Enhanced Construction Progress Monitoring through Mobile Mapping and As-built Modeling

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Abstract –

Construction projects are often suffered from time delay and cost overrun, unavoidably leading to underperformance and low productivity of the construction industry. Inadequate monitoring of construction progress is one of the key factors behind this scenario that has a detrimental effect on subsequent construction activities. Recent development in 3D Building Information Modelling (BIM) and laser scanning technology has made it possible to actively monitor construction progress. This paper aims to obtain timely and accurate progress information of construction activities through integrating mobile mapping techniques with as-built BIM. A novel method of construction progress monitoring to measure progress of work in terms of percentages, is presented. Having updated as-designed BIM model as well as construction site scan data, Hausdorff distance is introduced to filter out the noise and extract elements of interests from the site scan data. The extracted elements are then converted to as-built BIM model and compared with as-planned BIM model. Python script and Dynamo programming are used for color codes to indicate status of activities and obtain related progress percentages. A case study was conducted in the Engineering building at the University of New South Wales (UNSW) to obtain real site scan data. The result shows that the method has achieved an average of 95.9% accuracy in estimating progress percentages. In addition, the take-off quantities from the as-built BIM model could be used for several purposes, such as construction schedule update and procurement management.

Keywords –

Construction progress monitoring; Laser scanning; SLAM; Scan-to-BIM; Hausdorff distance.

1 Introduction

Construction industry is a major contributor to the global economy, accounting for around to 10% and 25% of Gross Domestic Product (GDP) in both developed and developing countries respectively [1]. In Australia, the industry contributes about 9% to GDP, producing annual revenue of $360 billion [2]. However, the industry's low productivity rate compared to other industries has remained a challenge for construction practitioners and researchers [3, 4].

One of the areas that has a major impact on low productivity rate is construction progress monitoring. Because the traditional construction progress monitoring, which is a manual observation and data collection process, is time-consuming, costly, error-prone, infrequent, and unsafe resulting in time and cost overrun in construction projects [5, 6]. A timely and accurate progress monitoring system not only contributes to successful completion of a project, but also helps to increase productivity and enhance safety performance of a project. For instance, using advanced reality capture technology contributes to workers at construction site exposed to COVID-19 hazards [6]. Therefore, measuring construction progress in a timely and reliable manner by implementing new techniques and technologies are vital in addressing the challenges in traditional system [7, 8].

The aim of this study is to use Simultaneous Localization and Mapping (SLAM) and scan-to-BIM techniques to obtain timely and accurately progress percentages of construction activities, which is used in schedule update. The study's key contributions are using mobile scanners, which improve usability while also minimizing noise; introducing Hausdorff distance to extract objects of interest from scan data while also filtering out the noises; and calculating work progress in percentages. A case study was conducted in engineering building at University of New South Wales (UNSW) and produced successful results.

The rest of the paper is organized as follows. A review of previous studies is discussed in section 2 followed by research methodology and the case study. Finally, the discussions and conclusions of the study are reviewed.

2 Literature Review

Automated progress monitoring using various methods and technologies has been widely studied in recent years to overcome the problems with traditional approach. This part of the paper provides information about available reality capture techniques, as-built BIM, and data-driven progress monitoring in previous works.

2.1 Reality capture techniques

Technology development recently resulted in several types of reality capture techniques using in data acquisition from construction sites. For example, imaged-based or photogrammetry, Laser Scanning (LS), Radio Frequency Identification (RFI), Ultra-Wideband (UWB), Global Positioning System (GPS), Wireless Sensor Network (WSN), and Unmanned Aerial Vehicle (UAV) [9]–[11]. The RFI, UWB, and GPS are found to be impractical for progress measurement of cast-in-place activities [10]. Laser scanning, photogrammetry, and RFI are preferred for progress monitoring [11].

The photogrammetry technique has widely used in progress monitoring but still there are associated problems: all photos and videos are affected by severe weather conditions, lighting and shadow [12, 13]. In addition, it is not capable of covering entire project and due to complexity of indoor environment limited studies have been conducted pertinent to indoor progress monitoring [14, 15].

The 3D laser scanning technique is comprehensive and accurate approach. However, errors in calibration, environmental factors' impact such as sun and wind on instrument movement and thermal expansion, surface reflection and dynamic field settings are certain drawbacks [16]. Additionally, several scanners are required to cover entire area [13, 15] and improvements are also needed to accelerate registration of multiple scans [17].

To overcome the problems of photogrammetry and static laser scanning approaches, numerous studies have been conducted using simultaneous localization and mapping (SLAM) technique in construction domain. For example, Kim et al. [18] introduced object recognition and navigation method based on SLAM that implemented and tested on a mobile network platform for 3D real-time data acquired from a construction site. Shang and Shen [19] studied integration of SLAM with UAV as pilot study for construction site real-time mapping. Asadi et al. [15] used SLAM technique in unmanned ground vehicle (UGV) for real-time image localization to automatically register site images to as-planed BIM model. Therefore, the SLAM could be used in progress monitoring to mitigate problems in static laser scanning and photogrammetry approaches such as time spent in registration of scans as well as available noise in scan data [13].

2.2 As-built BIM

Building Information Modelling (BIM) provides an outstanding opportunity to the construction industry since almost all data acquisition technologies are integrated with BIM which provides a better platform for construction sites particularly for progress monitoring [16, 20].

Scanning data with BIM can be used in two different ways: scan-to-BIM and scan-vs-BIM. In the scan-to-BIM approach scan data from a construction site is first converted to a BIM model manually or semi-automatically before performing additional analysis [21]. This approach is often used for existing structures including historical buildings and could be applied in various phases of a construction projects as well [22].

In the scan-vs-BIM approach a scan data is aligned into coordinate system of a CAD model and further analysis is performed [23]. This approach has been widely used by scholars for the experiments to compare as-built with as-planned data [5]. The comparison of visualized as-built and as-planned construction data through BIM results in enhanced identification, communication, and analysis of discrepancies in progress [24]. In this study a scan-to-BIM approach is used to create as-built BIM model.

2.3 Data-driven Progress Monitoring

In recent years photogrammetric and laser scanning point clouds with BIM have been used to measure progress of construction works. For example, Bosche et al. [25] investigated the potential of laser scanned data for progress control by merging time-stamped 3D laser scan data with a 3D CAD model, which was later improved by Bosche et al. [26] as well. Similarly, Turkan et al. [27] used a 3D CAD model with 4D BIM to update project schedule automatically. Turkan et al. [28] used a 4D BIM model and laser scanned data to track progress of work. The result indicated reasonable and automated estimation of project progress for structural erection in terms of earned value. Golparvar-Fard et al. [29] used point cloud created from images in which progress was color coded. Martens [30] also indicated progress of work in color codes using Hausdorff distance in the method.

Pucko and Rebolj [31] and Pucko et al. [5] conducted studies with multiple scanners mounted in labors' helmets. Continuous modifications were captured with scanners and the as-built model compared with 4D BIM model for progress monitoring. Kim et al. [32] also used laser scanners to acquire data and compare the incomplete 3D data with 4D BIM model to propose a fully automated method for progress measurement. Zhang and Arditi [17] conducted experiments in laboratory environments using point cloud to evaluate automatic progress control. There are several other studies used point clouds and BIM models for progress measurement. This study also uses SLAM-based approach utilizing point clouds and BIM model with below research methodology for progress monitoring. SLAM-based approach reduces noise and the time spent in registration of scans.

3 Research Methodology

The designed and selected research methodology for current study is divided into three phases: 1) digital twin in which as-designed, as-built and as-planned models are provided, 2) progress analysis that includes a model-to-model comparison and quantification of progress percentages, 3) schedule updates using obtained progress percentages from phase two. The entire research methodology diagram has shown in Figure 1. The study covers phase one and phase two while phase three will be studied in the future. These two phases are further described in below sub-section.

3.1 Data Filtration and As-built BIM

There are two steps that are used in data filtration: first, coarse and fine registration are carried out between construction site and benchmarking point clouds. Secondly, Hausdorff distance is introduced to extract object of interest from registered point clouds.

The benchmarking point cloud is a virtual point cloud created from as-design BIM model for construction elements that are under construction on jobsite. This point cloud is noise free and includes only objects of interest that will be extracted from scan data. Hausdorff distance is used to quantifying the similarity between two arbitrary point sets without necessity to establish the one-to-one correspondence between the point clouds. In mathematics, the Hausdorff distance measures how far two subsets of a metric space are from each other, or it shows the maximum deviation between two models. Given two nonempty point sets as below:

$$A = \{x_1, x_2, ..., x_n\} \qquad B = \{y_1, y_2, ..., y_n\}$$

the Hausdorff distance between A and B defines as H (A, B). Which H (A, B) = max(h(A,B),(h(B,A))
Where:

$$h(B,A) = \max_{y \in B}\left(\min_{x \in A}\|y - x\|\right) \quad h(A,B) = \max_{x \in A}\left(\min_{y \in B}\|x - y\|\right)$$

h (A, B) and h (B, A) are one-sided value from A to B and from B to A, respectively. In most engineering applications, the number of point sets obtained by 3D model is not identical, and it is difficult to establish one-to-one correspondence between the point clouds. Hence, the Hausdorff distance is suitable for measuring similarity between 3D models in engineering practices [30, 33].

The Hausdorff distance is used to filter the as-built point cloud against a benchmarking point cloud in this study as well. Following the Hausdorff distance, the RANSAAC shape detection algorithm is also applied to remove unnecessary points remained in the result of Hausdorff distance. Finally, the cleaned point cloud as a result of RANSAAC algorithm is converted to a BIM model called as-built BIM. The as-built BIM is later used in comparison with as-planned BIM model to indicate the status of activities and obtain progress percentages.

3.2 Progress Monitoring

Work progress is also monitored in two stages: determining the status of activities and calculating progress percentages based on take-off quantities.

The as-built and as-planned models are registered in same coordinate system using Autodesk Revit's shared coordinate system to determine status of activities in terms of ahead of schedule, behind of schedule or on schedule. Three different colors are used for color coding as below: red color is used to indicate behind of the schedule activities. Blue Color is used to indicate on schedule activities. No color or white color is used to indicate ahead of schedule activities. Python scripting and Dynamo visual programming were used to perform the task.

Following determining the status of activities, Dynamo visual programming is used to obtain volumes of the as-built elements and transferred it to Excel

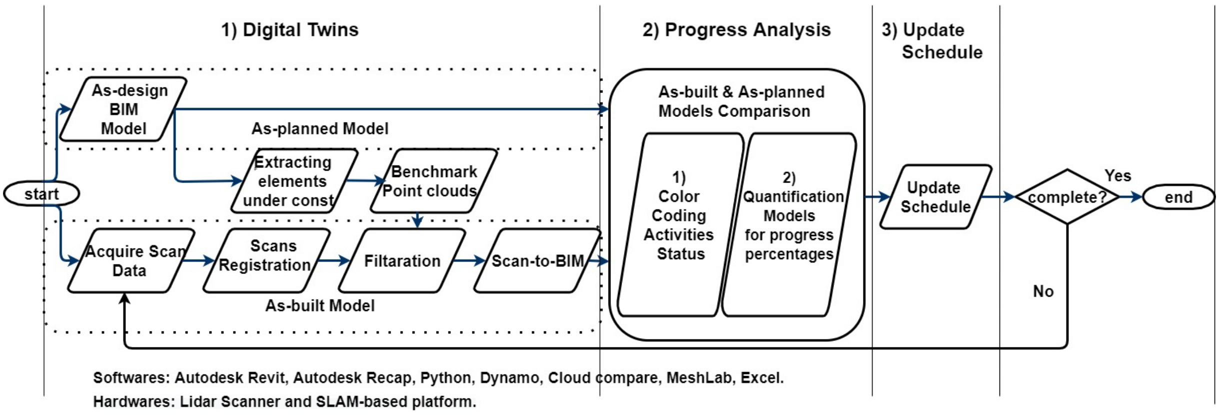

Figure 1. Proposed research methodology.

spread sheet. The obtained volumes are used in comparison with as-planned BIM model volumes to calculated progress percentages. A unique element ID is assigned to each element which contributes to both Python and Dynamo programming as well as calculating progress percentages.

4 Case Study

This case study was carried out in Civil Engineering Building (H20) at the University of New South Wales (UNSW). The study included two rooms, meeting room and its associated kitchen, each with an area of 58.78 m^2 and 21.56 m^2 respectively. The primary goal of performing the research in an existing structure is to validate the methodology. The as-designed model, which is a complete 3D BIM model of the building as shown in **Figure 2**, was produced in Autodesk Revit 2020 using correct room dimensions measured by hand with a tape measure. Site scan data were collected by Geo-SLAM ZEB-REVO laser scanner as shown in **Figure 3**.

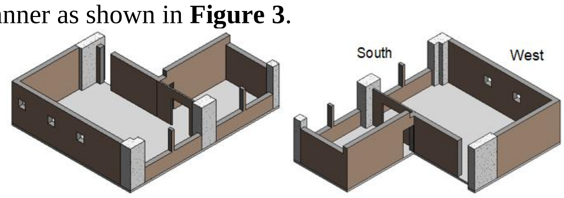

Figure 2. Two different views of as-designed BIM model of building H20, room 402 at UNSW.

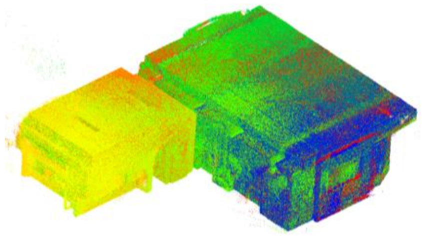

Figure 3. Point cloud data produced by the mobile handheld scanner for room 402 building H20 at UNSW.

The Geo-SLAM ZEB-REVO laser scanner is handheld, lightweight, and easy to use scanner that can perform a fully automatic scan. This laser scanner has maximum range of 30m, scan rate of 43200 points/s and relative accuracy of 1-3 cm. The SLAM condition is also shown in color scale from blue to red as good to poor respectively [34]. The color was not considered in process of point cloud in this case study. The scan data were collected in less 10 minutes for the case study.

The progress of the work is measured by comparing the as-built and as-planned BIM models. The as-planned model is a subset of the as-designed BIM model that is intended for construction within a certain time frame. The as-built model is developed using scan data to show the construction site's status. It is assumed that an accurate as-designed BIM model exists, which is modified on a regular basis with change orders and contract modifications.

The study's focus is limited to the progress of the walls. Hence, the scan data was manipulated into four different cases to measure progress in different time periods. These four cases are: 1) not started with no progress; 2) partly completed with progress until the floor of larger windows on the south side of the building; 3) work progress until the floor of small windows on the west side of the building and 4) completed with 100% progress. Scan data for second and third cases shown in **Figure 4**.

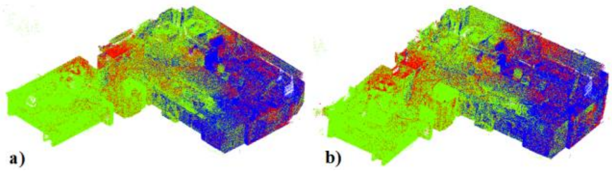

Figure 4. Simulated point cloud data: (a) second case: work progress until the floor of windows on the south side of the building; and (b) third case: work progress until the floor of windows on the west side of the building.

4.1 Filtration and As-built BIM

A benchmark point cloud of walls was generated from as-design BIM model in Cloud Compare followed by coarse and fine registration with side scan data as shown in Figure 5 (a). Hausdorff distance was implemented in MeshLab to filter out noise and additional construction elements in the scan data such as columns, floor, ceiling, and furniture. Figure 5**Figure 5** (b) depicts the result of Hausdorff distance.

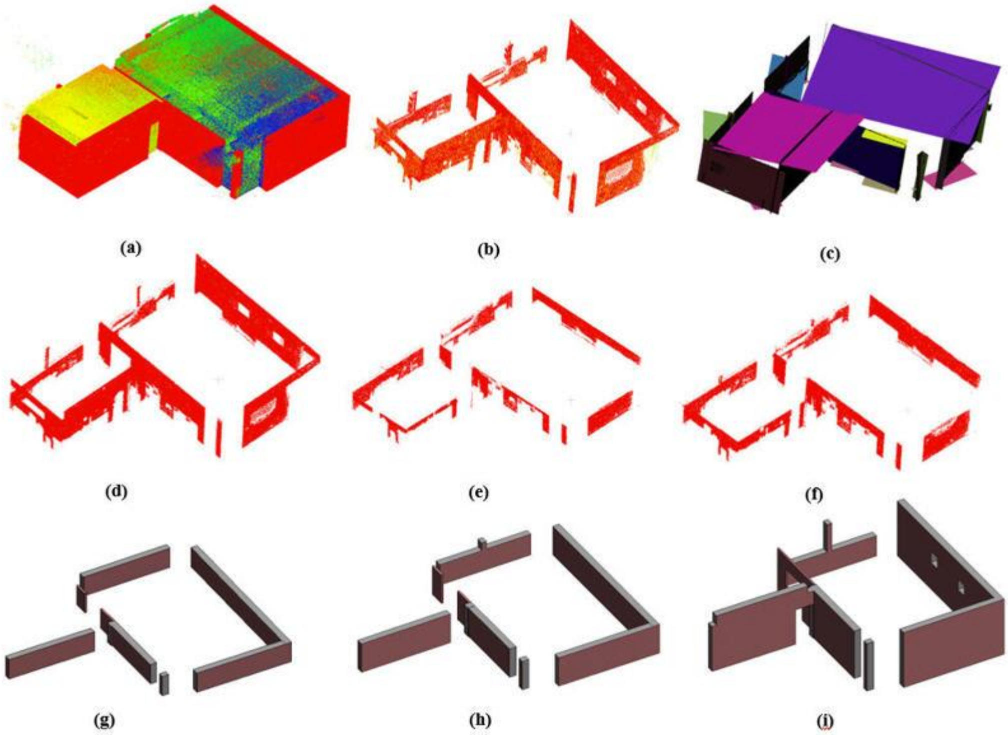

Figure 5. Procedures of data processing: (a) Point clouds registration: red is benchmarking point cloud and RGB is site scan; (b) Result of Hausdorff distance; (c) Planes detection using RANSAAC algorithm; (d) Fourth case: result of RANSAAC algorithm; (e) Second case: result of RANSAAC algorithm; (f) Third case: result of RANSAAC algorithm; (g) Second case: as-built BIM; (h) Third case: as-built BIM; and (i) Fourth case: as-built BIM.

RANSAAC shape detection algorithm from Cloud Compare was also applied to eliminate residual noise from the result of Hausdorff distance. Figure 5 (c) shows the RANSAAC detected planes for both interested objects and residual noise. The residual noise in the shape of planes is removed and required planes are kept only. The product of the RANSAAC application is a cleaned point cloud that is ready to be converted to as-built model as shown in Figure 5 (d). Parts (e) and (f) display the results of RANSAAC algorithm applied to the remaining other two partially completed cases. The as-built BIM models for the three separate cases were produced manually in Autodesk Revit 2020 considering the worst cases as shown in [Figure 5. (g, h, i)] respectively.

4.2 Status of Activities and Progress Percentages

The status of activities related to the construction schedule is determined by comparing as-built and as-planned BIM models. Since the research was performed on an existing structure, the following two assumptions were considered in the case study: 1) two as-built BIM model walls were approved as not yet completed or behind schedule, and 2) two as-built BIM model walls were accepted ahead of schedule. As-built and as-planned BIM models were registered in same coordinate system using Autodesk Revit shared coordinate system. Color codes were produced using Python script and Dynamo, as shown in Figure 6. Red elements indicate activities that are behind schedule, blue walls indicate activities that are on schedule, and no color or white color indicates activities that are ahead of schedule.

All the elements were assigned a unique ID starting at 100. The ID aids in comparison, data transfer to another environment, and schedule updates. To measure the progress percentages, the volumes of elements were transferred and compared to as-planned volumes, as shown in Table 1. A simple proportion was caried out considering as-planned values 100% complete in comparison. Activities 100,200,700 and 800, which are behind of schedule (B.S) and ahead of schedule (A.S) cannot be used in comparison. Hence, the progress is calculated for ongoing activities in different cases only. Ahead of schedule (A.S) activities could be used if the comparison is performed with as-designed model, which will be considered in future improvement.

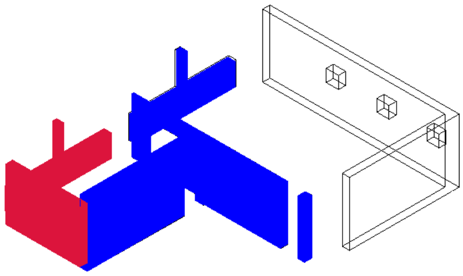

Figure 6. Status of activities in the fourth case.

The total accuracy of the work is calculated by calculating the errors in each wall in all cases. In calculating progress percentages, the errors are either increment or decrement. It is worth noting that the scanning device's accuracy is not covered in this case study. Because of the increase or decrease in values, the absolute values of errors are taken. Subsequently, the average and total average values for all the errors are determined. Finally, as shown in Table 1., the total accuracy is calculated.

5 Discussion

The case study revealed that the new method of progress monitoring using Hausdorff distance and as-built BIM can be used for completed and partially completed activities. This approach used a handheld scanner to collect data, which reduced the amount of noise as well as the time spent in registering multiple scans. The use of a mobile scanner and as-built BIM in progress monitoring, according to this report, not only improves measurement precision, but also contributes to resuming postponed projects, COVID-safe working, procurement preparation and a variety of other benefits.

The novel approach used in this study, which combined algorithms and modern technology, can provide the following advantages. These advantages include quickly extracting objects of interest, showing activity status, and obtaining progress percentages that assist project managers not only in assessing job progress but also in other phases of the project life cycle. In addition, using mobile scanner minimizes the drawbacks of photogrammetry and static laser scanning approaches.

The study like other research works, has some limitations. Some parts of the study such as registration, creating as-built BIM models in Autodesk Revit, and registering as-built and as-planned models in the same coordinate system, are still done manually. In addition, since Autodesk Revit does not allow to overriding color on a link model, the activities that are ahead of schedule are not colored as shown in Figure 6.

Table 1. Progress percentages and accuracy calculation

Accuracy calculation													
Activity Description		**As-planned Model Volumes (m^3)**				**As-built Model Volume (m^3)**				**Work Progress (%)**			
Activity ID	**Activity Name**	**Case 1**	**Case 2**	**Case 3**	**Case 4**	**Case 1**	**Case 2**	**Case 3**	**Case 4**	**Case 1**	**Case 2**	**Case 3**	**Case 4**
100	Wall 35 cm	0	1.86	1.89	1.96	B.S	B.S	B.S	B.S	0	B.S	B.S	B.S
200	Wall 35 cm	0	1.42	1.92	3.26	B.S	B.S	B.S	B.S	0	B.S	B.S	B.S
300	Wall 35 cm	0	1.90	2.59	5.52	0	1.88	2.79	5.4	0	98.97	107.72	97.82
400	Wall 35 cm	0	1.65	2.22	3.96	0	1.76	2.3	3.75	0	106.88	103.76	94.70
500	Wall 10 cm	0	0.23	0.31	0.66	0	0.23	0.31	0.62	0	100.49	100.05	93.94
600	Wall 35 cm	0	1.86	1.89	1.96	0	1.93	2.02	2.05	0	103.79	106.88	104.6
700	Wall 35 cm	A.S	A.S	A.S	A.S	0	3.75	5.22	9.68	A.S	A.S	A.S	A.S
800	Wall 35 cm	A.S	A.S	A.S	A.S	0	1.97	2.81	5.45	A.S	A.S	A.S	A.S
Activity Description		**Errors in Each Case (100-pregess of case)**				**Errors Absolute Value**				**Average Absolute Values**		**Total Average**	**Total Accuracy**
Activity ID	**Activity name**	**Case 1**	**Case 2**	**Case 3**	**Case 4**	**Case 1**	**Case 2**	**Case 3**	**Case 4**				
100	Wall 35 cm	0	B.S	B.S	B.S	0	B.S	B.S	B.S	B.S		4.1	95.9
200	Wall 35 cm	0	B.S	B.S	B.S	0	B.S	B.S	B.S	B.S			
300	Wall 35 cm	0	1.03	-7.72	2.18	0	1.03	7.72	2.18	3.64			
400	Wall 35 cm	0	-6.88	-3.76	5.3	0	6.88	3.76	5.3	5.31			
500	Wall 10 cm	0	-0.49	-0.05	6.06	0	0.49	0.05	6.06	2.20			
600	Wall 35 cm	0	-3.79	-6.88	-4.6	0	3.79	6.88	4.6	5.1			
700	Wall 35 cm	A.S	A.S	A.S	A.S	A.S	A.S	A.S	A.S	A.S			
800	Wall 35 cm	A.S	A.S	A.S	A.S	A.S	A.S	A.S	A.S	A.S			

6 Conclusions

Construction progress is still measured manually, which is biased and error prone and has negative impact on project success in terms of time, cost, quality, and safety. This research work with a novel method addresses this problem to obtain the accurate and reliable progress of work in terms of percentages.

The method was evaluated on real scan data in a case study, with various elements such as floors, columns, furniture, and kitchen items assumed as noises, yielding the following advantages.

Utilizing Geo-SLAM mobile scanner in progress monitoring system helps to gather data in different environments, reduces number of allocated resources, time and costs, and contributes to resuming projects and safe working environment. In addition, integrating Hausdorff distance and benchmarking point cloud makes it simple to remove noises and redundant elements from scan data to obtain objects of interest.

Project stakeholders could also see the status of the activities in visual format, and reliably calculate work progress in percentages, which is challenging task in traditional approach. The obtained progress percentages could also be used for automatic schedule updates, procurement management, contract dispute resolution, and project resumption after a breach of contract.

In future work, shortening filtration process, overriding a color to ahead of schedule activities, and application of the methodology in other tasks will be studied.

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