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Terrestrial Laser Scanning and UAV Laser Scanning: Comparing Point Cloud Accuracy for Digital Elevation Model

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Terrestrial Laser Scanning (TLS) and Unmanned Aerial Vehicle (UAV) Laser Scanning (ULS) are both emerging technologies for rapidly capturing detailed 3D data of structures and environments. This study provides a comparative analysis between these two scanning techniques in terms of the accuracy and differences of the resulting 3D point clouds. A case study was conducted where TLS data was collected from ground-level scan positions while ULS data was captured through automated flights around the facility exterior. The point clouds from each platform were evaluated based on point density, geometric accuracy assessments, and ability to capture fine details. The TLS scans produced a highly accurate and detailed point cloud which was used as a benchmark in this study. The UAV scans exhibited less accuracy when compared to static TLS. However, the UAV was better able to capture hard-to-reach areas and provide a more complete model of the study site exterior. This research provides quantitative and qualitative comparisons between these scanning platforms to help determine the best approach based on requirements. The results will help professionals select the optimal scanning technology for generating the Digital Elevation Models (DEMs) depending on the application and accuracy requirements of the targeted DEMs.

Key Words: DEM, Reality Capture, TLS, UAV Laser Scanning, Point Cloud

Introduction

A Digital Elevation Model (DEM) is a representation of the Earth's surface topography or terrain in a digital, three-dimensional form. It provides a set of elevation values at regularly spaced intervals point by point across a landscape (Polidori & Hage, 2020). These models are extensively used in various fields such as geography, geology, construction, civil engineering, and environmental sciences. DEMs play a pivotal role in the Architecture, Engineering, and Construction (AEC) industry by providing precise elevation data that is indispensable throughout the project lifecycle. The AEC industry relies on orthophotos and DEMs as crucial data for designing and implementing projects, as well as for regular monitoring of project progress. Consequently, understanding the accuracy of the data and ensuring it falls within acceptable limits becomes necessary (Martínez-Carricondo et al., 2018). This detailed information is particularly crucial for foundation design, grading, and earthmoving activities. DEMs contribute to the optimization of road and infrastructure layouts, ensuring alignment with the natural terrain. Additionally, they assist in drainage planning, slope stability analysis, and the calculation of cut and fill volumes, aiding in cost estimation and resource utilization. The ability to visualize construction sites in 3D enhances communication among stakeholders, facilitating better decision-making. Moreover, DEMs support compliance with regulatory standards and environmental impact assessments, reinforcing their significance in creating sustainable and well-planned construction projects. The generation of accurate topographical data involves the utilization of Light Detection and Ranging (LiDAR) technologies and unmanned aerial vehicles (UAVs), facilitating the generation of 3D point clouds that depict ground features. Point clouds have vast application areas, including the generation of DEMs (Yilmaz et al., 2018). Terrestrial Laser Scanning (TLS) and UAV Laser Scanning (ULS) techniques are both capable of generating detailed point clouds, but both approaches have some advantages and limitations. TLS provides great accuracy; however, its stationary nature requires manual intervention when scanning extensive areas, resulting in a labor-intensive and time-consuming process. In contrast, UAVs offer the capacity to survey large regions with increased efficiency and lower reliance on manual labor. The focus of this research is directed toward ULS to assess the extent of technological advancements in mitigating these limitations, enhancing the efficiency of data acquisition, and accessing its accuracy as compared to TLS. Figure 1 portrays how this research plans to conduct the comparative analysis.

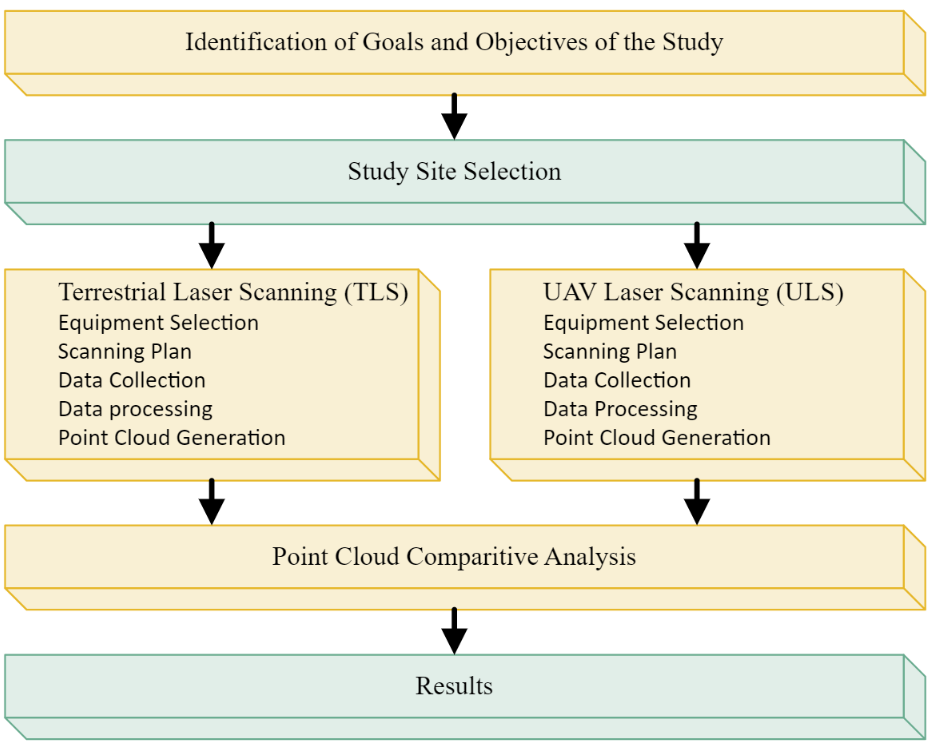

Figure 1. Planned Workflow

Literature Review

The construction industry has undergone significant advancements globally through digital transformation, leading to the implementation of innovative methods and strategies for massive infrastructure projects. Technology has been leveraged to address challenges such as labor shortages, prolonged durations, inefficient practices, poor quality, and cost overruns. Reality Capture (RC), utilizing laser scanners and photogrammetry, has emerged as a pivotal technology and its adoption is gaining momentum in the AEC industry (Alathamneh et al., 2023). It swiftly produces point clouds, enhancing efficiency, accuracy, value, and safety. RC enables the creation of detailed 3D models encompassing building geometry, construction typology, and material quantities. This digital data replication of the physical world offers a substantial advantage over traditional acquisition methods, allowing seamless planning, progress monitoring, and quality control. As a driving force behind Construction 4.0, RC plays a crucial role in the industry's embrace of the digital revolution by facilitating efficient data acquisition and analysis in the AEC domains (Fobiri et al., 2022).

Terrestrial Laser Scanning (TLS)

Terrestrial Laser Scanning (TLS) emerges as an efficient and reliable methodology for the acquisition of point clouds, which have multiple implications across the AEC domain (Maalek et al., 2018). The utility of point clouds extends to various applications within this sector. However, the effectiveness of their application is contingent upon the assurance that acquired point clouds meet specified data quality standards and adhere to predetermined time constraints. The main objective is to ascertain that all scanning targets are captured with the precision and accuracy required for the intended application. The efficiency of data collection has a pivotal role, not only in enhancing the overall quality of acquired data but also in mitigating disruptions to job site activities, underscoring the need for quick and seamless data acquisition processes (Aryan et al., 2021). TLS can be categorized into two primary types: static TLS and mobile laser scanning (MLS). In static TLS, a laser scanner mounted on a tripod is strategically placed in a fixed location, scanning the surrounding environment from various positions to obtain highly detailed data (Almukhtar et al., 2021). This method is prevalent in the AEC domain, where precise measurements of building and site conditions are crucial. On the other hand, MLS involves a laser scanner mounted on a mobile platform, such as a vehicle, UAV, backpack, or hand-held device. The MLS scanner captures 3D data of the environment while the platform is in motion, facilitating rapid and efficient data acquisition. MLS finds applications in surveying, mapping, and infrastructure management due to its ability to swiftly capture data in diverse settings (Liu et al., 2023).

UAV Laser Scanning (ULS)

The ULS technology facilitates data collection across a very large piece of land, with minimal ground access to the site. The capturing of ULS data requires the utilization of sophisticated equipment and the establishment of robust ground control networks for precise control and calibration. These requirements often contribute to elevated costs, rendering ULS data capturing financially impractical for smaller project sites. While ULS data present outstanding visualization of large-scale terrain features, they present challenges when dealing with a large dataset as it demands substantial computational resources for effective processing (Lato et al., 2014). The study will use a reference to a data quality framework established by the General Services Administration (GSA) to describe the required Level of Accuracy (LOA) and Level of Detail (LOD) for laser-scanned point clouds. The following “Table 1”, acquired from (U.S. GSA, 2009), provides a concise overview of this standardization. Typically, higher LOA/LOD standards are applied to indoor environments characterized by smaller dimensions, such as indoor layouts and HVAC systems. Conversely, lower LOA/LOD standards are deemed appropriate for outdoor settings featuring larger dimensions, such as building facades and outdoor structural components (Tang & Alaswad, 2012). This research will only consider the LOA for the comparison of point clouds between ULS and TLS.

Table 1

LOA & LOD standards for capturing point clouds established by GSA, US.

GSA Level	Description	LOA (Tolerance) mm (in)	LOD (Data Density) mm x mm (in x in)
1	Point Cloud	± 51 (± 2)	152 x 152 (6 x 6)
2	Plan	± 13 (± 1/2)	25 x 25 (1 x 1)
	Elevation	± 13 (± 1/2)	25 x 25 (1 x 1)
	Surface Model	± 13 (± 1/2)	25 x 25 (1 x 1)
	Point Cloud	± 13 (± 1/2)	25 x 25 (1 x 1)
3	Plan	± 6 (± 1/4)	13 x 13 (1/2 x 1/2)
	Elevation	± 6 (± 1/4)	13 x 13 (1/2 x 1/2)
	Point Cloud	± 6 (± 1/4)	13 x 13 (1/2 x 1/2)
4	Surface Model	± 3 (± 1/8)	13 x 13 (1/2 x 1/2)
	Point Cloud	± 3 (± 1/8)	13 x 13 (1/2 x 1/2)

Methodology

This study employs a straightforward methodology to conduct a comparative analysis between TLS and ULS, specifically focusing on the accuracy of DEM that is to be obtained from both techniques. Both terrestrial and aerial data acquisition methods were implemented on-site, utilizing TLS and ULS equipment. Data processing involved pre-processing to eliminate noise, generating point clouds, and applying consistent parameters for fair comparison. The computational efficiency and adaptability of TLS and ULS in various scenarios are evaluated. This comprehensive approach aims to provide meaningful insights into the strengths and limitations of each method, facilitating informed decisions in selecting the most suitable technology for specific applications based on the accuracy requirements.

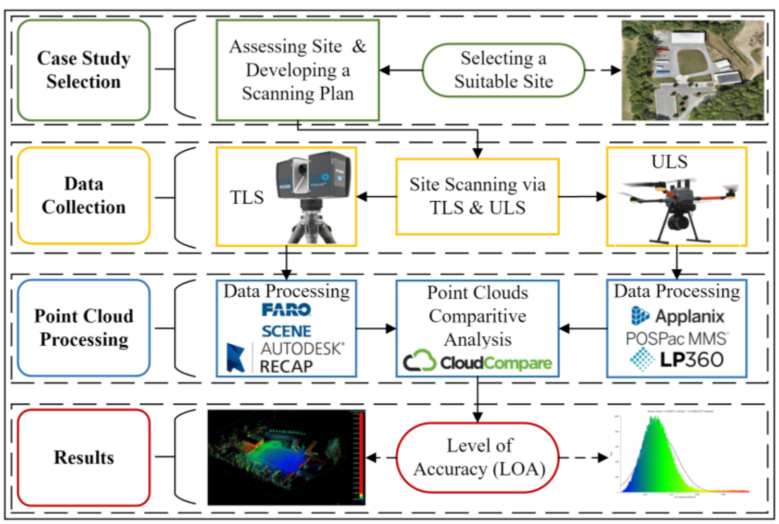

Figure 2. Methodology

Case Study and RC Instruments

Based on safety and availability, a non-active construction site was carefully selected as a suitable case study. The chosen site encompasses a substantial area, measuring approximately 10,600m^2 (114,100sf). There are a variety of building structures, including a trailer, containers, and workshop hangar of varying sizes and heights. These structures add complexity and diversity to the case study, providing an excellent opportunity to assess point cloud accuracy in a real-world environment with diverse architectural elements. For the research, the data acquired through “FARO Focus S350” was used as TLS, and “EasyOneLiDARUHR” was used as a ULS.

Figure 3. Left: Study Site – Middle: FARO Focus S350 – Right: EasyOneLiDARUHS

On-Site RC Data Acquisition

The static TLS data was collected on the 30th of August 2023. FARO Focus S350 was used as a scanner on a 5ft tripod. The study site was scanned with 4 scan station setups that were planned to be most suitable for this research. Table 2 enlists all the scanning specifications that were used in detail.

Table 2

Summary of TLS Parameters & Values.

Scanning Parameters	Values
Height	1.524 m (5’)
Quality	3x
Scan Size	8192 x 3413 Pt
Scan duration	< 05:21 min:sec
Point Distance	7.0104 mm (1/4”) / 9.144 m (30’)
Color	On
Point Counts	28.0M
Number of Scans	4
Total Scan Duration (Including equipment setup time)	~ 28:00 min:sec

Note: <, less than; ~ approximately; M, million; mm, millimeters; m, meters; min:sec, minutes seconds.

The data collection with ULS was conducted on the 23rd of August 2023. An EasyOneLiDARUHR was used as a ULS to scan the study site. The data was captured at a height of 80m (260 ft). All the obtained data was stored on an online repository for safe storage. A summary of the data collection by both techniques is described in the following Table 3.

Table 3

Summary of Data Collection.

Date	RC Technology	Platform Base	Sensor	Height a.g.l.* m (ft)	Scan Locations	Scan Duration min:sec
08-30-2023	TLS	Terrestrial	Focus S350	1.524 (5)	4	28:00
08-23-2023	ULS	UAV	Pandar XT	80 (260)	n/a	14:35

Note: n/a, not applicable; min:sec, minutes seconds. *Above ground level

RC Data Processing

The data obtained from FARO Focus S350 was processed through the software "FARO Scene". The output was in the form of a Point Cloud in e57 format. Similarly, the data acquired from the EasyOneLiDARUHR was processed using the LP360 software. The resulting Point Cloud was then converted into e57 format so there is no discrepancy in file format between the two captured data sets. The following Figure 4 displays both point clouds that were obtained. The ULS was able to get the inaccessible details as compared to TLS.

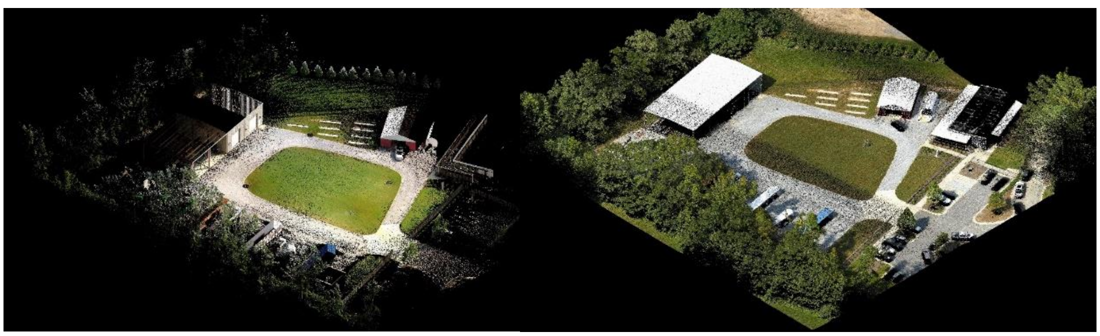

Figure 4. TLS Point Cloud (Left) and ULS Point Cloud (Right)

Comparison of Point Clouds

"CloudCompare" was used as a comparison software for both point clouds. It is an open-source and reliable software (Balla et al., 2020). The analysis was performed by importing both point clouds into the software. After that, the first segmentation was performed just to make both points clouds clear and relevant to each other as a summary provided in Table 4. To align the point clouds together the software requires a minimum of 4 tie points from both point clouds. But to be precise this research used 5 tie points so that the alignment and scaling are up to the mark.

Table 4

Summary of Point Clouds.

Point Cloud	TLS	ULS
Points after first Segmentation	60M	45M
Points after Random Subsampling "C2C"	10M	10M
Subsampling Ratio	83.3%	77.8%
Points to be Compared "C2C"	10M	10M

Note: n/a, not applicable; M, million; C2C, Point cloud to point cloud.

After performing this step data registration was performed and a second segmentation was completed so that point clouds appeared as a single entity for a comprehensive examination. Then subsampling was performed, as shown in Table 4, as the number of points in the point cloud obtained from FARO Focus S350 was near 60 million. As a result of segmentation, the total number of points was close to 10 million which was almost equal to the number of points in the ULS point cloud. After point cloud subsampling, the comparative analysis was run, and results were obtained. The analysis was performed first by keeping the TLS point cloud as the reference point for the ULS point cloud and the second time the analysis was performed vice versa. A summary of the comparative analysis is shown in the following Figure 5.

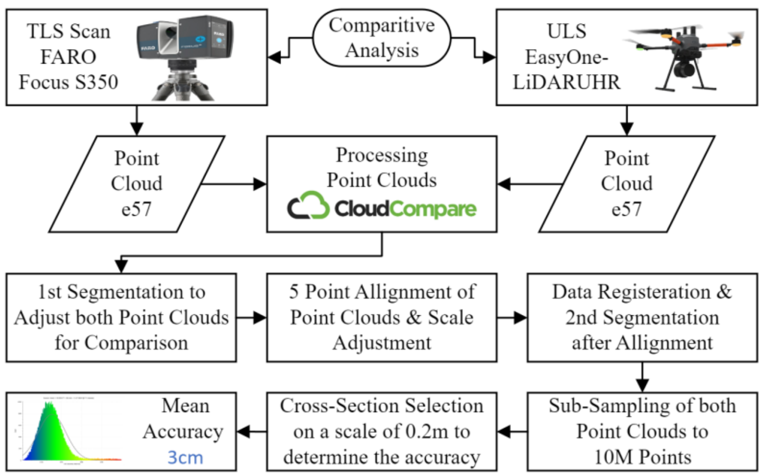

Figure 5. TLS and ULS Point Cloud Comparative Analysis Process

Results and Discussion

The comparative analysis between TLS and ULS for point cloud accuracy yielded insightful findings. TLS consistently demonstrated superior accuracy and higher point cloud density compared to ULS. After conducting this research, it can be stated that the ULS is at a point where it can be used in projects or places where LOA Level 1 is required as stated by the US GSA. Hence, the DEMs can be easily generated using this technology with great accuracy which was one of the main considerations of this research to be able to reflect on whether accurate DEMs can be generated with ULS. TLS using the FARO Focus S350 scanner produced very dense point clouds with a point cloud of 60M points over 10,600m^2 (114,100sf) in an outdoor environment. The UAV-based laser scanning generated a less dense point cloud with almost 45M points which was dependent on flight height. When comparing specific planar surfaces on the building facade, the TLS data showed that it had no trouble capturing the vertical surface points. However, the ULS was unable to capture the vertical surface points as the LiDAR sensor was pointed 90 degrees downward. Using an angular LiDAR in ULS would significantly improve the chances of capturing vertical surfaces that are otherwise missed. In addition, this method can successfully capture inaccessible points that are not visible from the scan stations of TLS, such as rooftops of nearby buildings and trees which can be seen in Figure 6 in red. The accuracy assessment of the ULS point cloud involved validation against the TLS point cloud as a reference and benchmark, employing statistical measures for quantitative analysis. The TLS recorded the detailed façade of the building with all fine architectural details captured. The ULS provided a good overview of the overall area but resulted in a more simplified model with some loss of detail. Overhanging portions and areas obscured at ground level were better captured by the ULS versus the terrestrial approach.

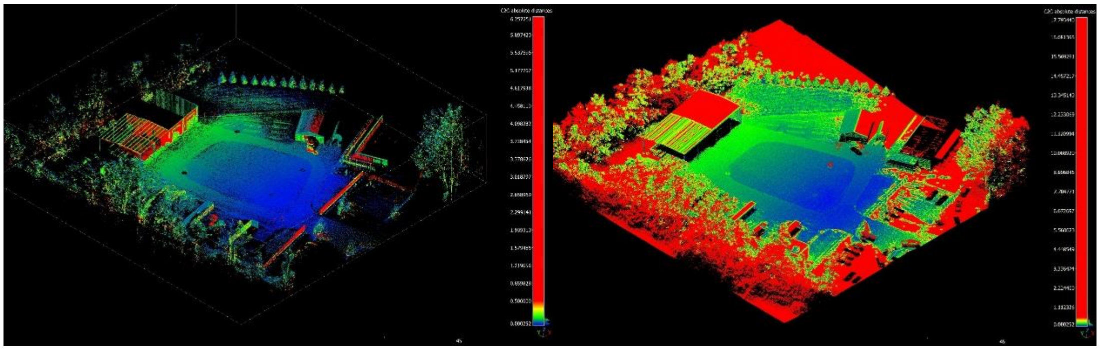

Figure 6. Point Cloud Comparison – TLS Reference (Left) & ULS Reference (Right)

The accuracy analysis based on checkpoint coordinates showed an average deviation of 1-5 cm (0.394-1.968 inches) for the ULS point cloud with a mean value of 0.030571m (almost 3cm, or 1 3/16 inches) as shown in Figure 7. In summary, the TLS data showed higher accuracy and detail as compared to the ULS. However, the ULS provided better access to difficult-to-reach areas and a more complete exterior model.

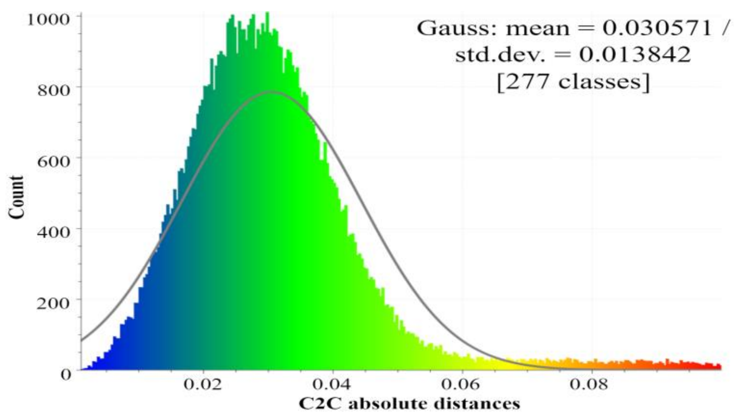

Figure 7. CloudCompare – Result. C2C, point cloud to point cloud, distance in meters.

Conclusion

In conclusion, the findings of this study unveil a comparative analysis between TLS and ULS, specifically investigating the point cloud accuracy. The noticeable outcome is that TLS exhibits a consistent superiority in both accuracy and point cloud density over ULS. Impressively, the average deviation in point clouds derived from ULS registers at a notably diminished scale, mostly ranging between 1-5cm (0.394-1.968 inches), considering TLS as a benchmark. The increased accuracy of TLS comes from the firm stability of its scanning setup, standing in stark contrast to the challenges posed by the dynamic movement and vibrations inherent to UAV platforms. However, the UAV-centric approach unveils its unique strengths by not only facilitating the scanning of otherwise challenging and inaccessible areas but also presenting a more holistic and comprehensive model of the structure's exterior. While static TLS undoubtedly champions the realm of providing exactly precise point clouds, the UAV-centric approach steps into the spotlight with its added advantages, offering unparalleled flexibility, expedited data capture, and an expansive overview of the structure under consideration. The strategic selection between these modern techniques ultimately hinges on the application and specific project requirements. In instances where accuracy is to be preferred and time is not a consideration, TLS is the way to go. Conversely, where accuracy can be tolerated to a certain limit, time is the main consideration, the UAV-based approach emerges as an advantageous alternative as it can cover large areas in less time. The suitability of each approach depends on the specific project requirements and desired level of accuracy. Moving forward, future research should strategically expand the limits of testing these scanning methodologies across more extensive and diverse structures. Additionally, there is a pressing need for concerted research efforts directed towards refining UAV laser scanning accuracy, exploring possibilities such as better platform stability and the integration of a better navigation system. This trajectory of ongoing technological enhancements holds the promise of ultimately establishing ULS as a formidable and competitive alternative to TLS, particularly in the realm of achieving unparalleled accuracy in point cloud generation.

References

Alathamneh, S., Liu, J., Azhar, S., & Burt, R. (2023). Reality Capture (RC) Technology for Drywall Installation: A Scan-to-Prefab Approach. *XVI International Conference on Durability of Building Materials and Components DBMC 2023, China*.

Almukhtar, A., Saeed, Z. O., Abanda, H., & Tah, J. H. M. (2021). Reality Capture of Buildings Using 3D Laser Scanners. *CivilEng 2021, Vol. 2, Pages 214-235*, *2*(1), 214–235. https://doi.org/10.3390/CIVILENG2010012

Aryan, A., Bosché, F., & Tang, P. (2021). Planning for terrestrial laser scanning in construction: A review. *Automation in Construction*, *125*, 103551. https://doi.org/10.1016/J.AUTCON.2021.103551

Balla, E., Madureira, M., & Georgiadou, Y. (2020). WEB Open Drone Map (WebODM) a Software Open Source to Photogrammetry Process. *Smart Surveyors for Land and Water Management, 10-14 May 2020, Amsterdam, The Netherlands*, 1–17. https://iris.unica.it/handle/11584/300743

Fobiri, G., Musonda, I., & Muleya, F. (2022). Reality Capture in Construction Project Management: A Review of Opportunities and Challenges. *Buildings 2022, Vol. 12, Page 1381*, *12*(9), 1381. https://doi.org/10.3390/BUILDINGS12091381

Lato, M. J., Jean Hutchinson, D., Gauthier, D., Edwards, T., & Ondercin, M. (2014). Comparison of airborne laser scanning, terrestrial laser scanning, and terrestrial photogrammetry for mapping differential slope change in mountainous terrain. *Https://Doi.Org/10.1139/Cgj-2014-0051*, *52*(2), 129–140. https://doi.org/10.1139/CGJ-2014-0051

Liu, J., Azhar, S., Willkens, D., & Li, B. (2023). Static Terrestrial Laser Scanning (TLS) for Heritage Building Information Modeling (HBIM): A Systematic Review. *Virtual Worlds 2023, Vol. 2, Pages 90-114*, *2*(2), 90–114. https://doi.org/10.3390/VIRTUALWORLDS2020006

Maalek, R., Lichti, D. D., & Ruwanpura, J. Y. (2018). Robust Segmentation of Planar and Linear Features of Terrestrial Laser Scanner Point Clouds Acquired from Construction Sites. *Sensors 2018, Vol. 18, Page 819*, *18*(3), 819. https://doi.org/10.3390/S18030819

Martínez-Carricondo, P., Agüera-Vega, F., Carvajal-Ramírez, F., Mesas-Carrascosa, F.-J., García-Ferrer, A., & Pérez-Porras, F.-J. (2018). *Assessment of UAV-photogrammetric mapping accuracy based on variation of ground control points*. https://doi.org/10.1016/j.jag.2018.05.015

Polidori, L., & Hage, M. El. (2020). Digital Elevation Model Quality Assessment Methods: A Critical Review. *Remote Sensing 2020, Vol. 12, Page 3522*, *12*(21), 3522. https://doi.org/10.3390/RS12213522

Tang, P., & Alaswad, F. S. (2012). Sensor Modeling of Laser Scanners for Automated Scan Planning on Construction Jobsites. *Construction Research Congress 2012: Construction Challenges in a Flat World, Proceedings of the 2012 Construction Research Congress*, 1021–1031. https://doi.org/10.1061/9780784412329.103

U.S. GSA. (2009). *GSA Building Information Modeling Guide Series: 03-GSA BIM Guide for 3D Imaging*. www.gsa.gov/bim

Yilmaz, V., Konakoglu, B., Serifoglu, C., Gungor, O., & Gökalp, E. (2018). Image classification-based ground filtering of point clouds extracted from UAV-based aerial photos. *Geocarto International*, *33*(3), 310–320. https://doi.org/10.1080/10106049.2016.1250825