A comparative study on the use of laser scanners for construction quality control and progress monitoring purposes

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ABSTRACT: Laser scanning is an emerging technology used on construction sites for defect detection and progress monitoring. Most previous studies in this domain use data from a single scanner while discussing various data collection, processing and accuracy analysis strategies. With the purpose of comparing the technical characteristics of two scanners and identifying the challenges of using them on construction sites, we conducted a case study on indoor laser-scanning of one floor of a five-storey commercial building in Pittsburgh/PA/USA during its construction. The two scanners used in this study adopt two different positioning techniques: pulsed-time-of-flight (obtaining the distance to an object by timing the round-trip traveling-time of the laser) and amplitude-modulated-continuous-wave (comparing the phases of emitted and received signals for indirect measurements of laser traveling time). For each tested scanner, we highlight its unique advantages and technical challenges, as well as relevant technical trade-offs regarding their utilization on a construction-site for quality control and progress monitoring purposes.

1 INRODUCTİON

In the domains of construction and facility management, researchers have conducted various research studies investigating the issues related to utilizing laser scanners for a wide range of purposes including fast workspace modeling (Kwon et al. 2004), real-time safety management on-site (Teizer 2008), construction progress monitoring (Bosche & Haas 2007, Rebolj et al. 2008), defect detection (Akinci et al. 2006, Gordon & Akinci 2005), and as-built modeling (Cheok et al. 2000, Heinz et al. 2001, Kim et al. 2005). In the domain of infrastructure management, previously investigated applications of laser scanned data sets include various geometric assessments of existing transportation systems, such as deflection assessments of bridges (Gordon et al. 2004, Jaselskis et al. 2006, Jaselskis et al. 2005, Kretschmer et al. 2004, Tang & Akinci 2008, Tang et al. 2007), and pavement thickness assessments (Jaselskis et al. 2006). These previous research studies mainly focus on evaluating the data collected by a single scanner, and analyzing practical issues of using it on-site, such as the time requirements and the interferences of scanning activities with other on-site activities.

There are different types of scanners utilizing different working principles. Their data are of different accuracies, data densities, which can have different usage implications. Hence, different scanners might be suitable for different purposes. With this observation, we conducted a case study to perform a comparative analysis on the technical capabilities of two different scanners, and their applicability to specific usages. This study involved the indoor laser scanning of one floor of a five storey commercial building in Pittsburgh, USA during the construction. The two scanners used in this study are adopting two different scanning technologies: pulsed-time-of-flight –PTOF- (obtaining the distance to an object by timing the round-trip traveling-time of the laser) and amplitude modulated continuous wave -AMCW- (comparing the phases of emitted and received signals for indirect measurement of the laser traveling time). These two types of scanners are the two major-stream terrestrial scanners widely used in the construction industry.

This paper first discusses related studies, then overviews the case study, followed by the descriptions about the research methodology and research findings.

2 LITERATURE REVIEW

The laser scanning related studies discussed before indicate the potential of laser scanning technology in the Architecture Engineering and Construction (A/E/C) domain. With this observation, GSA (General Services Administration) is exploring a variety of applications of laser scanned data during the life cycle of a facility for the GSA National Building Information Modeling (BIM) program. The specific use cases of laser scanned data include as-built modeling of existing buildings for renovation design, spatial program validation of existing buildings, and energy performance analysis (GSA 2007).

In recent years, with the appearance of more accurate, faster and more mobile scanners, contractors show increasing interests in the applications of laser scanning technology to tasks requiring faster and more accurate geometric data collection. Two examples of these tasks are construction defect detections and progress monitoring. Regarding the construction defect detection and quality control, several previous research studies showed the potential of laser scanning technology. Akinci et al. showed that laser scanning technology enables frequent and fast geometric assessments of constructed buildings (Akinci et al 2006). Tang et al. characterized two scanners and three algorithms for detecting flatness defects on concrete surfaces (Tang et al 2009). Regarding construction progress monitoring, some case study based investigations exist. Su et al. investigated the utilization of laser scanning technology for excavation progress monitoring in a case study (Sue et al. 2006). Cheok et al. investigate the accuracy of laser scanned data for extracting volumes of objects (Cheok et al. 2000, Cheok et al. 2001). A research group at the National Institute of Standards Technology (NIST) has investigated how to utilize laser-scanned data for locating objects on construction sites (Lytle & Saidi 2006). Haas et al. investigated the technical feasibility of integrating a CAD model and laser scanned data for automated construction progress monitoring (Bosch´ 2008, Bosche & Haas 2007, Bosche & Haas 2008).

Most of above studies include some discussions about the technical characteristics of the used scanners, and their implications to the qualities of the collected data for specific application scenarios. However, most of these studies used one type of laser scanner for one project. Hence, their discussions about the technical feasibilities of scanners might be limited to a specific scanner or a specific case. Meanwhile, there are multiple scanners with different technical characteristics on the markets, and the most suitable laser scanner for a given task might vary case by case. Hence, there is a need for comparing the performances of multiple types of scanner on various geometric assessment tasks. Specifically, there are two predominant underlying technologies used in current commercially available laser scanners: pulsed time of flight (PTOF) and amplitude modulated continuous waveform (AMCW). A PTOF scanner emits laser pulses, and measures the time interval between sending and receiving the pulses, while an AMCW scanner emits continuous laser wave, and uses the phase-differences between the emitted signal and reflected signal to estimate the range. Hence, it is necessary to conduct comparative analysis of the technical characteristics of these two types of scanners on a common testbed for exploring technical trade-offs of using different types of scanners, and develop knowledge about appropriate technologies for specific use cases. We are not aware of any existing comparative studies of two major types of scanners on common test cases within the A/E/C domain. Hence, this paper targets this lack of knowledge by conducting a case study using one AMCW scanner and one PTOF scanner on the same construction site, for two different application scenarios (defect detection and progress monitoring).

3 RESEARCH METHOD

In order to compare the technical capabilities of the two tested scanners, we performed a case study on a building project during construction.

3.1 Case Overview

The case study project is a commercial building consisting of 5 storey and 189,000 square feet of usable spaces. The main structural elements in the building are steel beams and columns. The exterior and enclosure are modeled to be composed of brick walls with metal studs and curtain walls. We conducted two visits to the construction site. For the first visit, structural beams, columns and the slabs were in place with the metal stud related works in progress. For the second visit, studs with insulations and some of the inside walls were completed with the windows related works in progress.

3.2 The scanners used and their technical properties

As described in the literature review section, the two scanners used in this study adopt two different positioning techniques: PTOF and AMCW. Table 1 presents their technical properties. This table shows that generally, the used PTOF scanner can deliver more accurate data, and has a longer range. However, it is slower in terms of the data collection rate.

Table 1: Technical Characteristics of Scanners

Technical Properties	PTOF	AMCW
Speed	50,000 points per second	125,000 points per second
Field of view	360X270 degrees	360X270 degrees
Rotation Speed	~ 60 round/min	1500 round/min
Longest Range	300 m	53.5 m
Positioning Accuracy	6 mm within 300 m	7 mm at 10 m 13.5 mm at 25 m
Highest density of data	< 10 mm within 300 m	3 mm at 10 m
Spot size	4 mm at 25m	8 mm at 25m

3.3 Performance Metrics of the Data Collection Process based on User Requirements

The authors performed investigations on the requirements of construction project managers about an approach for geometric on-site data collection. The investigations indicate that these requirements have three aspects: 1) time needed for data collection (efficiency); 2) accuracy of the collected data (accuracy); and 3) the smallest objects or shape variations that can be extracted from the data (level of detail). Based on these observations, we developed three metrics for evaluating the performances of different laser scanners for construction related applications.

- Efficiency: the efficiency metric represents the amount/density of the data collected within a certain period of time. This metric will be used to compare the time-density characteristics of the scanners.
- Accuracy: the accuracy metric stands for how accurate the objects are located in a 3D environment. It measures the localization accuracies of single points or objects being composed of multiple points. The difference between the single point and object accuracy arises from the fact that even if the locations of single points are not accurate, modeling algorithms can generate accurate surface models by averaging data noises in large number of data points.
- Level of detail (LoD): The LoD metric stands for the smallest features and objects captured in data that are of interest to the users. In deed, using this metric, the scan data will be compared in terms of the minimum size of a recognizable object and the smallest detectable variations in the object shapes (e.g. small bumps on a flat surface).

The three metrics described above can have tradeoffs amongst each other. For example, in terms of efficiency and accuracy, some scanners are very fast, but their single point error might be slightly larger than other scanners, which could be slower. Similarly, faster scanners can collect more data within a certain time period (high efficiency), hence can collect denser data and capture more detailed geometric information. However, as mentioned before, the data might not be as accurate as slower scanners. Regardless, as indicated by geometric fitting related theories, even though such dense point clouds are less accurate in terms of point-accuracy, fitting geometric features (e.g. planes) against larger number of points is still able to produce accurate geometric features.

3.4 Factors Impacting the Performance of Laser Scanners

The performances of the scanners, which can be measured by the aforementioned metrics, are affected by various factors. These factors can be categorized into two groups:

- Internal factors of scanners: data collection range, accuracy in locating 3D points, data collection rate (number of points per second), time required to set up and perform a scan
- Environmental conditions: surface characteristics (the make of the materials such as metallic or concrete surfaces, and water in the environment affect the reflection of the signals), dimensions of objects of interests, site conditions (site size, existing obstructions caused by equipments or materials, and movements of objects on-site)

We used two use cases varying in these factors to evaluate two scanners in this case study: 1) defect detection, which requires the detections of small variations on object surfaces; 2) progress monitoring, which requires tracking of objects on site with substantial changes such as size or composition.

3.5 Case Execution and Analysis

Within three months, we performed two major data collection activities on the construction site. The first visit involved using the AMCW scanner, and we performed six scans on the second floor of the building. The floor plan and the sequential scanner locations are shown in Figure 1a. The second visit which was three months after the first, involved using both the AMCW and PTOF scanners. With the AMCW scanner, we performed 6 scans on the same floor just like the first visit at similar scanning locations. With the PTOF scanner, we performed 2 scans and the scanning locations are shown in Figure 1b. The reason why we performed one third of scans with the PTOF scanner is that it took longer time in setting up and performing the scans and the time constraints of the project only allowed us to perform two PTOF scans.

The generation of as-built model of the construction projects requires the registration of multiple scans obtained at different locations, because of their limited data capture ranges as well as the occlusions on-site. Registration is the process of integrating and aligning multiple scans collected at multiple locations. Since each of the scan has its own local coordinate system, the registration process transforms scans into one global coordinate system. In order to see the range and level of detail captured by the scanners and to be fair in terms of the comparison, we registered and used only the 2^{nd} 3^{rd} and 4^{th} scan data of the AMCW scanner and compared them with 1^{st} and 2^{nd} scans of the PTOF scanner.

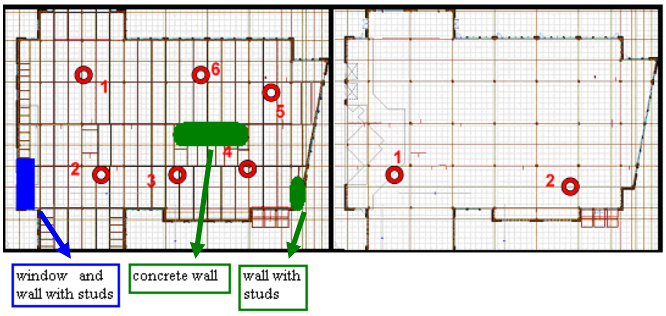


Figure1: Scanner positions, 1.a: AMCW and 1.b: Time-of-flight

We performed three analyses to compare the scanners based on efficiency, accuracy and LOD metrics, and to reflect on the internal and environmental factors. First, we compared the registered scanned data of both scanners from the second visit against the CAD model of the building to see which scanner can capture more accurate and more detailed surface deviations for defect detections. We visualized the patterns of these deviations by using color-coded error maps. Observations in this process indicate that the deviation from the CAD model of noisy data will show "high frequency" pattern (a lot of small wavy pattern), while less noisy data can show "low frequency" pattern. Second, we compared the scanned data of PTOF against the AMCW data from the second visit. The purpose for this analysis is to visualize and further understand the differences of these two scanners in the data capturing range, data density, noise level, and the capabilities of capturing the details and outlining boundaries of objects. Finally, we compared the scanned data of AMCW scanner belonging to first and second visits in order to see whether the progress on site can be accurately captured in the collected AMCW data.

4 RESULTS

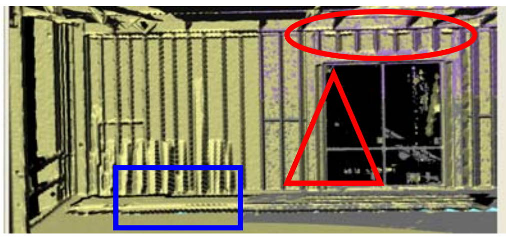
4.1 General Comparison

As discussed above, three major aspects that influence the suitability of a scanner for a specific application include: 1) efficiency (time-density characteristics) of the scanner; 2) accuracy (noise level of data in localization of points); 3) density and LOD of data (minimum sizes of objects and deviations detectable). Following paragraphs present general comparisons of the two scanners on these three aspects.

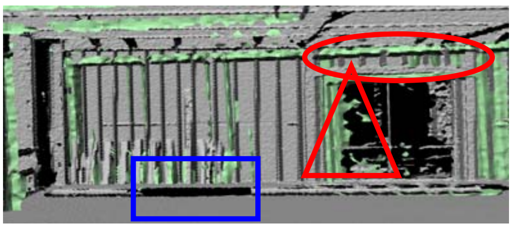
- Efficiency: The average time spent to set-up the scanners is 30 min for PTOF and 20 min for AMCW. The 10 minute difference is caused by the fact that it takes more time to set-up the tripod of the PTOF scanner, which does not have wheels to move around on-site, while the tripod used by the AMCW scanner has wheels and do not need to be disassembled for moving. In addition, PTOF requires an initial 5 min to "warm-up", and it need another 5 min to scan the site on its own to capture a site picture before conducting actual scanning. Besides the longer setting up time, the PTOF scanner needs additional time to conduct detailed scan of registration targets which took additional 20 minutes for this construction site. These targets are used as common reference points in two scan data sets to perform the transformation of coordinate systems and align them. The scanning activity for PTOF is 30 min on average for a density of 25 mm at 10 m, while AMCW needs 3 min 22 sec for collecting a scan with a density of 6mm at 10m. These discussions indicate that more time is required to perform a scanning activity with the PTOF scanner even for collecting a scan of a lower density.

- Noise level: Figure 2 shows a view of the floor –a picture from site, scan data of PTOF and AMCW respectively- focusing to a window and a wall with studs as annotated with a rectangle in Figure 1. PTOF scan data around the windows shows a low frequency pattern as compared to the wavy view of the AMCW scanner points as shown with a triangle indicating the existence of more noisy data captured with AMCW scanner. Moreover, AMCW did not capture a portion of the material lying in the floor as highlighted with a rectangle. The reason for this phenomenon might be that the raw data of PTOF contain less data noises (smoother), so that data processing software, which automatically detect and remove noisy data patches, keep more raw data of the PTOF.

a) Picture of a window & wall with studs



b) PTOF data of window & wall with studs



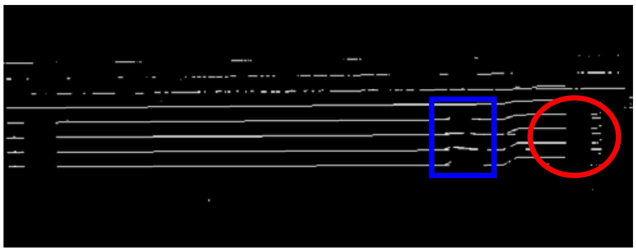
c) AMCW data of window & wall with stud

Figure 2: Window and wall with studs

- LOD: In Figure 2 the difference of the scanners in terms of capturing the small studs on top of the window frame is shown with an ellipse. The difference is that PTOF captures more detailed geometries for locating the studs and capturing their sizes. In order to perform a more detailed comparison of the scan results, we took the cross-section of the concrete wall as shown with a rounded rectangle in figure 1. The site picture depicting the concrete wall and cross-sections generated from the PTOF and AMCW scanners are presented in figure 3. We found that the PTOF scanner could not capture some of the points on the wall as shown with a circle because of its sparser data. Moreover, the AMCW data captures the side wall behind the door as shown with a rectangle, while the PTOF data misses parts of it due to the lower data density.

a) Picture of a concrete wall (14')

b) Cross-section of PTOF focusing to the concrete wall



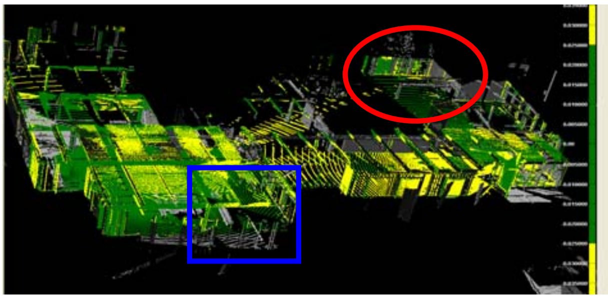
c) Cross-section of AMCW focusing to the concrete wall

Figure 3: Concrete wall

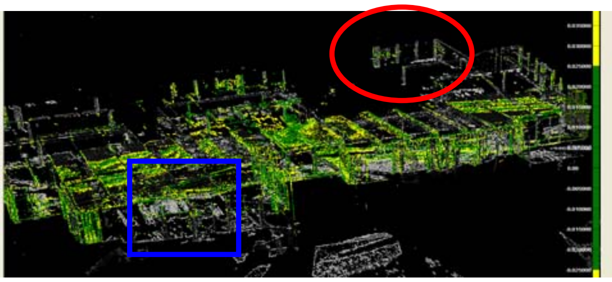
As a summary, we observed that the scanning activities of the PTOF generally take longer time, while producing less noisy data of lower LOD. In fact, PTOF could achieve the same LoD as AMCW but it takes much longer time to scan for achieving the same data density as the AMCW data. Hence, relatively, the AMCW scanner can capture more detailed geometries in shorter time.

4.2 Quality Control

In order to identify the performances of the two tested scanners for construction defect detection, we compared the registered scanned data of PTOF and AMCW with the CAD model of the floor separately to understand their capabilities for capturing detailed surface deviations, which could be construction defects. For this comparison, we used a 0.05 m distance range and binary-color coding system for visualizing the deviations between the as-built model and the CAD model. Green points stand for difference between 0 and 0.025 m and yellow ones stand for 0.025 to 0.05 m. The deviations more than 0.05 m is represented without a color (grey). The scan data of PTOF and AMCW are presented in Figure 4.



a) PTOF CAD comparison for 0.05 m

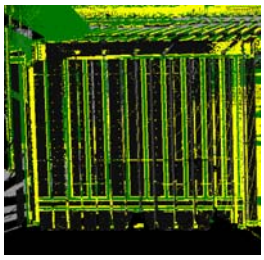


b) AMCW-CAD comparison for 0.05 m

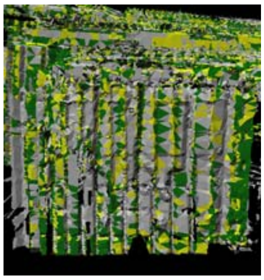
Figure 4: Comparison of PTOF and AMCW scanners from the second visit with CAD model of the floor

The first observation from the comparison of the scan data sets with the CAD model is that PTOF has a larger data collection range. It is indicated by the data points of the windows, as highlighted with circles in the Figures 4a and b. These windows are far from the scanning locations, while more parts of them are captured in the PTOF data. The scatterings of the green and yellow colors indicate that the PTOF scanner has more points overlapping with the CAD model. This fact confirms that the PTOF is more accurate in locating 3D points. Most of the grey and yellow colors are caused by the ductwork in place, many boxes and formworks on the floor, which was not captured in the CAD model. Another observation is that the exposed ceiling is made of aluminum, and both of the scanners cannot capture accurate data on such metallic surfaces. Windows and studs in the floor are highlighted with a rectangle in Figure 4 as well. For these objects, it is also observed that the AMCW data is noisier.

In order to illustrate the LOD captured for the wall with studs as identified in Figure 1, we focused to the wall view as shown in Figure 5 for both scanners. The wavy patterns observed in the AMCW data indicate that the data are noisier than the TOF data. The larger green regions observed in the PTOF data indicate that the PTOF data is more accurate. In this figure, the grey color for the insulation being identified in AMCW but not identified in PTOF is caused by the fact that AMCW collects denser data capturing these detailed object features. However, these captured features are mixed with wavy patterns, which indicate that the AMCW scanner captures more details, but might not accurately capture them.



a) PTOF CAD comparison for 0.05 mm, focus to wall



b) AMCW-CAD comparison for 0.05 mm, focus to wall

Figure 5: Comparison of PTOF and AMCW scanners from the second visit with CAD model of the floor, zoomed to stud wall

As a summary, the comparison of the PTOF and AMCW scanners with the CAD model demonstrates that the PTOF scanner is more accurate in terms of the locations of the points, has a higher data capture range, but its data was not dense enough for capturing some small defects on surfaces.

4.3 *Progress Monitoring*

We compared the scans of AMCW scanners from two consecutive visits with each other using the scan data sets captured when the scanner was located at point 4 of Figure 1. Figure 6 shows site pictures illustrating the locations of scanners', concrete wall's (annotated with rectangle) and wall with studs' (annotated with circle). Figure 7 shows the zoomed views of the scan data capturing both of these walls. Both the site pictures and the scan results indicate that during the first visit, the insulations were not in place for the brick veneer wall with studs and the concrete was not poured for the concrete wall. Hence, looking at the scan data, the progress in these walls could be identified.

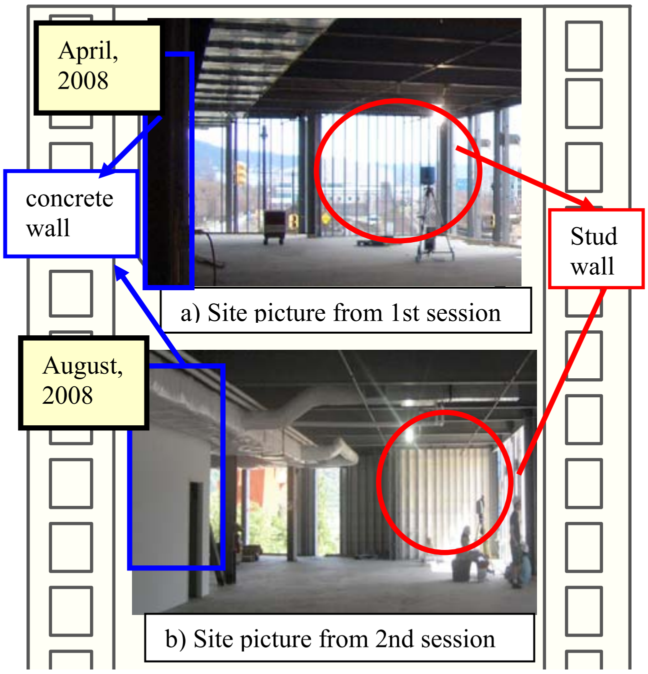


Figure 6: Site picture from the first session

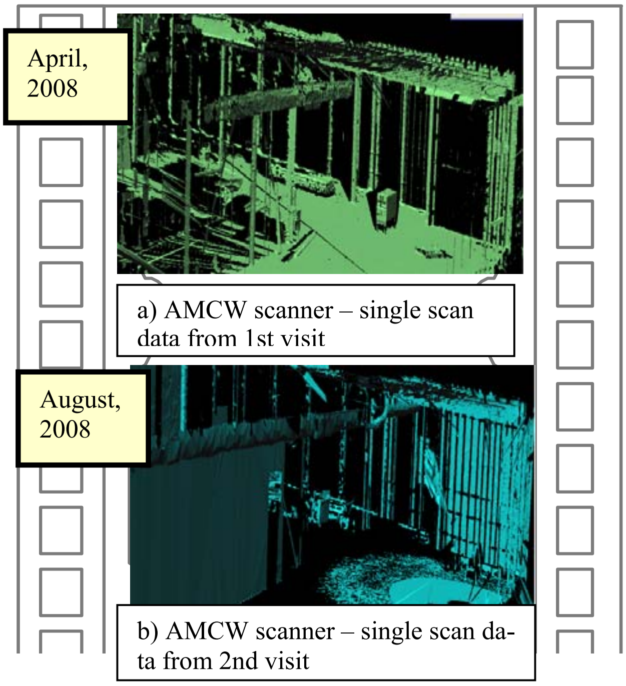


Figure 7: AMCW scanner – single scan data from first visit

The comparison of the scanned data from these two visits with each other, on a 0.05 m color coded error map is shown in Figure 8. The color-coding used in Figure 4 was applied here. That is to say, the points within 0 and 0.025 m and between 0.025 m and 0.005 m are represented with green and yellow colors respectively. The points with green color in Figure 8 demonstrates that some parts of the slab closer to the location of the scanner overlap in both of the scans however, some parts on the slab are grey. The existence of grey color arises from the fact that there were lots of obstacles including equipment and materials on the ground during the scanning periods. Since these obstacles were not identical during the two different visits that we performed, the difference in the localization of the points were greater than 5 mm. As discussed before, both of the scanners has a poor reflectivity for the aluminum surfaces and it creates noisy data. That's why the comparison of the points in the ceiling of the floor could not be performed.

Moreover, we observed multiple colors on the concrete wall. The parts where there are columns in both of the visits were identified with green colors. However, some parts of the wall were identified with green and yellow colors showing that it matched some points within 5mm accuracy but actually they should not. Indeed, there is void space between the columns belonging to the first visit corresponding to the yellow color area so that there should not be any points overlapping with the second visit data where there is concrete in-place. Hence, this phenomenon can be explained as using the triangulation algorithms some phantom surfaces were created for the first scan data set causing mislocalization of some points and they were matched with the second scan data.

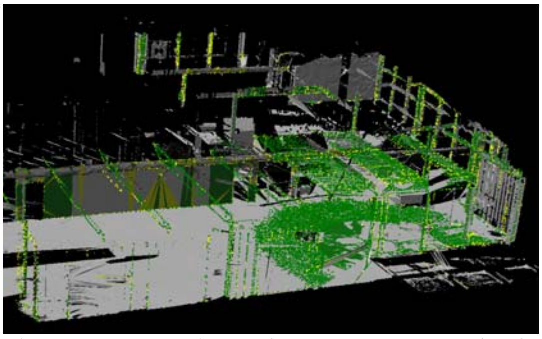


Figure 8: Comparison of AMCW scan results from different sessions on a 0.05m error map

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As a summary, we observed that the progress of the construction works, especially the stud, insulation and concrete works could be captured by the scanner. However, data from the slab and the ceiling composed of aluminum deck are noisy. That fact causes difficulties of generating clear progressing monitoring results. Hence, we regard that bigger changes on-site can be captured in laser scanned data, but it requires careful investigation and evaluation of the site conditions to understand the nature of the data, and carefully interpret the data patterns for visualizing and understanding construction progresses on-site.

4.4 Summary of Comparative Analysis Results

A summary of the comparison results with their applicability to the purpose of usage is presented in table 2. The results regarding the efficiency, accuracy and LoD of the scanners are consolidated in this table. The longer time requirement of PTOF scanner along with its better suitability to larger constructions sites and more accurate results are demonstrated in the table. On the other hand, this table shows that the AMCW scanner has faster data collection rate for collecting detailed geometries in short time, while the accuracies of the collected points might be slightly lower than the data points of the PTOF scanner.

Table 2: Comparison of scanners based on performance metrics

Metrics	Factors	Type of scanner & Suitability for the purpose (defect detection and progress monitoring)	
		PTOF	AMCW
Efficiency	Time to set up the scanners	30 min	20 min
	Time to perform a panoramic scan	About 30 min	3 minutes 22 seconds
Accuracy	Surface characteristics	Not good with specular surfaces (e.g. glass, metal)	Not good with specular surfaces (e.g. glass, metal)
	Size of the site (data capture range)	Large open spaces	Small sized spaces
	Locating the objects	High accuracy	Low accuracy
	Being affected by the existing obstructions	Affected	Affected
Level of Detail	Dimensions of objects	low LoD of object shapes	high LoD of object shapes
	Density of data	25 mm at 10 m	6 mm at 10 m

5 CONCLUSİON

Laser scanning technology is emerging in construction management domain for various purposes including defect detection and progress monitoring. Considering the existence of various commercially available laser scanners, it is important to know the suitability of these scanners to the purpose of usage. Hence, in order to compare the technical characteristics and processing implications of two different scanners we conducted a case study on a building project in Pittsburgh, PA. The two scanners used in this study adopt PTOF and AMCW techniques respectively. In this study, we identified important technical trade-offs involving data collection time, level of detail captured in the data, data processing time and related accuracy implications. Based on the discussions performed on the technical capabilities of the scanners and the comparisons of the scanned data, we can summarize the advantages and disadvantages of each scanner as follows;

Time-of-flight:

- Advantages: Long range, high accuracy, less noisy data at spatial discontinuities
- Disadvantages: Slower data collection speed, relative to AMCW
- Suitable for: static space requiring very accurate geometric information, small and large open space status tracking which do not require high level of detail of object shapes, large scale buildings requiring long range of scanners, and purposes which require high accuracy of object locations (crane operations), sites being static during the long time of scanning
- Not suitable for: small space requiring fast assessments, require high level of detail of object shapes, busy site which cannot be stopped for long time (half an hour), site requiring fast and frequent updating and evaluation

AMCW

- Advantages: fast data collection speed (ten times faster than PTOF scanner), can collect very dense data in short time
- Disadvantages: Medium range; medium level of accuracy; large spot size, fast rotation speed, more noise
- Suitable for: fast scanning of small to medium size space (with dimensions smaller than 100 m), assessments requiring high level of detail of the shape of objects, busy sites which cannot stop working for more than a couple of minutes (because of its speed in scanning)
- Not suitable for: large open space evaluation requiring long range (more than 100 m) (would require multiple scans) and high accuracy of object locations, small objects with small discontinuities

In addition to the differences of the scanners, some common technical issues identified as follows:

- Both scanners does not work well for some specific materials: glasses, steel, aluminum ceilings
- They require long set-up time
- There are mobility issue, in this study, moving scanner from one floor to another floor takes at least 15 minutes, without counting the time for disassembling the scanner and setting-up it on the new location

With our study we highlighted important technical trade-offs involving data collection time, level of detail captured in the data and related accuracy implications. These trade-offs can affect the selection of a scanner depending on on-site conditions, and help inspectors to select a proper scanner to meet their specific requirements

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