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Dynamic Progress Monitoring of Masonry Construction through Mobile SLAM Mapping and As-Built Modeling

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Abstract: Traditional progress monitoring can be inaccurate and time-consuming, potentially causing time delay and cost overrun in construction projects. With development in technology, tools such as cameras, laser scanners, and building information modelling (BIM) have been used to overcome existing problems in the traditional approach. However, noise mitigation, extracting objects of interest from laser point clouds, and detailed progress measurement are problems that still exist. In this study a novel method of construction progress monitoring to measure the progress percentage is presented. The study integrates the simultaneous localization and mapping (SLAM) technique with as-built BIM to gather quick and accurate construction site progress information. The Hausdorff distance is utilized to extract objects of interest and filter out noise from site-scan data. As-built and as-planned BIM models are compared using Python and Dynamo, to obtain progress percentage. A case study was conducted on a residential building located in Sydney, Australia, to validate the application of the developed method. The outcome demonstrates that utilizing the SLAM technique and Hausdorff distance are effective in mitigating noise and extracting objects of interest from site-scan data, respectively. In addition, with an accuracy of 94.67 percent in estimation, the progress percentage was obtained based on material quantities. The obtained progress percentage could also be used in updating construction schedules and assisting decision-making.

Keywords: construction progress monitoring; masonry construction; laser scanning; simultaneous localization and mapping; building information modeling; scan-to-BIM; Hausdorff distance

Citation: Ibrahimkhil, M.H.; Shen, X.; Barati, K.; Wang, C.C. Dynamic Progress Monitoring of Masonry Construction through Mobile SLAM Mapping and As-Built Modeling. *Buildings* **2023**, *13*, 930. https://doi.org10.3390/buildings13040930/

Academic Editor: Giuseppina Uva

Received: 7 February 2023
Revised: 7 March 2023
Accepted: 29 March 2023
Published: 31 March 2023

1. Introduction

Inaccurate progress monitoring can be one of the key factors affecting time and cost overrun in construction projects [1,2]. Despite recent advances in technology, the progress of work is measured traditionally, including paper-based manual data collection, which is time consuming and error-prone [3–6]. Manual data collection can also cause claims and disputes among stakeholders, and increase hazards on construction sites [1]. For instance, workers could be exposed to COVID-19 or other viruses at construction sites while collecting progress information [7].

Accurate and timely monitoring of progress reduces time, expenditure, and errors associated with traditional progress monitoring. Traditionally, 20–30% of time expended in progress monitoring is spent on data collection and updating schedules [8]. Site managers can spend 30–49% of their time collecting and analyzing site data [7]. Furthermore, more than 53% of typical construction projects are behind schedule due to inaccurate construction progress information [9]. Similarly, in a typical construction project, about 1% of the gross budget is spent on monitoring the status of construction activities [7], while approximately 66% of the construction projects suffer from cost overrun, partly due to poor monitoring [9]. Moreover, the traditional approach is labor-intensive, directly affecting project expenditure in terms of wages and other procurements [10]. In addition, data loss and poor-quality data capture frequently occur during transmission from one source to another in the traditional approach [11], which then requires data integration between interfaces to obtain the data in its original quality [12].

In recent years, different types of laser scanners have been used in the construction industry to overcome existing problems in the traditional progress monitoring approach. Construction data obtained by laser scanners is utilized, along with building information modeling (BIM), to accurately measure the work progress. BIM integrates with almost all data acquisition technologies, providing a better platform for progress monitoring [13,14]. Laser scanners capture the real condition of a construction site in minutes as point clouds. Although feasible progress has been made in previous research using laser scanners in construction progress monitoring, many technical challenges present in construction laser scanning, for instance, the arrangement of multiple scan stations to cover the entire site, time-consuming registration of multiple scans, occlusion from a static laser scanner, and the presence of noise in the point cloud.

In addition, it is challenging to effectively filter out noise and redundant elements from the site-scanned data, and to accurately estimate work progress based on material quantities. Accurate progress information can assist construction schedule updating and decision-making.

Therefore, the aim of this study is to use simultaneous localization and mapping (SLAM) and the scan-to-BIM technique to obtain an accurate and timely percentage of the progress of construction activities, which will then be used in schedule updates. The study's key contributions are a novel method utilizing mobile scanner, along with Hausdorff distance and detailed work progress percentages based on material quantities from BIM models. The mobile scanner is utilized for data collection, which improves data usability while minimizing noise, and the Hausdorff distance is applied to filter out noise and extract objects of interest from site-scan data.

The paper includes a comprehensive literature review of previous studies and the detailed methodology and framework developed in the study. The results of analysis and application of the developed methodology to a case study are also presented.

2. Literature Review

Numerous studies have been conducted in recent years to address the problems of traditional progress monitoring approach. This section incorporates information on the data capturing techniques and data-driven progress monitoring outlined in previous research works.

2.1. Reality Capture Techniques

Different approaches to data acquisition, such as image-based, laser scanning (LS), radio frequency identification (RFID), ultra-wideband (UWB), global positioning system (GPS), wireless sensor network (WSN), and unmanned aerial vehicle (UAV), have been used in the past to look at efficient and automated ways monitor the progress of construction projects. These techniques have been used for progress monitoring of cast-in-place activities on construction sites, except for GPS, UWB, and RFID, which are currently inefficient for measuring the progress of static activities [15,16].

In the image-based approach, which is also known as photogrammetry, site photographs are taken regularly to provide an as-built status of a construction site. This approach has several unresolved issues, such as the influence of severe weather on devices, light and shadow problems, occlusion, ability to cover the entire site, and frequency of images taken [10,17,18].

The laser scanning approach has higher accuracy compared to photogrammetry and has been used in the construction industry since the late 1970s. However, it was not commonly used due to its high cost and low precision; however, in the 1990s technological developments allowed the capture of comprehensive and accurate 3D data [19–21]. Although laser scanners are comprehensive and accurate compared to image-based approaches, they also have drawbacks, such as the need for several static scanners covering the entire area and improvements to accelerate the registration of multiple scans [8,17,22].

On the other hand, mobile scanners with different features compared to terrestrial laser scanners (TLSs), are emerging to try and increase the efficiency 3D scene capturing. These mobile scanners, known as SLAM-based scanners, are handheld, backpacked or trolley-based operational platforms. The SLAM-based scanners have faster data collection capacity and do not need targets for data registration. Hence, there is less occlusion in the data collection due to continuous manner of the scanners through their trajectories [23–25]. These features make them promising candidates to replace image-based approaches and static laser scanners in monitoring progress.

2.2. As-Built BIM

Building information modeling (BIM) provides an outstanding opportunity for the construction industry, since almost all data acquisition technologies can be integrated with BIM, providing an integrated platform for construction sites [18,22]. Hence, BIM can be used in different fields such as model-based take-off, construction simulation and coordination, change management, design alternatives exploration, and energy simulation [26]. Furthermore, BIM offers four dimensions, including a 3D computer model plus the pertinent schedule information, that significantly contributes to time-related issues in construction management. In a 4D BIM model, a project can be visualized at different project, activity, and operational levels, leading to the identification of problems in the project design and planning phases. Regardless of contractual parties, the visualization approach enables managers to quickly understand spatial constraints, as well as design and construction alternatives prior to commencing construction work [27].

To generate a 3D BIM model, the site-scan data need to be taken in a series of processes that include data editing, registration, and modeling [13]. The site-scan data along with a 3D BIM model is often used in two different purposes, namely scan-to-BIM and scan-vs-BIM [28]. In the scan-to-BIM technique, scan data are converted into CAD or BIM models [23]. This method can be employed during different stages of a construction project and is frequently used for existing structures, including historical buildings [29]. In the scan-vs-BIM approach, scan data are aligned with the coordinate system of a CAD model [30]. By comparing the as-built and as-planned construction data presented in BIM models, it is feasible to identify, communicate, and analyze discrepancies in the progress of a project [29]. In this study, an as-built BIM model is produced by adopting the scan-to-BIM approach.

2.3. Data-Driven Progress Monitoring

The procedure for construction progress monitoring is based on point cloud ranges from photographs to autonomous robotic mapping. Previous research work using photographs and point cloud, obtained through state-of-the-art technologies, has attempted to overcome the problems inherent in traditional progress monitoring. However, the monitoring problems have not been completely solved; new challenges associated with point clouds, such as data filtration and registration have emerged [17,30]. In this section previous research has been reviewed and categorized into three groups as described below.

First, some research papers have shown work progress as a percentage based on recognized objects in 3D point cloud, which is challenging in some areas. For instance, Bosche et al. [29,31,32] proposed a method in which the time-stamped 3D laser scan data and 3D CAD models are used to calculate progress. The method shows progress percentages based on the number of recognized objects in the scanned data and is not able to recognize the work that is ahead of schedule. In a similar study conducted by Turkan et al. [19], the measurement of progress of a cast-in-place concrete building was achieved as a percentage using the number of recognized objects in the scanned data. In addition, Turkan et al. [33] added earned value to the same method used in their previous studies, where a 4D model is linked with the cost account to create a 5D model recognition system. Here, each object is converted to its earned value to improve the accuracy of progress tracking. Although the result was improved in terms of progress percentage, the principle of the system is based on the number of objects recognized. Furthermore, Turkan et al. [34] studied the applicability of their method in secondary and temporary objects in a concrete construction project. Their study showed a feasible finding, but it is envisaged that superior results could be achieved if additional cues, such as color and 3D edge information, are used. Similarly, Bosche et al. [21] applied the object recognition system in mechanical, electrical, and plumbing (MEP) systems. The result of the study indicated that the proposed system is challenged when tracking MEP infrastructure constructed using traditional on-site fabrication; changes or adjustments made on-site can lead to variation in the component layouts compared to the designed layouts. In another study conducted by Reja et al. [35], work progress is also measured as a percentage based on the number of points in as-built and as-designed data. The accuracy of this method has not been determined and the status of activities, such as being ahead of schedule, on schedule, and behind schedule, has also not been shown.

Another characteristic that has been utilized in earlier research to show the status of the task is color-coding, which is not detailed. For instance, Golparvar-fard et al. [10,36] utilized color codes for progress monitoring with three colors to indicate the status of activities compared with the plan. In these two studies, a 4D BIM model, time-lapsed photographs, and unordered daily photographs were used within an augmented reality (AR) environment. Industry foundation classes (IFCs), the as-planned model and the work breakdown structure (WBS) in the schedule are considered the basis of monitoring in this approach. Similarly, Golparvar-fard et al. [37] used an enhanced approach for visualization of project progress, using daily photographs and an IFC-based 4D model. Kavaliauskas et al. [38] integrated a 3D point cloud with an IFC-based BIM model to measure and depict the progress of work using color codes and object global IDs. The drawback of this study is the identification of incomplete objects as built components on the jobsite. The use of earn value concepts in 5D progress tracking of building activities was also examined by El Qasaby et al. [16]. In this study, color coding was employed to represent each element's condition in accordance with its recognition and scheduling state. Although the color-code used to indicate progress is not detailed, several columns were not recognized by the device due to obstruction in its line of sight.

In the third group, the progress of the work was shown with a focus on elements or types of work either ahead of or behind schedule. For instance, Pučko et al. [39] used point cloud obtained in a continuous manner from a construction site. In this study, the progress of work was shown as a list of elements that were ahead or behind schedule, utilizing a comparison of as-built and as-designed BIM models.

Although feasible progress has been made in previous research, the issues of removing noise and redundant elements from site-scanned data, measuring work progress as a percentage based on material quantities, and progress of partially completed activities exist as a research gap, which needs to be further scrutinized. This study presents a novel method that contributes to effectively removing noise and redundant elements by the application of a mobile scanner and Hausdorff distance, and obtaining detailed work progress percentages based on material quantities, which is also applicable to partially completed activities.

3. Methodology

A comprehensive methodology with three primary phases, that serve as a broad framework for progress tracking, has been developed and is shown in Figure 1. Phase one includes data collection, processing, and point cloud conversion to the as-built BIM model. Data are gathered using a SLAM-based mobile scanner to perform a complete scan of the construction site, which saves the time spent on the registration of point clouds. Due to its mobility, the mobile scanner also mitigates sight occlusion. The site-scan data are registered with benchmarking point cloud, using coarse and fine registration to perform filtration.

The Hausdorff distance is then applied to acquire the objects of interest and filter out noise and redundant elements from the site scans.

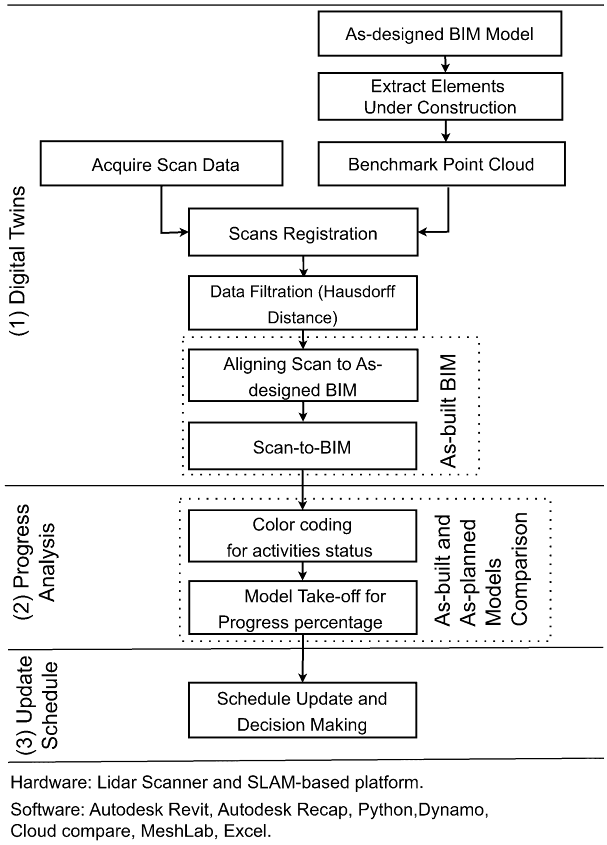

Figure 1. Proposed research framework for monitoring progress of construction projects.

Phase two contains progress analysis of the filtered point cloud from phase one. Work progress is shown in two steps: by color-coding and progress percentage. The progress percentage is calculated based on material quantities that are obtained from as-designed and as-built BIM models using Dynamo and Python. Phase three provides automatic schedule updates based on the percentage of progress.

This study is a continuation of previous research work published by the authors [40]. The improvements include a change in methodology by not using RANSAAC algorithm, color coding of the as-planned and as-built BIM models based on the status of activities using Python and Dynamo, and application of the methodology on a real construction site. More details of the methodology are provided in the following sections.

3.1. Data Filtration and As-Built BIM

Often, the point cloud obtained from construction sites includes noise and redundant elements due to the use of static laser scanners or occlusions on the construction sites. Hence, removing noise and detecting objects of interest is a challenging issue while processing point clouds to measure the progress of the work. In this study, Hausdorff distance and benchmarking point cloud have been used to filter out noise and redundant elements from site-scan data. The benchmarking point cloud is a virtual point cloud created from an as-designed BIM model for specific surfaces of the objects of interest, using Dynamo and Cloud Compare. The scanner captures the surfaces of the elements in point cloud; therefore, a benchmarking point cloud is also created for specific surfaces of the elements as well. Benchmarking point cloud and site-scan data are registered in the same coordinate system for filtration purposes, using coarse and ICP algorithms.

Hausdorff distance is applied on the registered point clouds to filter out noise and redundant elements from the site-scan data. 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, as shown in Equation (3). Given the two nonempty point sets, shown in Equations (1) and (2), the Hausdorff distance between A and B, defined as H (A, B), is shown in Equation (4).

$$A = \{x_1, x_{21}, \ldots, x_n\} \tag{1}$$

$$B = \{y_1, y_2, \ldots, y_n\} \tag{2}$$

$$h(B, A) = \max_{y \in B}\left(\min_{x \epsilon A}\|y - x\|\right),\ h(A, B) = \max_{x \in A}\left(\min_{y \epsilon B}\|x - y\|\right) \tag{3}$$

$$H(B, A) = \max(h(A, B),\ h(B, A))\ , \tag{4}$$

where h(A, B) and h(B, A) are one-sided values from A to B and from B to A, respectively. In most engineering applications, the number of point sets obtained by a 3D model is not identical, making it difficult to establish one-to-one correspondence between the point clouds. Therefore, the Hausdorff distance is suitable for measuring the similarity between 3D models in engineering practice [41]. In the current study the site-scan data are filtered by Hausdorff distance against a benchmarking point cloud to get similarity between the two-point clouds.

To create an as-built BIM model, the as-designed BIM model is modified based on the result of filtration. The filtered point cloud is aligned with the as-designed BIM model in Autodesk Revit to create an as-built BIM model. Generating the as-built BIM based on modification of the as-designed BIM model speeds up creating the as-built BIM and reduces errors in the process. The as-designed BIM is a complete model created prior to commencing the construction work, and serves as a blueprint for the construction activities. In this study, the as-designed BIM model is assumed to be accurate and modified regularly according to contractual modifications and change orders.

3.2. Progress Monitoring

The progress analysis phase includes two steps: the activity status and the progress percentage based on material quantities. The activity status, which is color-coded, is important for project managers and other stakeholders to understand the progress of the work at a glance. In addition, a color-code model could serve as a 3D construction schedule for non-engineers. To indicate activity status with different colors, the as-built and as-planned BIM models are compared in Autodesk Revit using Python and Dynamo. Green, red, and orange colors are used for on schedule, behind schedule, and ahead of schedule activities, respectively. A unique element ID is assigned to every element of the as-designed and as-built BIM model contributing the Python and Dynamo programs to color models, automatically calculate progress percentage and update the construction schedule. The same ID is assigned to the as-built BIM model through modification of the as-designed BIM model.

Accurately assessing the percentage of progress is a crucial item in construction schedule updating and decision-making. The progress percentage in this study is automatically calculated based on material quantities obtained from BIM models using Dynamo. The obtained quantities from the as-built BIM are compared with the available quantities from as-designed and as-planned BIM models to calculate progress percentages. The progress percentages are then calculated considering the as-designed quantities as 100 percent complete, as shown in Equation (5).

$$\text{Progress percentage} = \frac{\text{As} - \text{built quantities}}{\text{As} - \text{design quantities}} \cdot 100 \quad (5)$$

The accuracy of the method is calculated based on actual values and estimated values using the error percentage method. Error percentages are calculated by considering the actual progress percentage on the construction site and progress that has been made according to the scanned data, as shown in Equation (6). The total accuracy of the method is obtained by calculating the average values of error percentage in each round of scans.

$$\text{Percent error} = \left| \frac{\text{Estimated value} - \text{Actual value}}{\text{Actual value}} \right| \cdot 100 \quad (6)$$

4. Case Study

A case study was conducted on the construction of a brick veneer granny flat with an area of 56.51 m^2 located in the Quackers Hill suburb of Sydney, Australia. The study includes creating a 3D as-designed model of the building, filtering site-scan data based on benchmarking point cloud, and the calculation of progress percentages according to obtained material quantities. Scaffolding around the building, timber elements inside the building, and other elements in the vicinity of the building are considered as noise in the data filtration. The as-designed 3D BIM model of the property was created in Autodesk Revit, using the exact dimensions from the 2D drawings, as shown in Figure 2.

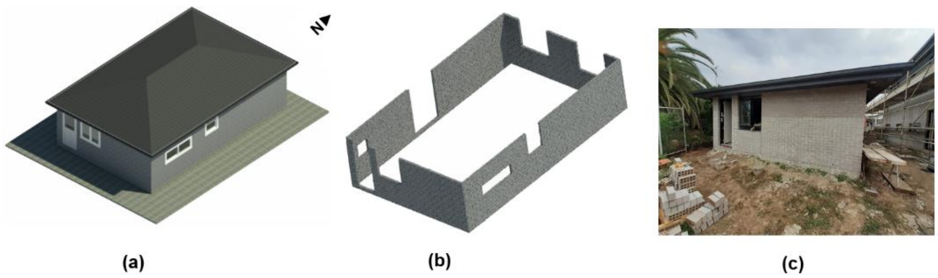

Figure 2. As-design and actual models: (**a**) as-designed BIM model; (**b**) as-designed walls only; (**c**) actual model under construction in which scaffolding, roof and other objects are accepted as noise.

4.1. Data Collection and Filtration

Data from the construction site were collected with a 3D mobile laser scanner, the Geo-SLAM ZEB-Revo, which has the maximum range of 30 m, a scan rate of 43,200 points/s, and a relative accuracy of ±1–3 cm [42]. The Geo-SLAM is a high mobility scanner that can be mounted on any mobile platform and performs a fully automatic scan, as shown in Figure 3. Utilizing the Geo-SLAM mobile scanner reduces both the number of scans and time spent on the registration of scans compared with those that are acquired with terrestrial laser scanners. Although the accuracy of Geo-SLAM ZEB-Revo is less than terrestrial laser scanner [43], it is suitable for obtaining quicker and full scans of the construction site. In addition, noise in the scanned data is also mitigated by utilizing Geo-SLAM ZEB-Revo due to its mobile condition compared with a static terrestrial laser scanner. The output of the Geo-SLAM has several options, including color-scanned data, which shows the SLAM condition and time of scan [42].

A total of six scans, each with a time of less than 10 min, were performed to cover the entire progress of the work in this study. The collected site scans were registered with the benchmarking point cloud using coarse and fine registration. Since the scan data from sites always contains surfaces of the focused elements (exterior surfaces of walls in this study), the benchmarking point cloud was also generated for the exterior surfaces of the elements, as shown in Figure 3b. The idea behind using benchmarking point cloud is to get similarity between the two types of point clouds, the site-scan data and benchmarking point cloud, and remove noise and redundant elements. The benchmarking point cloud is clean, as it is generated from the as-designed BIM model and includes only the elements that are under the construction process.

The Hausdorff distance with a threshold of 0.02 m was then applied to obtain similarity and remove noise and redundant elements from the site-scanned data. For all the six scans, the Hausdorff distance was used to eliminate noise and obtain similarity (see Figure 3d–i). Different thresholds of 0.01 m, 0.02 m, 0.03 m, 0.04 m, 0.05 m, and 0.1 m were used; the 0.02 m threshold was accepted due to clean and complete result of filtration.

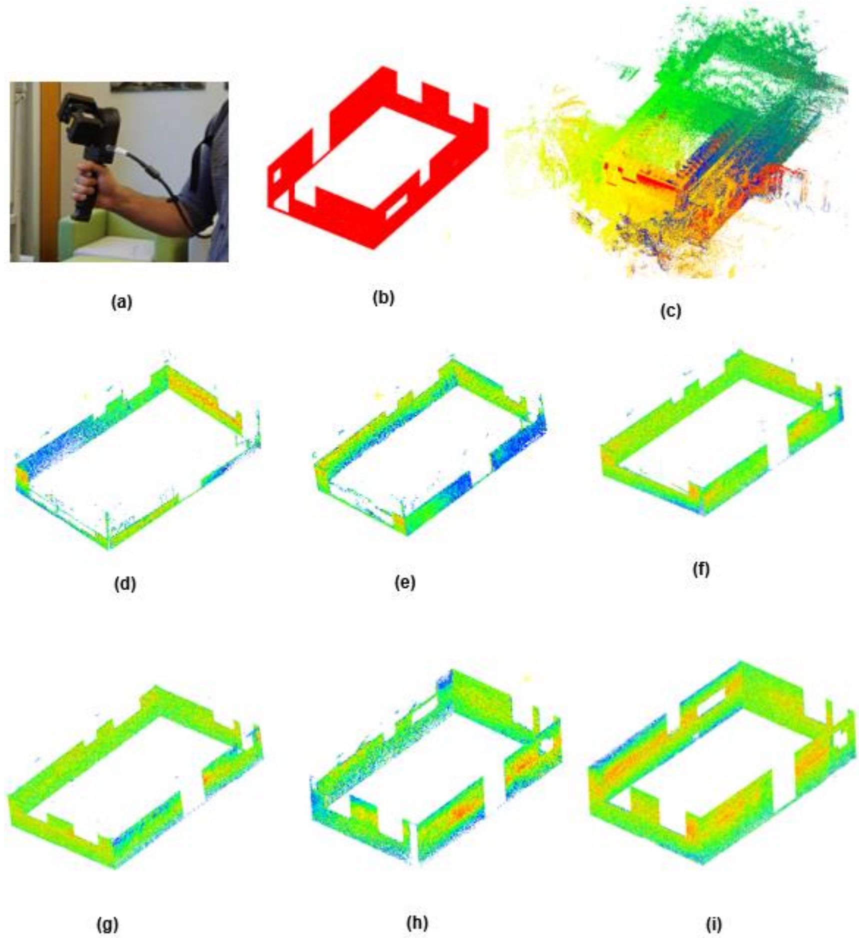

Figure 3. Site scan and filtration result: (**a**) Geo-SLAM ZEB-Revo scanner; (**b**) benchmarking point cloud for exterior surfaces of walls; (**c**) registration of site scan and benchmarking point cloud; (**d**) result of filtration, first scan; (**e**) result of filtration, second scan; (**f**) result of filtration, third scan; (**g**) result of filtration, fourth scan; (**h**) result of filtration, fifth scan; (**i**) result of filtration, sixth scan.

4.2. As-Built BIM

The as-built BIM models were constructed based on filtered point clouds and modification of the as-designed BIM model. The as-designed BIM model is aligned with the filtered point cloud and modified to create an as-built BIM in Autodesk Revit 2018. Modification of as-designed BIM model simplifies the process of creating as-built BIM and improves the accuracy of the work. A total of six as-built BIM models are included in this case study to highlight the gradual progress of the work, as shown in Figure 4.

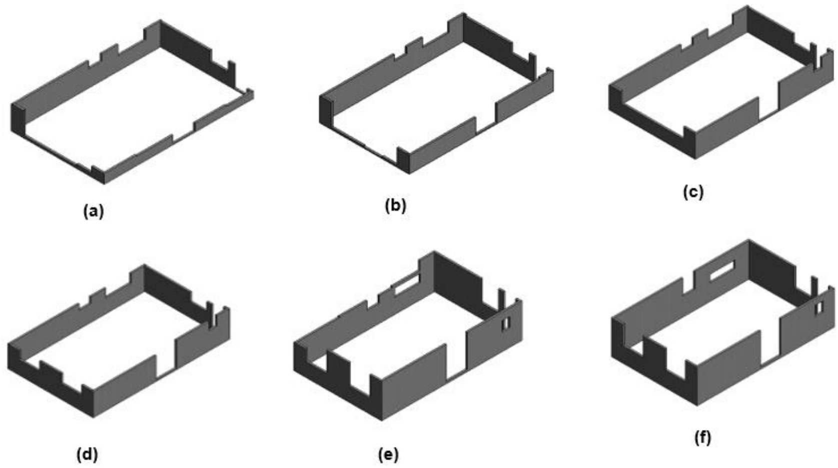

Figure 4. As-built BIM models: (**a**) first round of scan; (**b**) second round of scan; (**c**) third round of scan; (**d**) fourth round of scan; (**e**) fifth round of scan; (**f**) sixth round of scan.

4.3. Progress Calculation

Work progress is shown in two steps: the activity status and progress percentages. To indicate the activity status using different colors, the as-planned and as-built BIM models were compared in Dynamo using unique IDs. The as-planned BIM model is that portion of the as-designed BIM model that is expected to be built in a specific time interval. Three different colors, green, red, and yellow, were utilized to indicate on-schedule, behind-schedule and ahead-of-schedule activities. Activities that are available in the as-planned BIM model, but not in the as-built BIM model, are behind the schedule and are shown with a red color. Similarly, activities that exist in the as-built BIM model, but not in the as-planned BIM model, are ahead of the schedule and indicated in yellow. On-schedule activities are highlighted in green and are available in both the as-planned and as-built BIM models.

A unique activity ID, starting from 100, was assigned to every element of the as-designed BIM model and later to the as-built BIM model through modification, which assists the algorithms. The unique ID is used to execute the algorithms, and assist the identification of elements both in comparison and material take-off, as well as in the construction schedule update.

The working strategy for the current construction site was performed in two steps. First, work on all the walls up to scaffolding height, and then complete the remaining walls once the scaffolding is in place. Since all the walls were under construction at the same time, the as-designed model was the same as the as-planned model; this was used for comparison with the as-built models to indicate the status of the activities. A three-color system is used to show the status of activities: green, red, and orange are used to indicate on-schedule, behind-schedule, and ahead-of-schedule activities, respectively. The result of color-coding shows the work on schedule in green, as work on all walls was carried out at the same time and none of the activities were behind or ahead of schedule. Due to the similarity of all the rounds of scans, the color code for the first round of the scan is shown as an example in Figure 5.

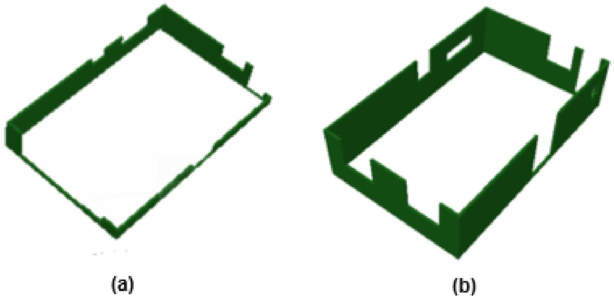

Figure 5. Activities status: (**a**) as-built BIM model of the first round of scan; (**b**) as-designed BIM model.

The progress percentage was calculated based on material quantities obtained from the as-built BIM and the as-designed BIM models using Python and Dynamo programs. The actual quantities from the construction site were also calculated manually, as shown in Table 1. The progress of the work was calculated for each activity using Equation (5) as below.

$$\text{Progress percentage} = \frac{\text{As} - \text{built volumes}}{\text{As} - \text{design volumes}} \cdot 100$$

Table 1. Construction progress calculation.

Activity ID	Activity Name	As-Design Quantities (m^3)	As-Built Quantities (m^3)	Actual Quantities (m^3)	Percentage from Scan	Actual Percentage
			First round of scan			
100	Southern Wall	1.209	0.68	0.71	56.24	58.73
200	Western Wall	2.162	0.492	0.52	22.76	24.05
300	Northern Wall	1.143	0.265	0.2	23.18	17.50
400	Eastern Wall	2.386	1.487	1.48	62.32	62.03
			Second round of scan			
100	Southern Wall	1.209	0.784	0.8	64.85	66.17
200	Western Wall	2.162	1.049	1.1	48.52	50.88
300	Northern Wall	1.143	0.277	0.26	24.23	22.75
400	Eastern Wall	2.386	1.564	1.48	65.55	62.03
			Third round of scan			
100	Southern Wall	1.209	0.808	0.82	66.83	67.89
200	Western Wall	2.162	1.466	1.52	67.81	70.10
300	Northern Wall	1.143	0.666	0.65	58.27	56.74
400	Eastern Wall	2.386	1.52	1.48	63.70	62.03
			Fourth round of scan			
100	Southern Wall	1.209	0.848	0.83	70.14	68.26
200	Western Wall	2.162	1.542	1.46	71.32	67.74
300	Northern Wall	1.143	0.85	0.84	74.37	73.37
400	Eastern Wall	2.386	1.55	1.48	64.96	62.03
			Fifth round of scan			
100	Southern Wall	1.209	1.182	1.21	97.77	100.05
200	Western Wall	2.162	2.157	2.19	99.77	101.16
300	Northern Wall	1.143	1.057	1.09	92.48	95.23
400	Eastern Wall	2.386	1.812	1.72	75.94	71.92

Table 1. *Cont.*

Activity ID	Activity Name	As-Design Quantities (m^3)	As-Built Quantities (m^3)	Actual Quantities (m^3)	Percentage from Scan	Actual Percentage
			Sixth round of scan			
100	Southern Wall	1.209	1.205	1.24	99.67	102.60
200	Western Wall	2.162	2.166	2.20	100.19	101.64
300	Northern Wall	1.143	1.149	1.20	100.52	105.38
400	Eastern Wall	2.386	2.391	2.38	100.21	99.63

To obtain accuracy of the method, an error percentage was calculated based on actual and estimated values for each activity, as shown in Equation (6).

$$\text{Percent error} = \left|\frac{\text{percentage from scan} - \text{percentage actual}}{\text{percentage actual}}\right| \cdot 100$$

The total accuracy was obtained by 100 minus the total average error percent as shown in Table 2.

Table 2. Total accuracy calculation.

Activity Description		Error Percentages in Each Scan						Total Values	
Activity ID	Activity Name	First Scan	Second Scan	Third Scan	Fourth Scan	Fifth Scan	Sixth Scan	Total Average	Accuracy
100	Southern Wall	4.23	2	1.56	2.75	2.29	2.86	5.33	94.67
200	Western Wall	5.38	4.64	3.27	5.29	1.38	1.43		
300	Northern Wall	32.50	6.54	2.69	1.36	2.89	4.61		
400	Eastern Wall	0.00	5.68	2.70	4.73	5.60	0.58		
Average		10.53	4.71	2.55	3.53	3.04	2.37		

5. Discussion and Limitations

This work demonstrates that the methodology proposed can be effectively applied in any noisy environment and progress percentages obtained based on material quantities. The construction site in the case study includes noise and redundant elements, which were removed effectively using the Hausdorff distance and benchmarking point cloud, as shown in Figure 3. Since the Hausdorff distance establishes the similarity between the two sets of point cloud, any point in one set of the point cloud that does not match another point in the targeted set of point cloud in a specific threshold is considered as noise and is removed. Benchmarking point cloud for the outer surfaces of the walls was used as a targeted set of points in data filtration, removing additional points from site scans considered to be noise and redundant elements. This procedure not only removes noise and redundant elements, but detects objects of interest in site scans as well.

Measuring the gradual progress of masonry work is a significant issue for construction schedule updates and decision-making. Therefore, the methodology developed in this study not only measures the progress of completed walls, but also effectively measures the progress of partially completed activities as well. The gradual progress of the work was calculated according to material quantities obtained from BIM models using Python and Dynamo.

It can be difficult to eliminate noise and to extract the objects of interest from point cloud, and these problems are typically best handled manually. Additionally, in previous studies the progress of the work was frequently depicted by color-coding, number of recognized objects in point cloud, status of elements being ahead or behind of schedule, without providing detailed progress information [10,29,31,32,34,36,39]. However, accurate and detailed progress information is needed for updating construction schedule and making timely decisions. Hence, in this study, objects of interest from the point cloud are successfully retrieved by applying the Hausdorff distance while considering the as-designed BIM model. In addition, detailed and accurate progress of work has also been shown in color-coding and percentage based on material quantities. Moreover, using this approach makes it possible to monitor the progress of partially complete activities as well.

Site scans using terrestrial laser scanners require several stations to scan the entire site and later register the obtained data. However, the mobile SLAM-based ZEB-Revo scanner, which was used in this study, performed a complete scan of the site and reduced the time spent on the registration of the site scans. The error of the Geo-SLAM ZEB-Revo scanner is around ±1–3 cm, but this did not have a significant impact on the result of the study due to the following reasons: the minimum progress of work in a masonry wall is often equal to the thickness of a brick or concrete masonry unit, which is larger than the 3 cm the error of the scanning device. Second, the progress of work is often measured at the end of the day, when sufficient progress has been made in a masonry wall. The major factor impacting the accuracy of the method is the conversion of the scanned data to the as-built BIM model, which was done manually. Although the as-built BIM models were created by modification of the as-designed BIM model based on filtered point cloud, aligning the filtered point cloud with the as-designed BIM model needs to be automated for higher accuracy.

The main limitation of the study is the availability of an accurate and updated as-designed BIM model that is used for generating the benchmarking point cloud and creating the as-built BIM models. Often, construction projects lack an accurate and updated 3D BIM model. However, for projects that lack an as-designed BIM model, a one-off accurate 3D BIM model of the project can be created in available software by utilizing the 2D drawings and design requirements. In this study, accurate 3D BIM models were created according to 2D drawings, as well as design requirements.

6. Conclusions

Traditional progress monitoring is time-consuming, inaccurate and error-prone. To overcome these problems, photogrammetry and static laser scanning approaches have been used in previous research. However, these approaches are also associated with some major drawbacks, such as inaccurate planning and installation of the instruments, influence of severe weather and shadow, and the need for many devices to cover the entire site. In addition, detecting objects of interest and filtration of noise from site-scan data is also challenging. The following conclusion can be drawn from this paper.

- This paper presented a novel method to monitor construction progress utilizing a SLAB-based mobile scanner instead of terrestrial laser scanner (TLS) and a scan-to-BIM approach.
- The objects of interests are effectively extracted from the point cloud data by applying the Hausdorff distance using benchmarking point cloud.
- A two-step progress analysis was used to indicate the status of activities and their detailed progress percentage. A color code was applied to indicate the status of activities to assist project managers and clients in understanding the progress of the work at a glance. The work progress percentage was obtained based on material quantities, which can be used in automatic schedule updating.
- The novel method presented in this study was applied and validated in a case study conducted on a residential building located in the Quakers Hill suburb of Sydney, Australia, and achieved an accuracy of 94.67 percent. In addition, the obtained progress percentage could also be used in decision-making, material management and resource allocation.

A future study will be conducted on other types building structures to test the validity of the method. To further evaluate the methodology applicability, it is also suggested that it be extended to various types of work, including mechanical, electrical, and plumbing (MEP); the duct system; and temporary structures, such as formwork. Additionally, manual registration of Hausdorff distance with as-designed BIM model would be greatly improved by automating the process.

Author Contributions: Conceptualization, M.H.I., methodological framework, M.H.I.; content analysis and results, M.H.I.; writing—original draft preparation, M.H.I.; writing—review and editing, M.H.I., X.S., K.B. and C.C.W.; visualization, M.H.I.; supervision, X.S. and K.B. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: The data is not available due to privacy issue.

Acknowledgments: This study was supported by the Australian government research training scholarship program. The authors are also grateful for the support provided by Core Bricks Pty Ltd. and KMK Property solutions Pty Ltd. in data collection.

Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

BIM	Building Information Modeling
GPS	Global Positioning System
ICP	Iterative Closest Point
IFC	Industry Foundation Classes
LS	Laser Scanning
MEP	Mechanical, Electrical and Plumbing
MLS	Mobile Laser Scanning
RANSAAC	Random Sample Consensus
RFID	Radio Frequency Identification
SLAM	Simultaneous Localization and Mapping
TLS	Terrestrial Laser Scanner
UAV	Unmanned Aerial Vehicle
UWB	Ultra-wideband

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