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Photogrammetry as an Affordable Alternative to Laser Scanning for Small and Mid-Size Construction Firms

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Accurate 3D documentation of built environments is essential for renovation, verification, and coordination tasks in construction. However, terrestrial laser scanning (TLS) remains cost-prohibitive for many small and mid-size construction firms. This study investigates the feasibility of using affordable consumer-grade 360-degree cameras, Insta360 X2 and X4, as alternatives to high-end TLS systems, specifically the FARO Focus S350, for generating point clouds. A comparative analysis was conducted at an active healthcare construction site, where data from all three devices were captured, processed, and exported as E57 files. Point clouds were aligned and analyzed using CloudCompare through cloud-to-cloud (C2C) distance calculations, descriptive statistics, and visual deviation maps. Visual assessments included RGB renderings and framing plan overlays with the original design drawings. Results show that while the FARO scan achieved the highest accuracy and detail, the Insta360 X4 in particular produced point clouds with acceptable levels of deviation, averaging around 6 cm, and preserved key structural elements. The 360-camera workflow also significantly reduced on-site capture time and required no specialized training, making it practical for everyday field use. For general documentation and as-built applications, Insta360 cameras provide a viable low-cost alternative for firms with limited resources. Limitations include the single-site scope and reliance on one photogrammetry platform. Future work should explore broader use cases, additional processing tools, and integration of AI-driven workflows to enhance point cloud usability.

Keywords: Photogrammetry, Laser Scanning, Reality Capture, Construction Technology, Cost-Effective Solutions

Introduction

Reality capture technologies have become essential for various industries, including construction, cultural heritage documentation, and environmental monitoring. These technologies facilitate the creation of accurate and detailed digital representations of real-world environments, supporting applications such as as-built modeling, installation verification, and existing conditions assessments (McHugh et al., 2021; Sebar et al., 2022; Xie et al., 2022). Among the various reality capture methods, photogrammetry has gained widespread attention due to its flexibility and the availability of increasingly affordable hardware. Compared to laser scanning, photogrammetry does not require expensive equipment or intensive training, making it a practical alternative for small and mid-size construction firms seeking to implement as-built documentation and verification workflows without incurring high capital costs.

In recent years, 360-degree cameras have emerged as a particularly promising tool within the photogrammetric domain. Devices like the Samsung Gear 360 enable rapid scene capture in a single shot, significantly reducing both field time and the number of images required for reconstruction (Barazzetti et al., 2017, p. 360, 2018). These consumer-grade devices can achieve millimeter-level image orientation accuracy and deliver reasonably accurate surface reconstructions, making them suitable for applications in interior documentation, long corridor scanning, and confined-space surveys (Fangi et al., 2018; Marcos-González et al., 2023). Although metric accuracy can be a concern, calibration procedures and the use of alternative image projection methods have shown potential to mitigate such limitations (Barazzetti et al., 2017). Furthermore, integrating 360 camera workflows with Global Navigation Satellite System (GNSS) data and GIS platforms enhances the spatial referencing and processing efficiency of photogrammetric outputs (Barazzetti et al., 2022).

Beyond 360-degree cameras, other low-cost alternatives such as DSLR cameras and smartphones have proven effective in generating 3D models through Structure-from-Motion (SfM) techniques. DSLR-based photogrammetry has long been used for artifact modeling and building façade documentation due to its straightforward operation and relatively low cost (Kaufman et al., 2015). Meanwhile, modern smartphones, equipped with high-resolution cameras and LiDAR or depth-sensing capabilities, offer comparable accuracy to professional systems in several domains, including geology and medical modeling (Van & Naprstkova, 2024). However, ensuring the reliability of these models necessitates rigorous validation techniques, including comparisons with laser-scanned references or the use of Coordinate Measuring Machines (CMM) (Vacca, 2019). Calibration remains critical to performance, with standards like ISO 15530-3 providing guidance for verifying measurement accuracy in photogrammetric setups (González-Jorge et al., 2011; Lavecchia et al., 2018). In summary, the convergence of affordable hardware and robust validation standards is democratizing photogrammetry, enabling broader adoption across industries traditionally limited by the high costs of laser scanning technologies.

Despite the growing accessibility of photogrammetric tools, such as 360-degree cameras, DSLRs, and smartphones, their integration into mainstream construction workflows, particularly among small and mid-size general contractors, remains limited. One of the key barriers is the uncertainty regarding the spatial accuracy and reliability of these lower-cost systems compared to industry-standard terrestrial laser scanners. While several studies have demonstrated the general feasibility of these tools in controlled environments or niche applications, there is limited empirical research evaluating their performance in real-world construction settings for specific tasks such as framing alignment, ceiling plan verification, or column positioning. This gap is particularly relevant given the high upfront cost and technical demands associated with TLS adoption. Therefore, the present study seeks to address this need by evaluating the effectiveness of using affordable 360-degree cameras as a viable alternative for reality capture in construction. The goal is to determine whether these tools can offer sufficient accuracy and practical value to support existing condition documentation and installation verification tasks, thereby offering a cost-effective solution for firms traditionally excluded from leveraging high-end scanning technologies.

Methods

This study aims to evaluate the feasibility and effectiveness of using affordable 360-degree cameras as alternative reality capture technologies to terrestrial laser scanners (TLS) for small- to mid-sized construction firms. The goal is to assess whether consumer-grade 360 cameras, such as the Insta360 X2 and Insta360 X4, can generate point clouds suitable for key construction applications, including renovation documentation, as-built verification, clash detection, and slab flatness analysis.

The research design presented in this study (see Figure 1) outlines a comparative workflow to evaluate the viability of affordable photogrammetry-based solutions using consumer-grade 360-degree cameras as alternatives to traditional laser scanning for construction documentation. The testing site is an active healthcare construction project selected for its practical accessibility and representativeness of typical commercial construction environments. A convenience sampling approach was used for the site selection, considering factors such as proximity, permission to access, and suitability for spatial data capture. Data was collected from a single level of the facility, including a total gross area of approximately 775 square meters (8,342 square feet). This floor had completed concrete slab work, structural steel framing that had been inspected and coated with fireproofing, and no framed-out interior partitions at the time of capture, ensuring consistent environmental conditions and a clear geometry for comparing capture technologies.

The Capturing phase involves three different technologies: a FARO Focus S350 TLS representing the industry-standard high-accuracy solution, and two consumer-grade Insta360 cameras (X2 and X4), both used in walkthrough video mode. These walkthrough videos were uploaded to the Cupix Vista cloud platform to process and convert them into point clouds, while FARO scans were processed using FARO SCENE software. All resulting datasets were exported in the E57 format, a standardized point cloud file type that facilitates cross-platform analysis and preserves spatial fidelity across different capturing technologies.

Next, the CloudCompare (v2) software was used for point cloud comparison. The three point clouds were imported and manually aligned using a 4-point alignment method, followed by additional manual correction to enhance spatial congruence. The FARO point cloud served as the reference dataset due to its known precision. The alignment was finalized through the software’s final registration tools, ensuring that each dataset could be fairly compared using a unified coordinate system. This step is crucial in minimizing systematic error and enabling valid Cloud-to-Cloud (C2C) Distance Analysis.

In the final stages, two comparative tests were performed: Test #1 compared FARO with Insta360 X2, while Test #2 compared FARO with Insta360 X4. Initial C2C distance analyses revealed spatial deviations, which were refined using noise reduction and statistical outlier filtering (based on a custom formula identified as Formula 1 in the methodology). The noise and outlier filtering were applied to both INSTA360 datasets. A thresholding method based on the mean (μ) and standard deviation (σ) was used, specifically removing values beyond $\mu + k\sigma$ to eliminate extreme outliers while retaining approximately 95% of the original points. This filtering step aimed to improve the data quality. Formula (1) is used to remove extreme outliers. This cleaning step enhances the signal-to-noise ratio in the datasets, allowing for more accurate statistical comparisons. The refined point clouds were then subjected to Final C2C Distance Analysis, where output visualizations included heatmaps, deviation maps, and descriptive statistics. These results informed the study's conclusions about spatial accuracy, usability, and potential of 360-camera photogrammetry as a practical alternative to expensive TLS systems for small and mid-sized construction firms engaged in renovation, as-built documentation, and field verification.

$$\text{Threshold}=\mu+k\cdot\sigma \qquad (1)$$

Where:

- k is a constant (commonly $k=2$ for ~95% of a normally distributed dataset)
- Points with values greater than this threshold are considered outliers and removed

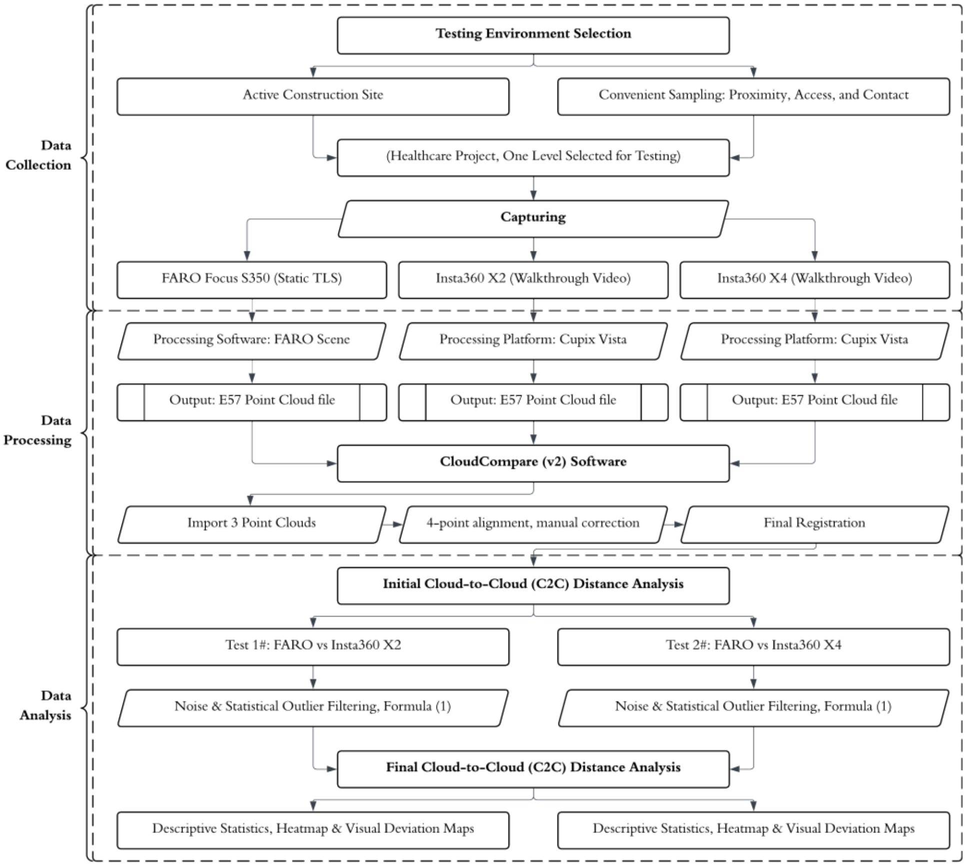


Figure 1. Research Design Map

Results and Discussion

This section presents the findings from the comparative analysis between the TLS (FARO Focus S350) and two consumer-grade 360-degree cameras (Insta360 X2 and X4), processed through photogrammetry. The goal was to assess the spatial accuracy and viability of these affordable alternatives for generating point clouds usable in construction documentation. The results are discussed in terms of C2C distance measurements, statistical distributions, and visual deviation maps.

Point Cloud Acquisition Time and Density Comparison

Table 1 provides a comparative overview of point cloud data acquisition and filtering across the three capture devices used in this study: the FARO Focus S350 terrestrial laser scanner, and the Insta360 X2 and X4 cameras. Each device followed a distinct workflow but ultimately produced E57-format point clouds for interoperability. The FARO scanner required nine static scans processed in FARO SCENE software, while the Insta360 cameras used walkthrough videos converted into point clouds through CupixVista. Notably, the FARO method demanded significantly more on-site time, approximately 45 minutes, compared to only 3 minutes for each Insta360 capture session, highlighting a major efficiency advantage of photogrammetry-based approaches.

Table 1. Comparison of Point Cloud Data Acquisition and Filtering Across Three Capture Devices

Equipment	**FARO Focus S350**	**INSTA360 - X2**	**INSTA360 - X4**
Point Cloud Processing Platform	FARO SCENE	CubixVista	CubixVista
Exported File Format	E57	E57	E57
Number of Scans / Panoramas	9 Scans	20 Panoramas	22 Panoramas
Estimated On-Site Capture Time	45:00 Minutes	3:00 Minutes	3:00 Minutes
Raw Point Count	61,874,074	3,199,977	3,301,993
E57 File Size	888 MB	142 MB	146 MB
Noise and Outlier Filtering Applied	-	Yes	Yes
Mean Absolute Distance (m)	-	0.073292	0.07553
Standard Deviation (m)	-	0.078362	0.082543
Threshold (μ + kσ) for Outlier Removal	-	0.230016	0.240616
Post-Filter Point Count	-	3,087,311.00	3,145,967.00
Remaining Point Ratio (%)	-	96.48%	95.27%

Despite their speed, the photogrammetry-derived point clouds had considerably fewer raw points than the FARO dataset. The FARO scanner generated over 61 million points, compared to approximately 3.2 million for the Insta360 X2 and 3.3 million for the X4. This disparity reflects the inherent difference in resolution and point density between laser scanning and consumer-grade photogrammetry. However, both Insta360 datasets underwent statistical filtering to remove noise and outliers based on a threshold calculated as the mean absolute distance plus a multiple of the standard deviation (μ + kσ). The threshold values were 0.230 m for X2 and 0.241 m for X4, indicating a reasonable degree of consistency in the noise patterns between the two devices.

Accuracy Evaluation through Statistical Filtering

Post-filtering, the remaining point ratios for the Insta360 X2 and X4 datasets were 96.48% and 95.27%, respectively, indicating that the majority of the captured points were retained even after outlier removal. This suggests that the point clouds generated through photogrammetry, while lower in density, still maintain structural integrity and usability for applications such as as-built documentation and visual inspection. Additionally, the mean absolute distances for X2 (0.073 m) and X4 (0.076 m), along with standard deviations under 0.083 m, suggest that both devices offer a comparable level of spatial accuracy in relation to the laser scan baseline. These results, as summarized in Table 1, support the feasibility of using affordable 360-degree cameras for small and mid-size construction firms seeking rapid, low-cost alternatives to traditional laser scanning.

Visual comparison of the point clouds, as shown in Figure 2, further emphasizes the differences in resolution and surface detail across the three systems. The FARO Focus S350 scan (see Figure 2a) displays a high-density point cloud with fine structural details and more consistent RGB texture mapping. In contrast, both Insta360-based outputs (see Figure 2b and 2c) exhibit lower point density and occasional gaps or surface roughness, especially around structural edges and openings. However, the overall geometry remains well-preserved, supporting the viability of these low-cost alternatives for general as-built documentation purposes.

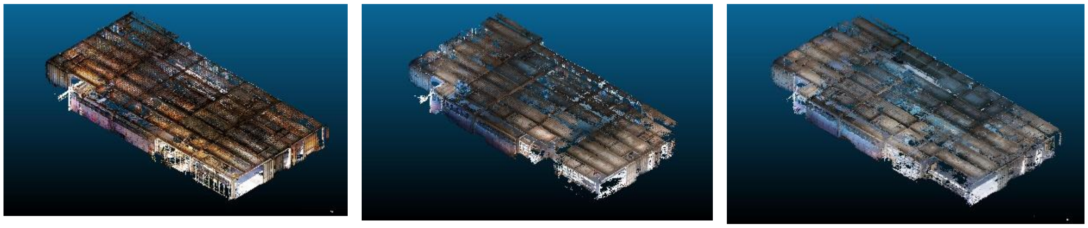

a) FARO Focus S350 - RGB b) INSTA360 - X2 - RGB c) INSTA360 - X4 - RGB

Figure 2. RGB-rendered point clouds generated from each capture device

Quantitative Assessment of Geometric Deviations

To better evaluate the spatial accuracy and consistency of the point clouds generated from the Insta360 X2 and X4 cameras, a series of descriptive statistical measures was computed for both Test 1 (FARO vs. Insta360 X2) and Test 2 (FARO vs. Insta360 X4), as shown in Table 2. These include the mean, median, and standard deviation of point-to-point distances calculated from the cloud-to-cloud (C2C) analysis. Additionally, the 95% confidence interval for the mean was derived to indicate the statistical reliability of each dataset's average deviation. The confidence intervals are notably narrow, less than a millimeter wide, suggesting a high degree of consistency in measurement and processing. This analysis provides critical insights into each camera's ability to replicate geometry relative to the FARO scan, which is treated as the ground truth.

Table 2. Statistical Analysis of Point-to-Point Distances from test 1 and test 2

Statistic	**Test 1**	**Test 2**
Mean (m)	0.062	0.062
Median (m)	0.049	0.047
Standard Deviation (m)	0.049	0.051
95% Confidence Interval for Mean (m)	0.0624 to 0.0625	0.06215 to 0.06227
95th Percentile Range (m)	0.0047 to 0.1907	0.00486 to 0.20288
% of Points Between 0 and Mean	60.59%	63.65%

The 95th percentile range reveals the upper bound of typical deviation values, extending to approximately 19 cm for the X2 and 20 cm for the X4. These values indicate the maximum expected error for 95% of all points in each respective dataset. Interestingly, the X4 dataset has a slightly broader error range, but it also demonstrates a higher percentage of points (63.65%) that fall between zero and the mean distance, compared to 60.59% for the X2. This suggests that while the X4 may include more high-error points on the upper end, it also delivers a greater density of accurate points in the low-deviation range. Overall, these results suggest that both devices produce comparable levels of accuracy, with the Insta360 X4 exhibiting slightly more favorable consistency in capturing precise spatial data.

Visual Analysis of C2C Distance Maps and Histograms

Figure 3 presents both the visual deviation maps of C2C absolute distances for the Insta360 X2 and X4 datasets compared against the FARO Focus S350 reference. The top row (see Figure 3 and 4) illustrates the spatial distribution of deviation across the scanned area. Blue regions indicate minimal error, while warmer colors, such as red and orange, reflect higher deviation. Overall, the deviation maps confirm that the largest discrepancies are concentrated along the edges and complex geometric elements, where photogrammetry struggles to maintain accuracy due to occlusions or image stitching artifacts. The X4 dataset (see Figure 4) appears to exhibit slightly more localized deviations in specific areas, particularly along vertical surfaces and recessed edges, whereas the X2 dataset (see Figure 3) shows a more dispersed pattern of variation.

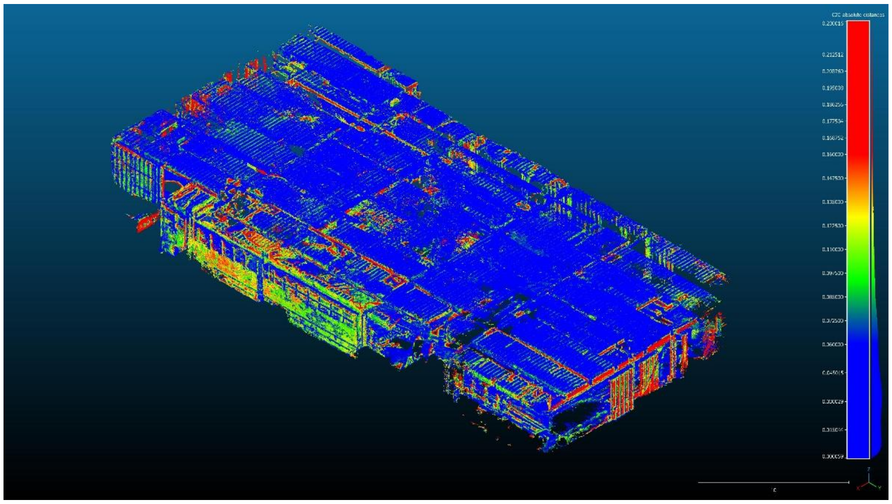


Figure 3. C2C distance visualization of INSTA360 – X2 vs FARO Focus S350

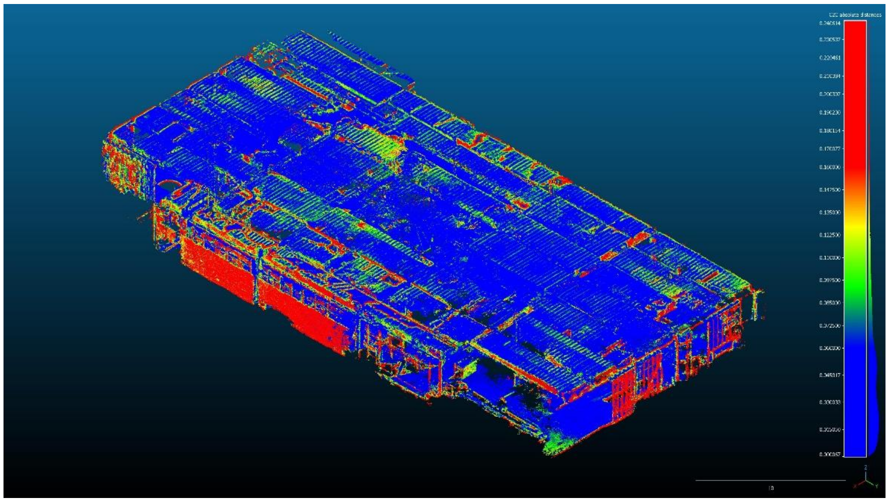
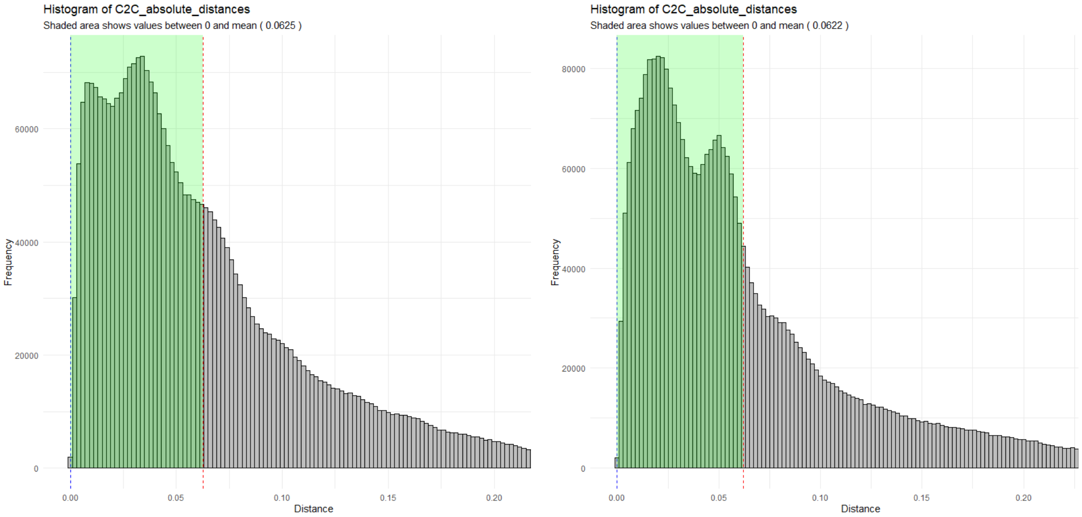


Figure 4. (C2C) distance visualization of INSTA360 – X4 vs FARO Focus S350

The histograms in Figure 5a and 5b reinforce these observations by showing the frequency distribution of absolute distances. In both datasets, the distributions are right-skewed, with the majority of points falling below the mean distance. The shaded green areas indicate points between 0 and the mean, emphasizing that a substantial proportion of points (see Table 2) have minimal deviation. Notably, the X4 dataset (see Figure 5b) shows a higher and narrower peak, suggesting tighter clustering of data points around low-error values. This supports the inference that the Insta360 X4 yields a more consistent point cloud, with fewer extreme deviations compared to the X2. These findings collectively demonstrate that while both cameras deliver usable geometry for general documentation, the X4 offers marginally better consistency and noise performance under the same site conditions.



a) INSTA360 - X2 vs FARO Focus S350 b) INSTA360 - X4 vs FARO Focus S350

Figure 5. Cloud-to-cloud (C2C) distance visualizations and histograms

2D Alignment with Design Documentation

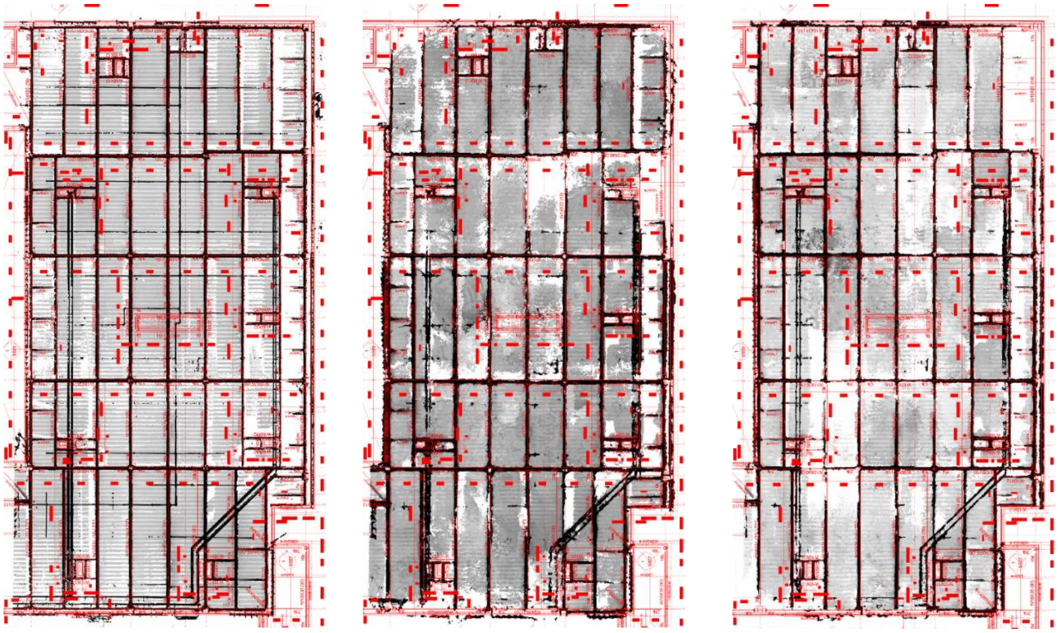
To complement the quantitative analysis, a visual comparison was performed by overlaying the point cloud-derived roof framing plan slices with the original 2D design documentation (shown in red), as illustrated in Figure 4. This method allows for intuitive assessment of alignment accuracy, geometry, and structural correspondence across the three capture methods. The FARO Focus S350 dataset, Figure 4(a), shows near-perfect alignment with the design drawings, with sharp linework, minimal noise, and highly accurate placement of beams and framing elements. This validates its role as a ground-truth reference, especially in environments requiring millimeter-level accuracy.

In comparison, the Insta360 X2 (b) and X4 (c) datasets show improved alignment, with the X4 producing crisper, more continuous framing elements than the X2. The X2 output exhibits more visual noise, blurring, and slight geometric distortion, particularly in the center of the floor plan and near high-contrast areas. The X4 point cloud better matches the red design overlay, especially around beam intersections and wall corners, suggesting improved consistency and definition in the captured geometry. These final visual results reinforce the conclusion that while 360-degree photogrammetry cannot yet replace high-end terrestrial laser scanning in precision-critical applications, it offers a practical, low-cost alternative with acceptable accuracy for many construction documentation and as-built workflows.

While terrestrial laser scanning offers superior geometric precision, its high upfront capital cost, annual software licensing, and training requirements present substantial barriers for small and mid-sized construction firms. In contrast, the Insta360-based workflow reduces initial equipment investment by over 95%, eliminates the need for specialized scanning personnel, and reduces on-site capture time by approximately 93%, as observed in this study (see Table 3). Although photogrammetry produces lower point density, the resulting accuracy was sufficient for general as-built documentation and verification tasks. These cost differentials position 360-degree photogrammetry as a practical entry-level reality capture solution for firms seeking to adopt digital documentation without incurring high capital expenditures. Costs presented in Table 3 are typical market ranges and are intended for comparative evaluation rather than exact pricing.

Table 3. Approximate Cost Comparison Between TLS and 360-Camera Photogrammetry.

Cost Component	**TLS**	**360 Cameras**
Hardware Cost (USD)	\$60,000–\$80,000	\$400–\$600
Annual Software License	\$3,000–\$5,000	Cupix Vista: \$1,200–\$2,000
Training Requirement	Specialized training	Minimal (walkthrough capture)
On-Site Capture Time (this study)	~45 minutes	~3 minutes
Personnel Skill Level	Trained scanning technician	General field staff
Typical Data Density	Very high (61M+ points)	Moderate (≈3M points)
Estimated Entry Cost (Year 1)	\$63k–\$85k	\$1.6k–\$2.6k



a) FARO Focus S350 b) INSTA360 - X2 c) INSTA360 - X4

Figure 6. Visual overlay comparison between point cloud ceiling plan slices and original design documentation (in red)

Conclusions

This study investigated whether affordable 360-degree photogrammetry can serve as an alternative to terrestrial laser scanning for construction documentation tasks. Using Insta360 X2 and X4 cameras, point clouds were captured at an active healthcare project and compared against a FARO Focus S350 reference. Data was processed into E57 files and evaluated using cloud-to-cloud distance analysis, descriptive statistics, confidence intervals, and visual overlays with design drawings. Results show that the FARO scan produced the highest density (61 million points), while the Insta360 X2 and X4 generated about 3.2–3.3 million points with much shorter capture times (3 minutes versus 45 minutes). Mean deviations relative to the FARO scan were about 0.06–0.08 m, with over 95% of points retained after filtering. The X4 showed slightly higher consistency than the X2. These results indicate that 360-camera workflows can support general as-built and documentation tasks when sub-centimeter accuracy is not required. Limitations include single-site testing and the use of one photogrammetry platform. Future research should examine multiple sites, alternative software, and AI-assisted processing workflows.

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