13 illustrates an instance of point cloud measurement using Cyclone REGISTER360.

FIGURE 13. Point cloud features measurements

Lastly, a comprehensive examination was conducted utilizing the software's functionality to identify and rectify any potential issues, ensuring the utmost precision of the outcome. Moreover, the creation of meticulous quality control registration reports, as depicted in Figure 14, is another crucial component of the procedure. These reports provide valuable insights into the accuracy of the registration, presenting statistical data and visual indicators that underscore the quality of alignment between the scans.

The documentation serves the purpose of validating the work performed. Additionally, it provides comprehensive documentation for stakeholders, demonstrating our commitment to attention to detail and maintaining high-quality standards throughout the project's life cycle. This level of detail ensures that every aspect of the registration process is meticulously documented and can be reviewed at any time, promoting transparency and accountability. By following these procedures, we can ensure that the processed point cloud data meets the demanding spatial accuracy and reliability standards necessary for complex analysis and decision-making in various fields.

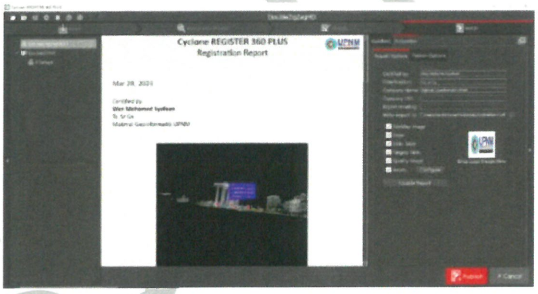

FIGURE 14. Registration report

RESULTS AND ANALYSIS

Point Cloud Quality

The quality of point cloud data generated from a TLS at various distances was assessed by analyzing several keys such as point count, overlap, strength, and cloud-to-cloud error. The results reflect how setup location impacts the quality of 3D point cloud data. The bundle error refers to the cumulative discrepancies encountered during the registration process of multiple scans. It measures how well the individual scans align with each other within the software environment. The cloud-to-cloud error assesses the alignment accuracy between overlapping point clouds from different scans. This error metric is used to understand the consistency of the point cloud data when integrated into a single model. Table 2 shows the results of quality data of overall point cloud data.

TABLE 2. Quality data of overall point cloud data

Setup Count	Link Count	Point Count	Bundle Error (m)	Overlap	Strength	Cloud-to-cloud error (m)
4	3	308,512,268	0.001	38%	28%	0.001

The analysis of the overall quality of the 3D point cloud data as assessed using a TLS at various distances demonstrates high accuracy and consistency. The total point count across all setups is 308,512,268, indicating a dense, high-resolution point cloud essential for capturing fine details

Previous research has indicated that to ensure sufficient coverage and detail for various infrastructure and construction applications, it is recommended to have an average point cloud density of at least 200 points/m^2 (Cahalane et al., 2014; Silva et al., 2017). However, it should be noted that the specific application and intended use of the data may necessitate different point cloud density requirements. Furthermore, the determination of the required point density should be based on the application as well as the desired level of detail and accuracy (Peng et al., 2021; Lassiter et al.,2020)

Error sources in TLS, such as outliers and noise, can be mitigated through the utilization of surface models and the implementation of best fit local planes. This approach effectively reduces the maximum errors from 50mm to 11mm and from 13mm to 1mm, depending on the specific scanner being used (Jaafar H.A & Sowter, 2018).

(Mill, 2020) found that when terrestrial laser scanners have a significant angle of incidence, the deviations in point clouds are observed to be within the millimetre range. While a substantial angle of incidence may cause noticeable discrepancies in the accuracy of point clouds, its effect on accurately detecting the size of objects was determined to be minimal. Therefore, the study concludes that the maximum bundle error in point clouds of terrestrial laser scanners is measured in millimetres.

Overlap percentages between consecutive setups range from 33% to 42%, ensuring sufficient common areas for effective merging and alignment of the scans. Although the strength values indicate confidence in scan alignment and are moderate (ranging from 26% to 31%), they are adequate for maintaining overall data integrity. The cloud-to-cloud errors are minimal, with values of 0.001 meters for link setup 1 & 2 and 3 & 4. For link setup 2 & 3, it is 0.002 meters, indicating close alignment and minimal discrepancies between the point clouds from different setups. Overall, the point cloud data quality is high, making it suitable for detailed analysis and further processing to create accurate 3D models of the scanned elevated structures. The detailed results of the point cloud for each setup are shown in Table 3 and Table 4.

TABLE 3. Point count for each setup

Setup	Point Count
1	86,798,257
2	74,593,559
3	69,779,531
4	77,340,921

TABLE 4. Quality data of each setup

Setup	Link error	Overlap	Strength	Cloud-to-cloud error (m)
1 & 2	0.001	33%	31%	0.001
2 & 3	0.002	38%	26%	0.002
3 & 4	0.001	42%	28%	0.001

The results shown in Table 2 indicate the number of discrete data points captured during each scanning session. The variations in point counts can be attributed to several factors, including the distance from the scanner to the target, the complexity of the structures, and the scanning resolution settings. Higher point counts generally suggest a higher density of captured data, which can lead to more accurate and detailed 3D models. These counts are integral to assessing the accuracy and quality of the 3D point cloud data, as they directly influence the level of detail and the precision of the measurements derived from the scans.

Table 3 shows the link error for setups 1 & 2 proved with 0.001 meters. Additionally, there was a 33% overlap and a strength of 31%. This setup demonstrated a cloud-to-cloud error of 0.001 meters. The configurations between setups 2 & 3 exhibited a slight increase in link error of 0.002. A higher overlap of 38% accompanied it, but a decrease in strength of 26%. Consequently, there was a cloud-to-cloud error of 0.002 meters. Finally, configurations 3 & 4 showed a link issue like setups 1 & 2. The overlap was the highest at 42%, with a strength of 28%, resulting in a cloud-to-cloud error of 0.001 meters.

The findings indicate that the link and cloud-to-cloud errors were consistently low in most setups. However, the overlap percentage varied, with setups 3 & 4 showing the highest overlap. It could enhance the reliability of the point cloud data. The variations in strength among various setups highlight the impact of scanning distance and configuration on the quality and precision of the resulting 3D point cloud data. A thoughtful assessment of setup configurations can significantly influence the accuracy of point cloud data in TLS applications.

Error Percentage Analysis

The accuracy of 3D point cloud data collected at various distances was systematically assessed using error percentage analysis. Quantifying the differences between the scanned data and the actual measurements of the elevated structures was the main objective of the investigation. The error percentages were calculated through these data sets to determine how various distances affected the accuracy of the TLS results. Equation 1 defines the error percentage formula where a υA is measured value, and υE is actual data. The significance of distance measurement in TLS to guarantee the best quality in 3D point cloud data gathering for elevated structures is highlighted by this experiment.

$$\delta = \left| \frac{\upsilon A - \upsilon E}{\upsilon E} \right| \bullet 100\% \qquad (1)$$

The error percentages were computed between six specific features: horizontal, vertical, and slope. The results are shown in Figure 15 for Pier 1, Figure 16 for Pier 2, and Figure 17 for Pier 3

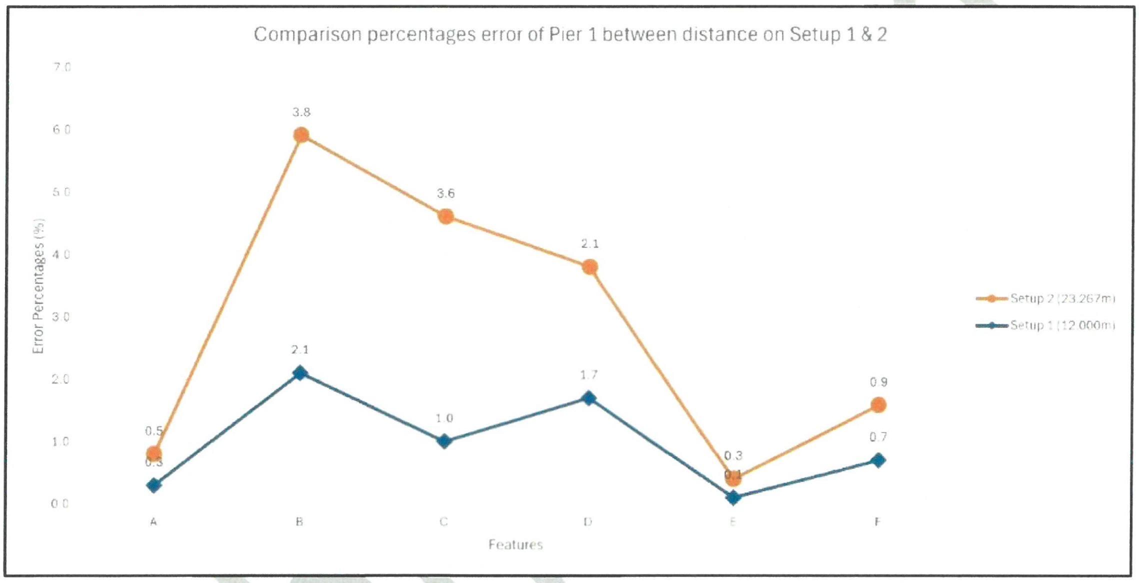

FIGURE 15. Comparison percentages error of Pier 1

Figure 15 presents a graphical overview of the error percentages for Pier 1 in two different setups at various distances. The first setup, labelled as Setup 1, is set up at 12.000 meters, while the second setup, referred to as Setup 2, is located at 23.267 meters. The analysis reveals an apparent discrepancy in the accuracy of the 3D point cloud data obtained from the TLS for these two setups.

In Setup 1, the error percentages remain relatively low and consistent across the features, with the highest error observed at Feature B (2.1%) and the lowest at Feature E (0.1%). It indicates a stable performance of the TLS at a closer distance of 12.000 meters, providing more precise measurements.

Conversely, Setup 2 shows dramatically more significant error percentages for all features, reaching the highest at Features B with an error rate of 3.8%. These findings indicate a significant decrease in accuracy as the distance is extended to 23.267 meters. However, the overall error rates are consistently higher than those observed in Setup 1.

The comparison highlights that only Setup 1 and Setup 2 produced distinct point clouds appropriate for measurement. Setup 1 demonstrated higher precision compared to Setup 2. The results represent the significant influence of the scanning distance on the error rates of the 3D point cloud data, emphasizing the importance of closer proximity for precise and reliable measurements in TLS applications for elevated structures.

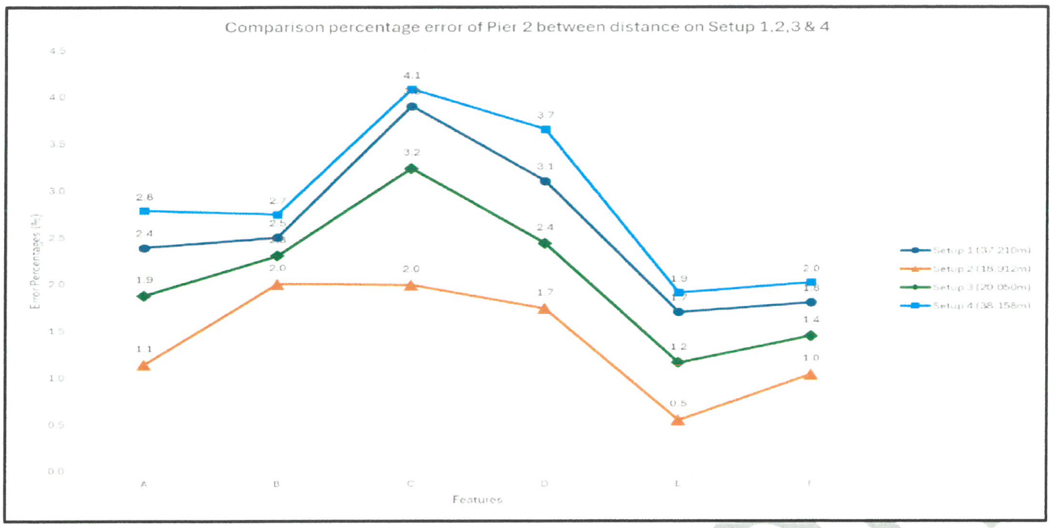

FIGURE 16. Comparison percentages error of Pier 2

The error percentage analysis of Pier 2 at various distances is presented in Figure 16. The graph compares the percentage errors of four different setups: Setup 1 (37.210 meters), Setup 2 (18.912 meters), Setup 3 (20.050 meters), and Setup 4 (38.158 meters) across features A to F.

Based on the graph, it is evident that Setup 4, located at a farthest distance of 38.158 meters, shows higher error percentages at several points, especially at Features C, D, and E, where the error percentage exceeds 4.1%. Setup 1, positioned at 37.210 meters, also shows significant errors, notably in Features B and C.

However, it is essential to highlight that Setup 2, which has the shortest distance of 18.912 meters, consistently exhibits lower error percentages. It consistently maintains values around 1.0% to 2.0% across all the points. Setup 3, located at 20.050 meters, exhibits balanced results with error percentages that are within acceptable limits. However, there is a slight increase in values at Features C.

Based on the analysis, it is demonstrated that the clarity and measurability of the point clouds are affected by the proximity of the scanner, subsequently affecting the accuracy of the data. When the distances are closer, as demonstrated in Setup 2, the point cloud data becomes more accurate, which results in lower error percentages.

Moreover, setups placed farther apart, such as Setup 4 and Setup 1, often exhibit higher error percentages. It is likely because of the increased distance between the setups and potential environmental interference. It emphasizes the significance of positioning the scanner optimally to guarantee the precise collection of 3D point cloud data in elevated structures.

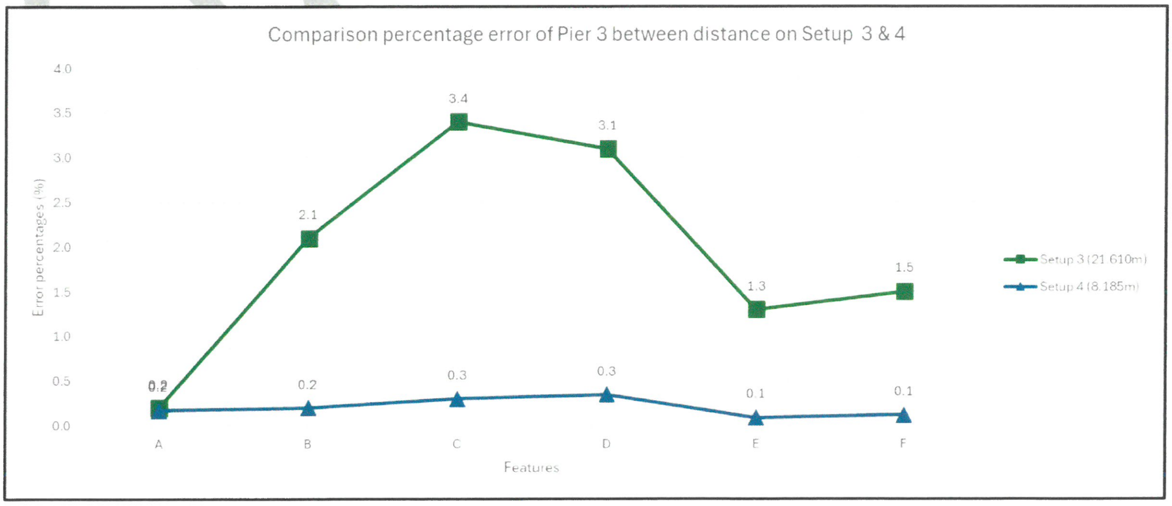

FIGURE 17. Comparison percentages error of Pier 3

Figure 17 presents the error percentage analysis of Pier 3 at various distances between Setup 3 (21.610 meters) and Setup 4 (8.185 meters). The results indicate a significant disparity in error percentages between the two setups. For Setup 3, the error percentages exhibited notable variability across different features, with the highest error observed at Feature C (3.4%) and the lowest at Feature A (0.2%). This setup consistently showed higher error percentages, peaking notably for Features B (2.1%), D (3.1%), and F (1.5%), which suggests a potential influence of the greater scanning distance on the accuracy of the point cloud data.

Moreover, Setup 4 consistently maintained a low and stable error percentage for all features, never rising above 0.3%. The setup exhibited the highest error rate in Features C and D, with a margin of 0.3%. However, the error percentages for Features A, B, E, and F were impressively low, ranging from 0.1% to 0.2%. The consistency and minimal error percentages in Setup 4 demonstrate the improved accuracy that can be achieved when scanning at a shorter distance.

This analysis highlights the significant influence that scanning distance has on the accuracy of 3D point cloud data. In Setup 4, the closer proximity allows for more precise measurements, as evidenced by the consistently low error percentages. Setups 3 and 4 were the only configurations that provided precise point cloud data that could be reliably measured. A shorter distance proved to be the more effective configuration for acquiring precise data in this context.

In the field of geomatics and the utilization of TLS models like RTC360, the precision of 3D modeling holds great importance. A range of standards and methodologies are employed to assess this precision, including the comparison of point clouds with more accurate measurement systems (Yazar et al., 2020). Error percentages are classified into low, medium, and high categories based on predefined thresholds. For example, in TLS output evaluation, an error of 4.1% may be deemed high due to its potential impact on the overall model precision and detail. Conversely, an error of 0.1% would be classified as low, indicating minor deviations that are unlikely to significantly affect the final quality of the 3D model (Ozendi et al., 2016).

CONCLUSION

This study evaluated the accuracy of 3D point cloud data of elevated structures TLS at various distances. The results revealed significant findings that contribute to the various disciplines. The analysis primarily involved comparing point cloud data collected from various TLS setup locations and distances to the actual measurement using a Total Station.

Moreover, using Cyclone Register360 software for data processing proved effective in optimizing and aligning the point cloud data. The software's features facilitated the noise filtering, visual alignment, and accurate registration of the scanned data, contributing to the overall precision of the final 3D models. The thorough examination and correction of potential errors during the post-processing phase were essential to achieving the desired level of accuracy.

As the findings have revealed, it is crucial to consider the proximity of the TLS to the scanned structures when determining the accuracy of the point cloud data. Setups of TLS distance closer to the target structures consistently resulted in lower error percentages, highlighting higher precision. More specifically, the point cloud data collected from setups at shorter distances showed very few differences when compared to the actual measurements. It emphasizes the importance of optimal TLS setup location to achieve precise and reliable 3D representations of elevated structures.

The analysis also showed that error percentages in the point cloud data tended to rise as the distance between the TLS and the target structure increased. This trend was evident in various aspects of the scanned structures, indicating that longer distances could give rise to more significant errors. The study emphasized the importance of precisely evaluating scanning distances in practical applications to ensure excellent quality acquisition of data.

In conclusion, this research demonstrated that TLS technology, when used with appropriate scanning distances and robust data processing techniques, can produce highly accurate 3D point cloud data of elevated structures. The study's insights are valuable for professionals in surveying, engineering, and architecture, guiding best practices for TLS setup configurations to enhance the accuracy and reliability of their measurements. Future studies could further explore the impact of other variables, such as scanning angles and environmental conditions, on the accuracy of TLS data.

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REFERENCES

Abbas, M. A., Lichti, D. D., Chong, A. K., Setan, H., Majid, Z., Lau, C. L., Idris, K. M., & Ariff, M. F. M. (2017). Improvements to the accuracy of prototype ship models measurement method using terrestrial laser scanner. *Measurement: Journal of the International Measurement Confederation*, *100*, 301–310.

Abdul Shukor, S. A., Wong, R., Rushforth, E., Basah, S. N., & Zakaria, A. (2015). 3D terrestrial laser scanner for managing existing building. *Jurnal Teknologi*, *76*(12), 133–139.

Cahalane, C., McElhinney, C P., Lewis, P., & McCarthy, T. (2014, May 27). Calculation of Target-Specific Point Distribution for 2D Mobile Laser Scanners. Multidisciplinary Digital Publishing Institute, 14(6), 9471-9488. https://doi.org/10.3390/s140609471

Chen, Z., Zhang, W., Huang, R., Dong, Z., Chen, C., Jiang, L., & Wang, H. (2022). 3D model-based TLS observation network planning for large-scale building facades. *Automation in Construction*, *144*.

Holst, C., Wieser, A., Zurich, E., Wunderlich, T., Neuner, H., & Kuhlmann, H. (2016). *Calibration of Terrestrial Laser Scanners Kalibrierung terrestrischer Laserscanner*.

Jaafar, H. A., Meng, X., & Sowter, A. (2017). Terrestrial laser scanner error quantification for the purpose of monitoring. Survey Review, 50(360), 232–248. https://doi.org/10.1080/00396265.2016.1259721

Kim, J. H., Moravej, M., Sutley, E. J., Chowdhury, A., & Dao, T. N. (2020). Observations and analysis of wind pressures on the floor underside of elevated buildings. *Engineering Structures*, *221*.

Kuçak, R. A., Erol, S., & İşiler, M. (2020). Comparative Accuracy Analysis of Lidar Systems. Turkish Journal of LIDAR, 2(2), 34–40. https://dergipark.org.tr/tr/pub/melid

Lassiter, H A., Whitley, T., Wilkinson, B., & Abd-Elrahman, A. (2020, December 21). Scan Pattern Characterization of Velodyne VLP-16 Lidar Sensor for UAS Laser Scanning. Multidisciplinary Digital Publishing Institute, 20(24), 7351-7351. https://doi.org/10.3390/s20247351

Lee, J. S., Hong, S. H., Park, I. S., Cho, H. S., & Sohn, H. G. (2016). Evaluation of Geometric Error Sources for Terrestrial Laser Scanner. *Journal of Korean Society for Geospatial Information System*, *24*(2), 79–87.

Li, S., Zheng, D., Yue, D., Hu, C., & Ma, X. (2023). A Method for Point Cloud Accuracy Analysis Based on Intensity Information. Sensors, 23(22). https://doi.org/10.3390/s23229135

Mill, T. (2020). Estimation of accuracy and reliability of terrestrial laser scanner in the detection of object shape. Baltic Journal of Modern Computing, 8(2), 337–346. https://doi.org/10.22364/BJMC.2020.8.2.09

Neza, I., Mohamed, M. I., & Syafuan, W. M. (2022). Surface Waviness Evaluation of Two Different Types of Material of a Multi-Purpose Hall Using Terrestrial Laser Scanner (TLS). *IOP Conference Series: Materials Science and Engineering*, *1229*(1), 012002.

Ozendi, M., Akca, D., & Topan, H. (2016). An emprical point error model for TLS derived point clouds. International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences - ISPRS Archives, 41, 557–563. https://doi.org/10.5194/isprsarchives-XLI-B5-557-2016

Peng, X., Zhao, A., Chen, Y., Chen, Q., & Liu, H. (2021, March 11). Tree Height Measurements in Degraded Tropical Forests Based on UAV-LiDAR Data of Different Point Cloud Densities: A Case Study on Dacrydium pierrei in China. Multidisciplinary Digital Publishing Institute, 12(3), 328-328. https://doi.org/10.3390/f12030328

Rashidi, M., Mohammadi, M., Kivi, S. S., Abdolvand, M. M., Truong-Hong, L., & Samali, B. (2020). A decade of modern bridge monitoring using terrestrial laser scanning: Review and future directions. In *Remote Sensing* (Vol. 12, Issue 22, pp. 1–34). MDPI AG.

Ruiz, P. R. S., Almeida, C. M., Schimalski, M. B., Liesenberg, V., & Mitishita, E. A. (2021). TLS and short-range photogrammetric data fusion for buildings 3d modeling. International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences - ISPRS Archives, 43(B3-2021), 279–284. https://doi.org/10.5194/isprs-archives-XLIII-B3-2021-279-2021

Schmitz, B., Holst, C., Medic, T., Lichti, D. D., & Kuhlmann, H. (2019). How to efficiently determine the range precision of 3D terrestrial laser scanners. Sensors (Switzerland), 19(6). https://doi.org/10.3390/s19061466

Scianna, A., Gaglio, G. F., & la Guardia, M. (2020). Digital Photogrammetry, TLS Survey and 3D Modelling For VR And AR Applications in CH. *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences - ISPRS Archives*, *43*(B2), 901–909.

Silva, C A., Hudak, A T., Vierling, L A., Klauberg, C., García, M., Ferraz, A., Keller, M., Eitel, J U H., & Saatchi, S. (2017, October 23). Impacts of Airborne Lidar Pulse Density on Estimating Biomass Stocks and Changes in a

Selectively Logged Tropical Forest. Multidisciplinary Digital Publishing Institute, 9(10), 1068-1068. https://doi.org/10.3390/rs9101068

Syafuan, W. M., Ismail, N., & Efandi, D. (2023). Comparison Assessment of Pier Dimension Measurement with Different Terrestrial Laser Scanner (TLS) Setup Location. *IOP Conference Series: Earth and Environmental Science*, *1240*(1).

Witzmann, S., Matitz, L., Gollob, C., Ritter, T., Kraßnitzer, R., Tockner, A., Stampfer, K., & Nothdurft, A. (2022). Accuracy and Precision of Stem Cross-Section Modeling in 3D Point Clouds from TLS and Caliper Measurements for Basal Area Estimation. Remote Sensing, 14(8). https://doi.org/10.3390/rs14081923

Wu, C., Yuan, Y., Tang, Y., & Tian, B. (2022). Application of terrestrial laser scanning (Tls) in the architecture, engineering and construction (aec) industry. In Sensors (Vol. 22, Issue 1). MDPI. https://doi.org/10.3390/s22010265

Yazar, S., Dergisi, T. L., Kuçak, R. A., Erol, S., & İşiler, M. (2020). Comparative Accuracy Analysis of Lidar Systems. Turkish Journal of LIDAR, 2(2), 34–40. https://dergipark.org.tr/tr/pub/melid

Zakiyon, A. M. A. A., Idris, A. N., Hezri Razali, M., Ghani, M. N. A., & Syafuan, W. M. (2023). Evaluating the Accuracy of UAV and TLS for 3D Indoor Modelling in Large-Scale Building Environments. IOP Conference Series: Earth and Environmental Science, 1240(1). https://doi.org/10.1088/1755-1315/1240/1/012003