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Georeferenced 3D Laser Scanning Workflow for Enhanced As-Built Engineering Data

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Abstract

Every built structure will endure a period of transformation over time, either due to natural deterioration or through intervention by renovation and preservation works. It is essential to record the building's current state by determining each component integrated with it, and this can be done by remodeling, referring to the dimensions of the building itself in the form of digital documentation. In common practice, the dimensions and data of the building are obtained by traditional measuring methods, where the process is time-consuming and may lead to errors. The objectives of these studies are to develop the workflow of built buildings' data documentation through 3D laser scanning with the aid of georeferencing to increase data accuracies. In the context of this study, the Student Centre located at Kampus Bandar, Universiti Tun Hussein Onn Malaysia, was chosen as the study area. The point clouds of the study area were documented and integrated with the georeferenced data, including three-dimensional coordinates (X, Y, and Z axis). As a result, it is ascertained that with the integration of georeferenced data on top of the point clouds, the outcome of the digital documentation will be more precise and accurate for future reference, specifically for design and construction works. The results demonstrate that incorporating georeferencing data into to the point cloud data significantly improves the spatial accuracy and reliability of the resulting as-built data. Such enhanced datasets provide a dependable foundation for engineering applications, including design refinement, construction verification, and detailed structural assessment.

1. Introduction

Building Information Modelling (BIM) provides a collaborative environment for planning, designing, and constructing a structure within a 3-D model [1]. This ecosystem integrates engineers, architects, contractors, and developers, promoting an ideal workflow that ensures efficient data management among consultants. Accurate data and information are required for a variety of applications, from managing a facility to assessing a structure, which is critical with the continued global growth of building construction [2]. In obtaining the measurements of the built structure, the classical measuring technique of a tachometric survey has been fundamental and historically proven. However, these traditional methodologies are often time-consuming, costly, and can lead to data erosion, which can significantly compromise the data's integrity [3].

Terrestrial laser scanning (TLS) is a ground-based remote sensing technique that utilizes laser beams to scan and capture detailed 3D information about the surface of objects or landscapes [4]. TLS instruments are capable of rotating their sensors in two axes, allowing them to capture data from various angles and directions, resulting in the generation of dense point clouds with millions of points [5]. TLS technology is known for its precision and ability to quickly scan objects, providing accurate 3D coordinates (x, y, z) through LiDAR technology [6]. Moreover, TLS is extensively used for visualization, modeling, and monitoring of man-made structures like buildings [7]. To ensure accurate 3D spatial information, meticulous scanning plans and proper post-processing techniques are essential when using TLS [8]. Additionally, TLS scanners are capable of generating geometrically accurate data, making them ideal for accuracy verification and change detection applications. The technology is also valuable for mapping indoor environments rapidly and accurately.

A 'georeferenced point cloud' refers to the datasets that not only tie to the three-dimensional Cartesian coordinates (X, Y, Z), but are also located within an Earth-fixed coordinate system [9]. Beyond location, each point possesses multiple attributes. These attributes, from the vantage point of measurement technology, are assessed and subsequently processed through point cloud workflows (which may include segmentation, classification, modeling, and visualization). In this context, stitching and processing the individual points is possible and thematic information may be added, making point clouds more extensive with a class label and additional attributes. Management of georeferenced point clouds typically involves regular spatial subdivisions that are both visualization-optimized and data-driven. The ability to customize and add attributes to point clouds using flexible models is what makes them valuable to multiple disciplines. The position of features in space is fundamentally defined by a coordinate system. These may be expressed in Cartesian coordinates (X, Y, Z), or geodetic (φ, λ, h) coordinates and include an ellipsoid [10].More precisely, ellipsoidal height (h) denotes the distance between a given point on the Earth's surface and the reference ellipsoid, whereas geoid height (N) denotes the distance between the reference geoid and the ellipsoid. Orthometric height (H) is the distance from a point on the Earth's surface to the geoid [11]. Longitude and latitude are fundamental positional coordinates specified in degrees [12].

The reliability and precision of coordinates in rapid GNSS surveys is not solely determined by the class of Global Navigation Satellite System (GNSS) receiver or the software used [13]. This is because coordinates can be recorded even when obstructed, as long as data collection is performed properly. Even though GNSS receiver and software manufacturers do not give surveyors specific methodologies, users are allowed to obtain an accurate baseline between two points. The natural change of survey and processing methodology of GNSS observations is dependent on the rapid static surveys the geo-referencing permanent reference stations. Using the methodology from the previous study, survey work was divided among one survey team with the rover GNSS receivers who captured GNSS observations at consecutive points during ultra-rapid static surveying. The use of traditional survey methodologies was not as accurate as the current techniques, which allowed high accuracy to be observed from rapid static surveys. The reliable coordinates of control points can be obtained in a few minutes despite any terrain obstructions, thanks to the GLONASS or GPS features.

This research attempts to develop and execute a workflow and construct a georeferenced 3D point cloud of a built structure and its surrounding environment. The most focused aim is to develop a 3D model of an existing built asset that is as accurate as possible and geospatially referenced. The study combines BIM software and TLS to develop comprehensive 3D models. The Student Centre located at the City Campus, Universiti Tun Hussein Onn Malaysia (UTHM), is chosen to be the specific case study for the purpose of this research. The results of this study are intended to provide substantial added value for the various users located within the UTHM Parit Raja campus, by providing advanced 3D models of its buildings, to improve their planning, maintenance, and operational processes.

2. Literature Review

The most common traditional technique for obtaining built structure measurement data is manual surveying. Nevertheless, these techniques have considerable limitations, especially when it comes to large and complex buildings. The surveyor must spend a considerable amount of time and possibly put themselves at risk in hard-to-reach or complex components of a built structure [14]. Due to the high risk of human error, manual surveys are often inaccurate and may incompletely represent a variety of details, or inaccessible areas that may be difficult to capture [15]. Additionally, the drawing and computation of survey results are highly time-consuming and required the high level of expertise, limiting the efficiency of final output [16] [17]. In most cases, recorded data of the building does not correspond to the physically built structure on site, due to changes in the built structure over time. The modification or deterioration mainly causes it. As a result, the surveyor had to repeat the surveying process periodically to ensure that the building's data was recorded correctly over time [14].

Building surveying has greatly benefited from the development of TLS technology, which can rapidly gather large amounts of 3D data with high accuracy in the form of point clouds [18]. In a matter of seconds, TLS can accumulate millions of accurate data points, resulting in high-resolution 3D models that are accurate to the millimeter [19], [20]. TLS technology can collect data on large built structures without the measurer having to enter any hazardous areas, which improves the safety of the operation [21], [22]. It greatly reduces the time during which a surveyor has to be physically present on a construction site, which reduces the project costs overall, and lessens the amount of mistakes that are made during data collection and writing down of the data [22], [23]. In addition to the coordinates, TLS can collect additional information such as surface reflectance and color which improves the data and aids in the architectural documentation and serves as a great complement to the Building Information Modeling (BIM) procedures [19], [20].

Despite the clear benefits of point cloud data, its utility can be severely compromised if not properly georeferenced. Point clouds are initially generated in a local coordinate system relative to the scanner's position [24]. Without georeferencing, these datasets cannot be connected to a global, real-world reference system which makes them disconnected and unable to be integrated with other forms of spatial information such as maps or other geodetic systems [25]. A lack of georeferencing makes almost every kind of spatial analysis, including multi-temporal change detection and situating the object with respect to the other entities in the surrounding context, extremely difficult [26]. Positional uncertainties and errors in the direct georeferencing procedure of TLS can propagate through the processes of registration and segmentation, impacting the quality of final 3D as-built models and structural monitoring results [27], [28]. Estimating the transformation matrix between different sensor overlapped point clouds is also challenging due to large outliers, differences in density, and partial overlaps [29].

Georeferencing is therefore a critical step that transforms point cloud data from its local scanner coordinate system into a precise global coordinate system, unlocking its full potential [25], [30]. By georeferencing the point clouds, the output is significantly accurate and reliable ot the spatial information. It is technically crucial in manipulating the data for precise architectural record, construction and structure monitoring, facility management, and the geographical information of the built structure [20]. The point clouds embedded with the georeference information will be efficiently integrated with other geospatial datasets, beneficial to be processed in the BIM tools and ecosystem, to allow for future data use in spatial analysis, deformation monitoring, and clash detection analysis [31], [32]. The interoperability capacity of this data allowed it to be used particularly in Historical Building Information Modelling (HBIM) for precise digital models of heritage built structures, in aiding the planning for preservation, restoration, and management [31], [33]. Direct georeferencing, through the use of known reference points, can be particularly beneficial for surveying building facades for integration into 3D city models [34].

While traditional surveying techniques set a baseline for standards in surveying and documentation, their time-consuming and labor-intensive processes, as well as their low accuracy, are being offset by modern technological advancements. Digital techniques and the acquisition of 3D data through Terrestrial Laser Scanners are fast and accurate. However, the full extent of the potential and usefulness of the point cloud derived from Terrestrial Laser Scanners can only be optimally achieved through the process of georeferencing. Georeferencing point clouds provides a highly reliable and detailed basis for spatial analyses, data synthesis, and contemporary (or future) surveys and documentation processes, as well as informed decision-making.

3. Methodology

3.1 Control Point Establishment for Survey

Control points serve as strategic reference points crucial for accurately positioning survey measurements, establishing a reliable framework, and monitoring potential deformations. The quality and placement of these points are pivotal for maintaining measurement precision, necessitating high-quality points and understanding distance impacts. Utilizing multiple control points aids in constraining nonlinear structures, enhancing scanning accuracy, and ensuring survey data stability [35]. The two main approaches to establishing control points involve Ground Control Points (GCP), which employ Global Positioning System (GPS) technology, and Independent Control Points (ICP), which use total stations, especially when some obstruction is encountered.

GCPs, which serve as reference points for point cloud data, are established with the aid of advanced GPS technology. GPS surveying typically employs some form of relative and differential positioning [36]. In this study, a relative positioning GPS unit, TOPCON HiPer V, as shown in Fig. 1, is used to capture the exact latitude, longitude, and altitude of benchmarks and some temporary benchmarks. This technique utilizes two GPS receivers that track the identical satellites to obtain relative coordinates. Dilution of Precision is a crucial concept in geomatics engineering and satellite navigation, used to quantify error propagation as a mathematical consequence of satellite geometry on positional measurement precision [37].

(a) **(b)**

Fig. 1 *Placement of (a) TBM 1; (b) TBM 2*

Fig. 2 shows an open traverse survey using a total station conducted in this study. This survey was used to obtain relevant data for the study, which allows the measurement of vertical and horizontal angles, distance, elevation, bearing, and to retrieve any other necessary survey data. Six stations were set up around the Student Center, City Campus UTHM, of which two were assigned as temporary benchmarks (TBM). TBM 1 and TBM 2 are located at City Campus and are referenced to a primary benchmark (BM) at the Parit Raja Post Office. Besides that, there are two (2) known bearing coordinates at two (2) stations that have been used in a previous open traverse survey.

Fig. 2 *TOPCON total station*

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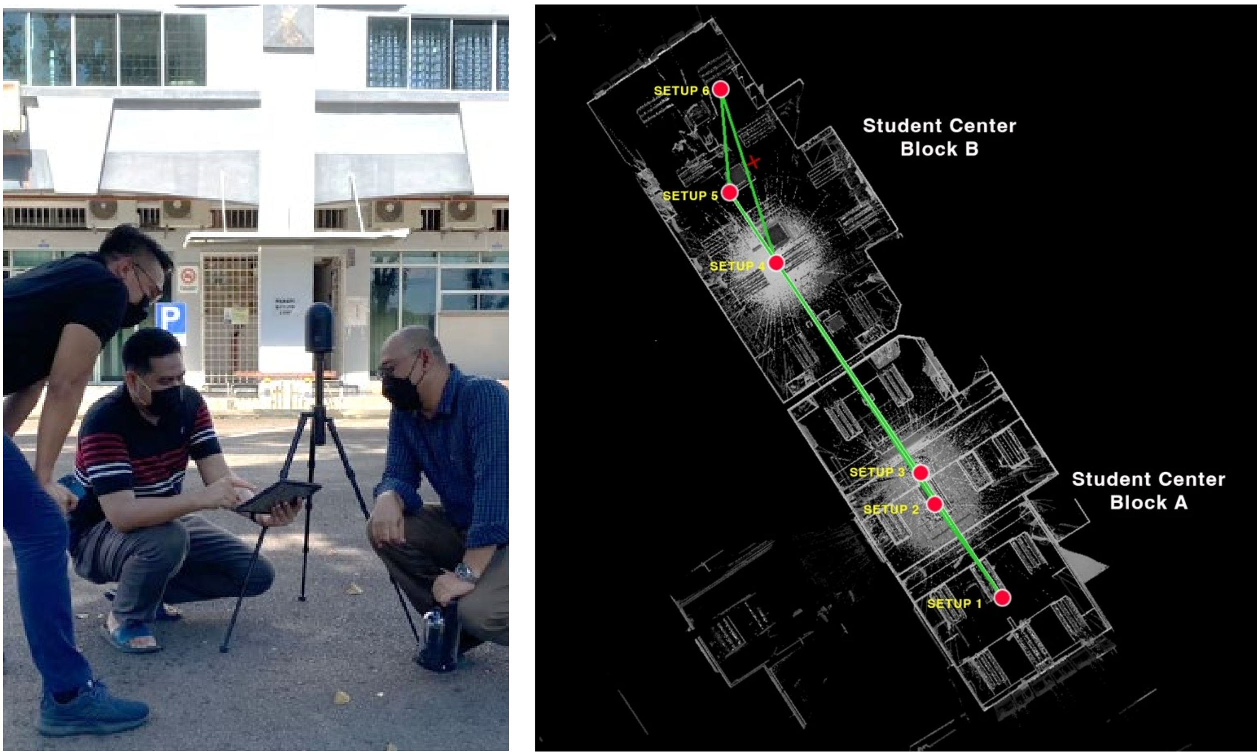
3.2 Laser Scanning

The laser scanning survey was conducted using a Leica BLK360 laser scanner (Fig. 3(a)) to obtain the point clouds [38]. The Leica BLK360 is used for capturing, visualizing, extracting, analyzing, sharing, and representing point cloud datasets [39]. Before collecting data, planning the setup for the stations is critical, ensuring that all setups are interlinked, which improves the accuracy of data registration [40]. In this study, six scanning setups were executed, with three setups in Block A Student Centre and three additional setups in Block B Student Centre, as shown in Fig. 3(b). The scanning procedure was conducted with the aid of Cyclone Field 360, where the point cloud output of the scanning will be evaluated to determine whether it covers the area sufficiently or not.

After the scanning process, the point cloud is exported into LEICA Cyclone REGISTER 360, where individual setup points are visualized and used to create/ recreate the links between setups (setup 1 to setup 6), known as registration and alignment [41]. The registered point clouds were then exported and processed in Autodesk ReCap to create point clouds and meshes required for 3D modeling and Building Information Modeling (BIM) authoring tools [42]. Before point cloud datasets are integrated into BIM environments, Autodesk ReCap enables the management, organization, and cleaning of large point cloud datasets [43].

Finally, the selected software for the Student Center BIM modelling is Autodesk Revit. This involves the use of post-processed data from Autodesk ReCap format (RCP) and is accomplished by techniques such as 'data slicing' to create relationships among elements [44], in building a comprehensive digital modelling of the Student Center as shown in Fig. 4.



(a) **(b)**

Fig. 3 *(a) Point Cloud data collection by using the LEICA BLK360 laser scanner at the Student Center, City Campus UTHM; (b) The six setups' location in the Student Center, City Campus UTHM*

Fig. 4 *The stitched dense point clouds portray the interior area of the Student Center, City Campus, UTHM*

4. Findings

The final outcome, presented as a high-quality georeferenced 3D model, signifies a precise and comprehensive digital representation of the building structure. In the context of this study, Georeferencing is a critical step that transforms the raw point cloud data, initially in a local scanner coordinate system, into a precise global coordinate system.

4.1 Control Points Establishment

The Post Office of Parit Raja was the nearest benchmark (BM) used for the first reference for coordinating and elevating further measurements. Thereafter, two temporary benchmarks (TBM) were set within City Campus UTHM using GPS surveying tools. The accuracy of these points will highly depend on the GPS method used for surveying. The first benchmark data were obtained from the Department of Survey and Mapping Malaysia (JUPEM) and were processed using the Magnet Tool to get the positional data for TBM 1 and TBM 2. This illustrates a crucial step in the processing process, where the quality of the data and the processing technique are essential for achieving high-accuracy results. Table 1 presents the processed benchmarks and temporary benchmarks data, explaining the methods used to establish the ground control points. The evaluation of the benchmark's positional data is shown in Fig. 5, through the Dilution of Precision (DOP). Fig. 6 shows the number of GPS satellites connected to the benchmark (BM) during each observation period. Satellite availability is consistent within the range of about 11 to 15 satellites. Small increases and decreases are typical with changes in satellite positioning and signal visibility related to the BM. A consistent number of satellites indicates that the benchmark provides dependable GNSS coverage, supporting precise and consistent positioning for surveying and georeferencing.

Table 1 *BM and TBM information*

Name	Grid Easting (m)	Grid Northing (m)	Elevation (m)
BM	-50166.741	-19654.511	2.588
TBM 1	-49540.469	-19767.846	3.749
TBM 2	-49567.048	-19733.627	3.323

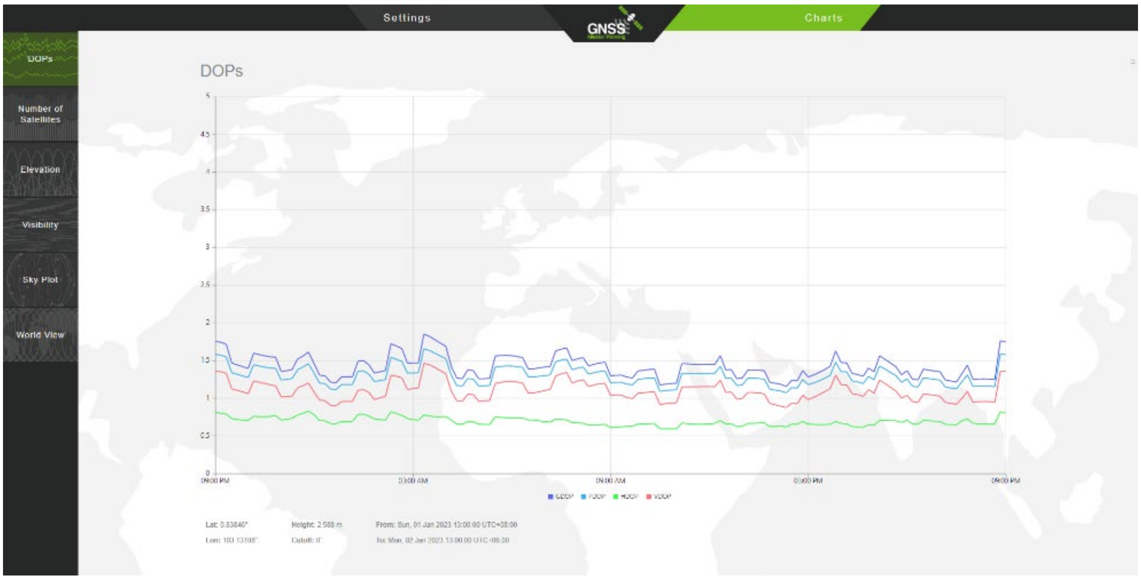


Fig. 5 *Dilution of precision (DOP) of BM*

Fig. 6 shows the number of GPS satellites connected to the benchmark (BM) during each observation period. Satellite availability is consistent within the range of about 11 to 15 satellites. Small increases and decreases are typical with changes in satellite positioning and signal visibility related to the BM. A consistent number of satellites indicates that the benchmark provides dependable GNSS coverage, supporting precise and consistent positioning for surveying and georeferencing. Fig. 7 shows the position and spatial distribution of GPS satellites as seen from the benchmark (BM) are indicated in the sky plot. Most of the satellites are positioned above the elevation cutoff, showing that there are little to no obstructions around the benchmark. The satellites are well distributed across the sky. This symmetry in satellite visibility is likely to allow the BM to receive satellite signals with greater precision and improve the BM's position.

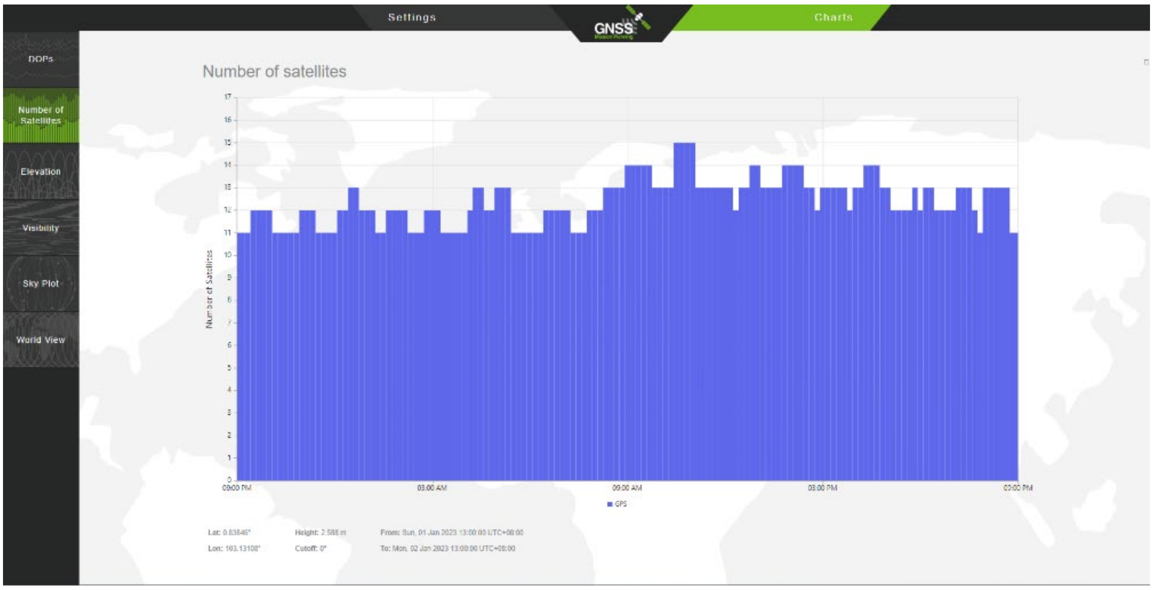


Fig. 6 *Number of satellites linked to BM*

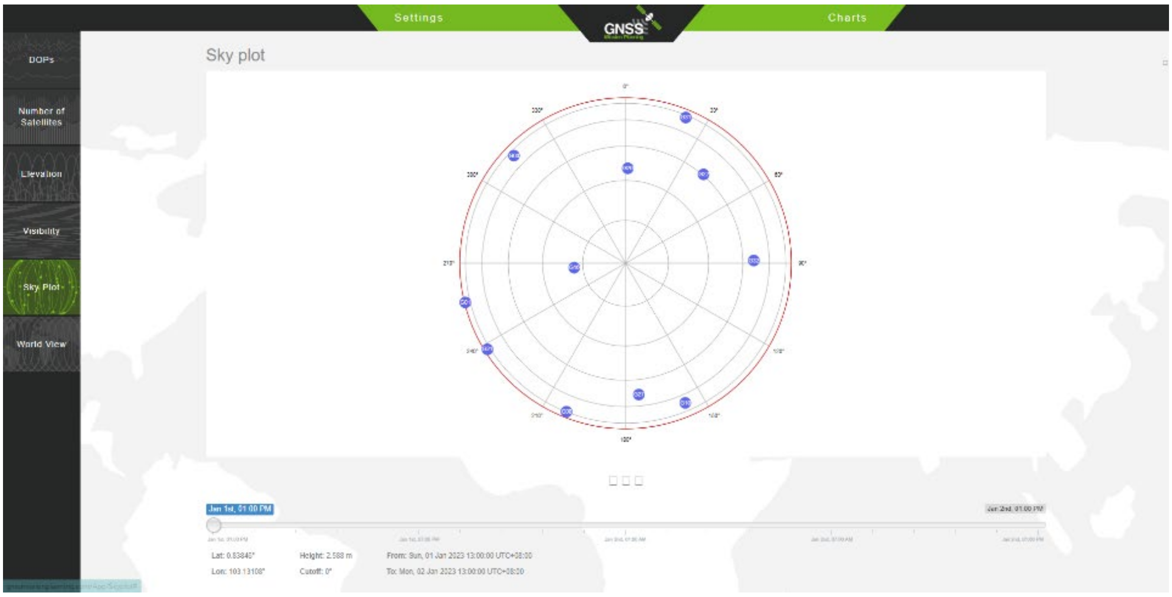


Fig. 7 *Sky plot of BM*

This study used six control points, including Ground Control Points (GCP) and Independent Control Points (ICP). An open traverse survey was used for data collection for these control points. An open traverse was chosen because of the confined nature of the study area. Six stations were set up in the study area to record their coordinates and elevations, as shown in Fig. 8. TBM 1 is station 1 and TBM 2 is station 2, providing two known points in this open traverse. The data for the traverse surveying was manually filed in the open traverse booking. The traverse data sets analysis was carried out to obtain the coordinates and elevations for each station. Table 2 presents the coordinates of the control points, along with other relevant details.

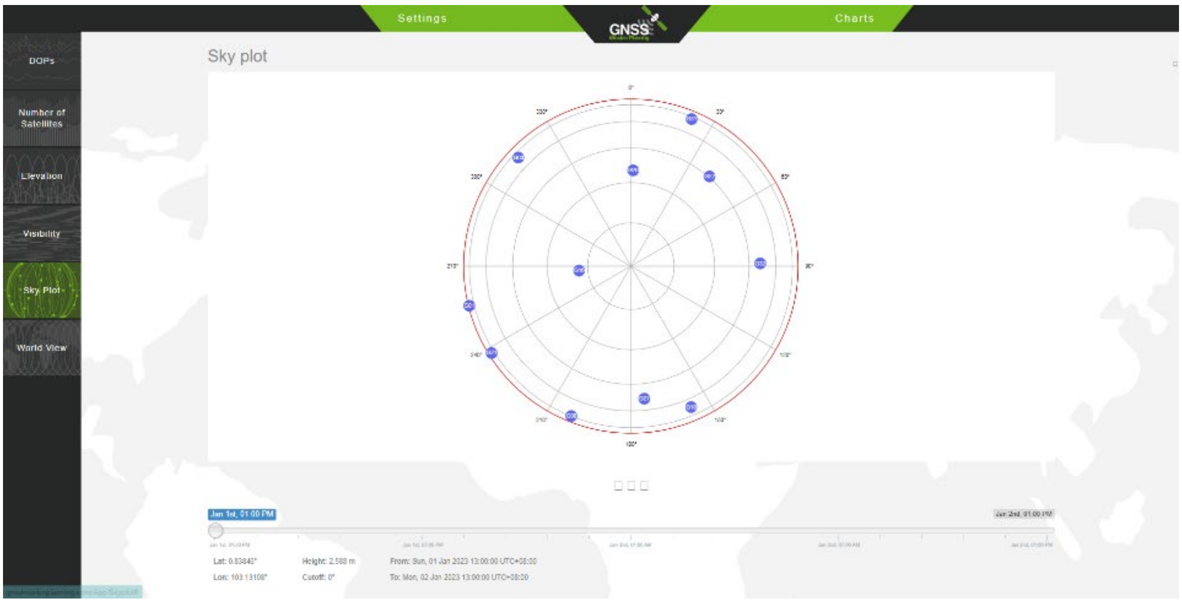


Fig. 8 *Location of the open traverse station*

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Table 2 *Control points information*

Pt ID	Line	Distance (m)	Bearing in decimal	Departure	Latitude	Coordinates		Elevation (m)
						Easting	Northing	
1						-49540.469	-19767.846	3.749
2	1 to 2	42.398	37.83764	26.0080358	33.48391	-49514.46096	-19734.36209	3.323
3	2 to 3	22.41	324.0743	-13.1487457	18.14714	-49527.60971	-19716.21495	3.741
4	3 to 4	12.643	322.6306	-7.67368755	10.04788	-49535.2834	-19706.16707	3.788
5	4 to 5	8.837	324.4251	-5.14107244	7.187624	-49540.42447	-19698.97944	3.595
6	5 to 6	7.689	239.0051	-6.59111184	-3.95954	-49547.01558	-19702.93898	3.581

The survey provided data on coordinates and elevation. These coordinates need to be converted from Geocentric Cassini-Soldner to Geocentric Datum Malaysia 2000. This conversion is necessary to establish a more robust coordinate system infrastructure that is compatible with GPS in navigational systems. More precisely, a geodetic point coordinate (obtained by GPS using WGS84) can be converted to a geocentric RSO plane coordinate using GDM2000 [45].

4.2 Terrestrial Laser Scanning (TLS) Survey

Prior to starting the Terrestrial Laser Scanning activities, six different positions were marked and are shown in Fig. 9. Among these positions, stations 3 and 4 are designated as control points. Given that they are critical control points, the alignment of each scanner position is set in such a way as to capture all required point cloud data as completely and accurately as possible. Once point cloud data is captured, data from the scanner is processed using LEICA Cyclone REGISTER 360. Since the captured data of individual point clouds may be set in different coordinate systems, cloud registration is required. Cloud registration is a process that repositions and aligns one point cloud to a new coordinate system so that the data is as close as possible in relation to one another and is even more within the overall point cloud data set. In addition, the point clouds obtained from the six different locations were merged into a single dataset in a process referred to as “stitching”. In Fig. 9, the values from bundle setups A to F, which have a total overlap of 54%, are presented. There were also no other non-overlap related issues. In Fig. 10, there is more evidence of how the connection and overlap of two different setups is utilized to enhance their connection. Lastly, from the optimized connections, Table 3 gives the similarity index of overlapping point clouds from different setups.

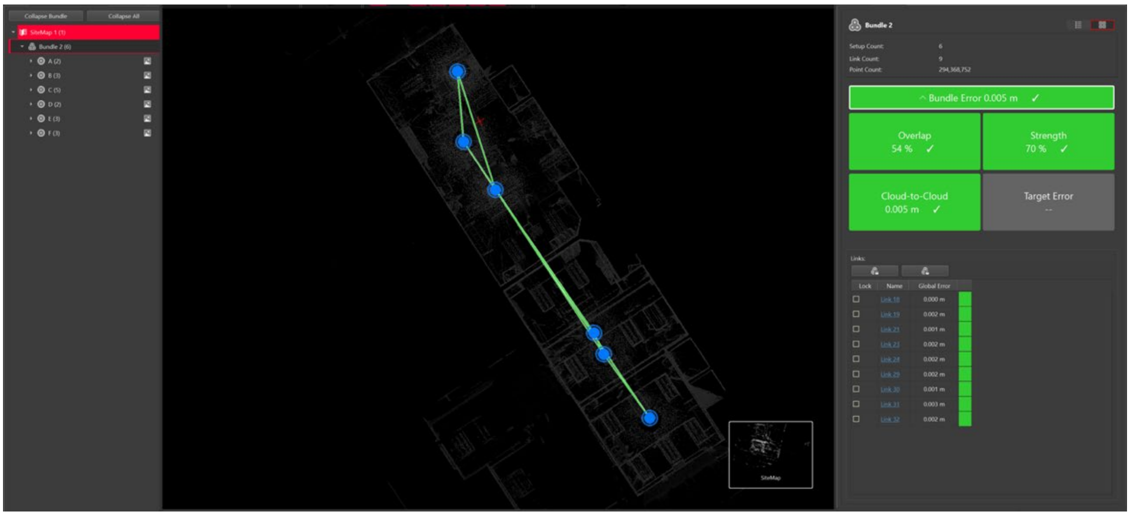


Fig. 9 *The TLS setup configurations, spanning from setup 1 (A) to setup 6 (F), demonstrate an overall overlapping percentage of 54% within bundle links, along with an overall strength of 70%, with no errors detected*

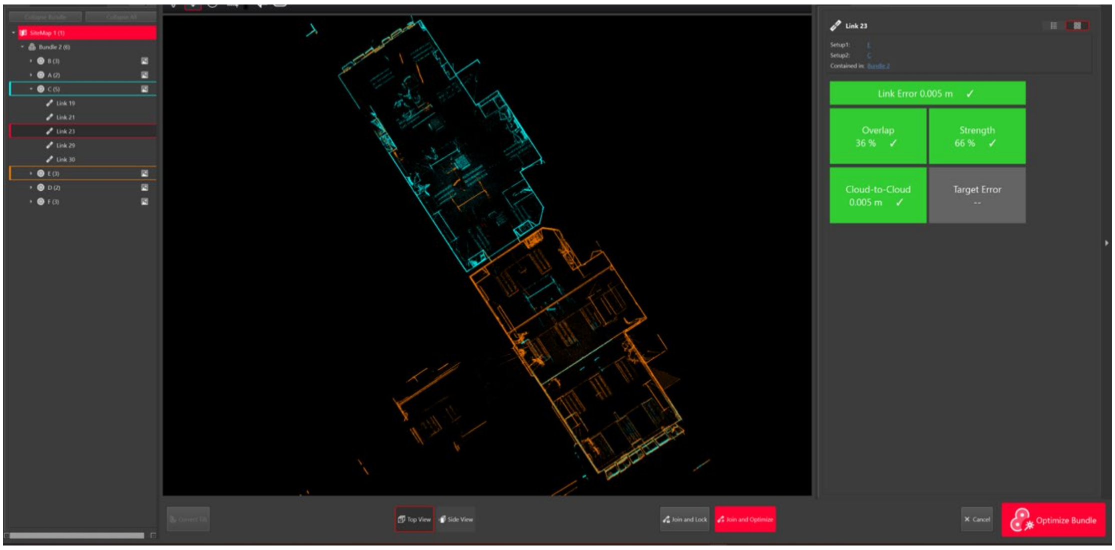


Fig. 10 *The optimization of the link between setup 1 (E) and setup 2 (C) resulted in an overlapping percentage of 36%. The optimized link is denoted as having 66% strength, with no errors detected*

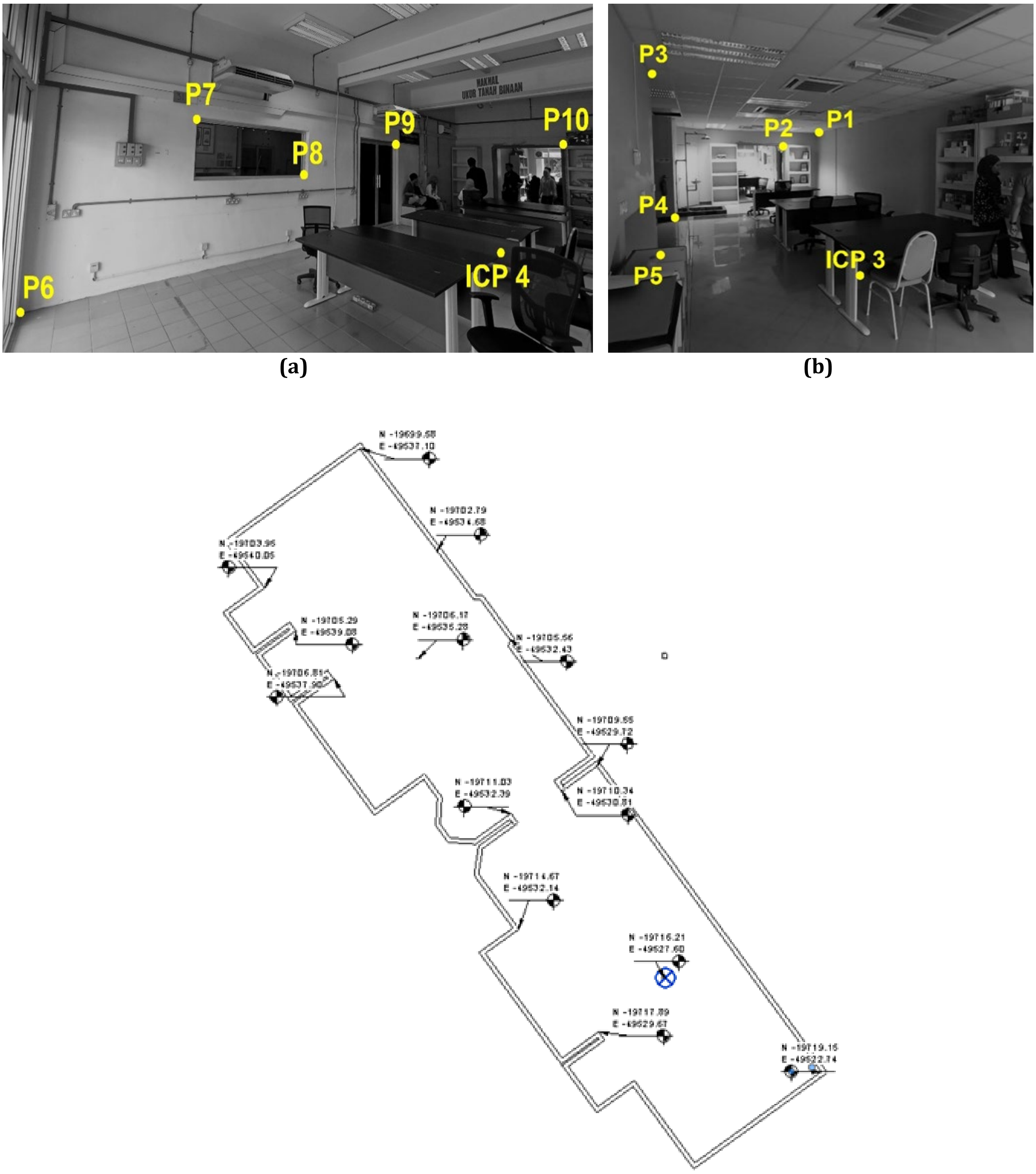
Table 3 *Similarity index of point clouds*

Link no.	Setup 1	Setup 2	Overlap (>30%)
1	B	A	66%
2	B	C	76%
3	A	C	64%
4	E	C	36%
5	D	E	80%
6	D	C	38%
7	F	C	28%
8	F	B	21%
9	E	F	77%

Terrestrial Laser Scanning created real point cloud data, which is then processed in the Autodesk ReCap software. These point clouds are stored with automatic accessibility, flexible import configurations, and filtering of unnecessary data. The high-density recorded Point clouds of the study area are utilized for generating georeferenced 3D Building Information Modeling.

4.3 Building Information Modelling

The developed 3D models allow for the further analysis of study area. The modeling incorporated two control points, specifically station 3 and station 4, which served as base points. Subsequently, georeferenced points can be identified within the Autodesk Revit software by interacting with the points it contains, a process fundamental to integrating BIM with geospatial data. Fig. 11 illustrates the georeferencing of these points, and Table 4 provides their corresponding coordinates and elevations.



(c)

Fig. 11 *(a), (b), (c) The establishment of Georeferenced Modelling (P1-P10) of Student Center, City Campus UTHM, providing a spatial reference framework for accurate indoor mapping and georeferencing*

Table 4 *Coordinates and elevations of the points*

Point	Easting	Northing	Elevation (m)
P1	-49529.7204	-19709.5518	6.401
P2	-49530.8104	-19710.3444	5.903
P3	-49529.6680	-19717.8946	6.401
P4	-49532.1387	-19714.6657	3.741
P5	-49529.6680	-19717.8946	3.741
P6	-49537.0977	-19699.5759	3.788
P7	-49536.1491	-19700.8401	6.072
P8	-49534.6846	-19702.7917	5.072
P9	-49532.4309	-19705.5644	5.896
P10	-49532.3908	-19711.0285	5.903`

5. Discussion

The data analysis verified the successful georeferencing of the generated 3D model structure with the integrated software, supporting critical information about the structure, in particular, the data about the coordinate system, which is essential for advanced building analysis, inspection protocols, and evaluation reports of the building. The resultant data, in terms of its reliability and accuracy, will depend on the user's level of experience and how they subjectively interpret the data. On the other hand, the uncalibrated and biased surveying tools, as well as the settings in which the other variables of the survey are performed. Therefore, the accuracy of the survey analysis is of utmost importance in the names of science and to keep the analysis more rigid and outstanding. Building Information Modeling (BIM) involves various Levels of Development (LOD) that are essential for different project requirements and stages [46]. This project had achieved LOD 400 because the unit was known that allowed exact sizes and locations informed. The study established a framework (Fig. 12) for the development of comprehensive Building Information Modeling (BIM) data integrated with geospatial coordinates, based on its application in the development of the Student Center, City Campus UTHM. This objective is pursued through the integration of Terrestrial Laser Scanning (TLS) point cloud data and georeferenced traverse survey data.

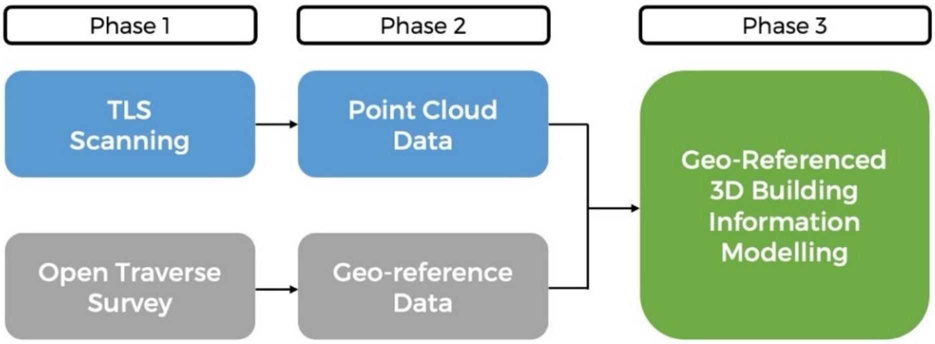


Fig. 12 *Framework for the development of geo-referenced Building Information Modeling (BIM)*

The most important benefit of using laser scanning is the quality of the data it collects. The precision and data quality of the laser scanning are due to the high levels of measuring the location of each point within the complicated 3D structure of the Student Center, City Campus UTHM, in the context of this study. For engineering purposes, the developed framework (Fig. 12) is crucial in generating output data that includes ties to essential 3D spatial reference data, which can be used within Integrated Building Models, Geographic Information Systems, and other design or survey data. The data can also be used for engineering assessments like monitoring deformation, volume calculations, clash detection, and as-built verifications in the designated geographic 3D space, which improves the overall construction management and quality assurance on the construction projects. The biggest challenge of doing laser scanning surveys in the student center has been the construction blocking elements (tables, chairs, and people), which can impede data collection and completely damage sampling.

Additionally, although TLS can scan an impressive 360° horizontally and 300° vertically, a significant drawback is that it can't capture any point cloud data directly under the setup positions. This operational limitation requires more scanning positions from other vantage points to achieve more complete data collection, indicating that the more detailed the data is, the more spatial and operational planning TLS requires to fill in the data gaps in more complex structures.

6. Conclusions

Overall, this study demonstrates that the integration of TLS and georeferenced survey data is proven to produce reliable as-built Building Information Model (BIM) frameworks. In dense point clouds with global coordinate systems, the spatial precision, interoperability, and engineering analysis and facility management usability of the data set are further improved. The developed georeferenced Model, classified as Level of Development (LOD) 400, demonstrates the framework's ability to produce precise geometries in correlation with the real world geodetic context. Operational constraints such as occlusions and blind spots have been documented. These are almost entirely avoidable with proper scan planning, further proving the framework's usefulness in extensive building documentation.

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Conflict of Interest

There is no conflict of interests regarding of the publication of this paper.

Author Contribution

The authors confirm contribution to the paper as follows: ***study conception and design:*** *Umar Radzuan, Hendy Fitrian Suhandri, Azmal Sabil;* ***data collection:*** *Umar Radzuan, Azmal Sabil, Muhamad Adli Faezal Bin Rosnan;* ***analysis and interpretation of results:*** *Umar Radzuan, Hendy Fitrian Suhandri, Azmal Sabil, Sarah Abdul Kareem Salih ;* ***draft manuscript preparation, review and editing:*** *Umar Radzuan, Hendy Fitrian Suhandri, Azmal Sabil, Muhamad Adli Faezal Bin Rosnan, Sarah Abdul Kareem Salih, Muhammad Ismail Hassan, Pandu Pradekso*

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