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Article

Reality Capture of Buildings Using 3D Laser Scanners

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Abstract: The urgent need to improve performance in the construction industry has led to the adoption of many innovative technologies. 3D laser scanners are amongst the leading technologies being used to capture and process assets or construction project data for use in various applications. Due to its nascent nature, many questions are still unanswered about 3D laser scanning, which in turn contribute to the slow adaptation of the technology. Some of these include the role of 3D laser scanners in capturing and processing raw construction project data. How accurate is the 3D laser scanner or point cloud data? How does laser scanning fit with other wider emerging technologies such as Building Information Modelling (BIM)? This study adopts a proof-of-concept approach, which in addition to answering the afore-mentioned questions, illustrates the application of the technology in practice. The study finds that the quality of the data, commonly referred to as point cloud data is still a major issue as it depends on the distance between the target object and 3D laser scanner's station. Additionally, the quality of the data is still very dependent on data file sizes and the computational power of the processing machine. Lastly, the connection between laser scanning and BIM approaches is still weak as what can be done with a point cloud data model in a BIM environment is still very limited. The aforementioned findings reinforce existing views on the use of 3D laser scanners in capturing and processing construction project data.

Keywords: 3D Laser Scanners 1; Point-cloud Data 2; Reality Capture; BIM; Refurbishment

1. Introduction

The construction industry is in a state of constant change as it evolves from weak productivity driven by poor management and outdated methods, to adopting new building technologies (Larsen, et al., 2016; Omar et al. 2018). In the architecture, engineering, and construction (AEC) domain, 3D models are increasingly being used to improve project management. The 3D models contain vital data associated with building projects crucial for Building Information Modelling (BIM) processes, far better than traditional construction approaches. BIM workflows provide the opportunity to organise project data, such as building geometry, construction typology, and material properties that can be used in making informed decisions (Ham and Golparvar-Fard, 2015; Sanhudo, Ramos, Martins, Almeida, Barreira, Simões, and Cardoso, 2020). While BIM facilitates the collaboration of supply chain members, the disparate backgrounds and the fact that they work on different aspects also present challenges related to data quality. Firstly, the various actors produce and capture different data at different stages of the project life cycle making it difficult to be able to obtain a complete model reflecting the project at any given time. Secondly, the different actors may decide to withhold models from others for various reasons such as professional secret or because they may not be involved in the later stages of the project. Thus, obtaining an accurate model that reflects the 'as-is condition' or 'as-built' in a project being deliver using BIM, talk less of traditional methods is hardly possible.

In recent years, major technological advances allowed for detailed three-dimensional (3D) models to represent the 'as-is condition' of buildings (Lagüela et al., 2014; Sanhudo et al., 2018). Collecting the best and most accurate data about real-world conditions often known as 'as-built' or 'as-is condition' is what is known as reality capture. 3D laser scanning is a reality capture technique. There are many reasons for real capturing of project data which include: progress monitoring during construction project phase, facility operations for maintenance work (Shalabi and Turkan, 2017), sustainability, and waste management (Jalaei, Zoghi, Khoshand, 2019; Wang & Kim, 2019). The captured data using 3D laser scanners is often called 'point cloud'.

While BIM's capability to support information creation, coordination, exchange, and application through the course of a building's lifecycle has been firmly established in the literature (Chan et al, 2019), the need for capturing 3D models or 'point cloud data' for existing buildings and civil infrastructure is becoming increasingly important and crucial for the development of the industry (Pica and Abanda, 2019). That said, digitalizing substantial amounts of geometric information, which may be outdated or even non-existent, can be overwhelming. Thus, appropriate survey techniques are required for capturing, managing, and visualizing building information are needed (Sanhudo, Ramos, Martins, Almeida, Barreira, Simões, and Cardoso, 2020).

Traditionally, as-built documentation using conventional surveying methods, such as a total station or a measuring tape, are labour-intensive, costly, and error-prone. In addition, only a portion of site elements can be monitored for practicality as traditional instruments can only provide spot measurements (Maalek, Lichti, and Ruwanpura, 2019). However, during the last decade, several new survey systems have been developed in the AEC industry to reflect different life cycles of a project (Remondino, 2011). While each of these techniques has its own advantages and limitations, it is important to understand the process from survey to 3D modelling, focusing on single precision data, overall accuracy, costs, acquisition, and processing times (Remondino et al., 2014; Guidi et al., 2014; Fassi, et al., 2013; Campi et al, 2017).

This paper first discusses recent literature then goes on to explain the methodology used for both the development of a systematic review of 3D point cloud data, laser scanning, and the survey process in section 3. It then goes on to discuss the acquisition and processing of 3D point cloud data and BIM integration. The paper finally concludes with research findings and recommended future work in section 4.

2. Related Studies

As one of the most widely used 3D imaging techniques, laser scanning is utilized for a wide range of processes including surveying, manufacturing inspection, quality control of building construction, and restoration of heritage buildings. Laser scanning devices are now integrated within numerous built environment applications (Pärn and Edwards, 2017), and are a consolidated technology for the collection, documentation, and analysis of three-dimensional data on the as-built status of buildings and infrastructure (Baladoa et al, 2018). Laser scanning, also known as high-definition surveying (HDS) or reality capture, is a means of using a laser to map an area with high accuracy. On a construction site, it is used to capture detailed data, providing accurate information for all stages of the project. The acquired data provides construction professionals with what is known as a 'point cloud', which is, a database connecting points in a 3D coordinate system. Point cloud systems keep an extremely accurate digital record of an object or space as it pertains to a project (Xiong, Adan, Akinci and Huber, 2013), and are composed of raw information that is processed to extract useful information for the applications they are intended to serve (Baladoa, et al, 2018). 3D point cloud data from 3D laser scanners are able to capture the surface geometries of target objects in an accurate and efficient manner, and provide accurate and fast records of the 3D geometries of construction-related objects (Wang & Kim, 2019).

Laser scanning has been extensively applied in conjugation with BIM to cover several aspects of construction such as monitoring (Bosché, et al., 2015; Sanhudo, Ramos, Martins, Almeida, Barreira, Simões, and Cardoso, 2020), cost estimation and quality assessment (Kim, et al., 2016), 3D visualization and spatial analysis (Chao Chen et al., 2019) in an effort to increase accuracy, reduce errors, and rework. However, to present, very little literature provides a complete framework for the acquisition of point cloud data and how it is applied in BIM, with most studies focusing on the process after the data has been exported to BIM (Sanhudo, Ramos, Martins, Almeida, Barreira, Simões, and Cardoso, 2020). In addition, the literature has shown that the demand for 3D models in the AEC industry is constantly increasing (Cheng, Han, Li, Chen, Xing, Zhao, and Li, 2018), leading to the development of various technologies that are able to capture or measure existing buildings or structures within the built environment, and then present them in 3D for modelling purposes (Cheng, Han, Li, Chen, Xing, Zhao, and Li, 2018).

Although laser scanners have been proven to provide high performance reality capture in an outdoor environment (Fryskowska et al., 2015; Cheng, Han, Li, Chen, Xing, Zhao, and Li, 2018), there is still a clear knowledge gap between the theory of laser scanning and its application for construction mapping due to technical limitations on portability and site constraints, and the cost of high-performance 3D laser scanners. Despite that increasing productivity in the construction industry could add up to $1.6 trillion USD in value (McKinsey & Research), many construction professionals are still hesitant to adopt these technologies. This is mostly due to limited knowledge, and a lack of a comprehensive framework that could assist built environment professionals during various lifecycles of a project.

Notwithstanding the numerous advantages of laser scanning such as shorter survey duration that results in the acquisition of over a million points per second, and improved accuracy that captures complex shape geometries (Lagüela et al., 2014; Fröhlich and Mettenleiter, 2004; Sanhudo, Ramos, Martins, Almeida, Barreira, Simões, and Cardoso, 2020), some limitations are still evident (Bhatla et al., 2012). These include the cost of equipment, the need for professional operators, integration with BIM systems, and the conversion of point cloud data into geometric forms that may be used to create the labelled BIM model elements (Göçer, Hua, and Göçer, 2016; Sanhudo, Ramos, Martins, Almeida, Barreira, Simões, and Cardoso, 2020). This paper attempts to investigate the theoretical and practical challenges of using laser scanners. It provides a brief literature review on the use of 3D laser scanners. Followed by a systematic review followed by a field study for surveying, acquisition, and processing of 3D point cloud for both exterior and interior spaces. Both the results of the systematic review and the case study were used to propose a framework that reviews various 3D laser scanners for data acquisition and different software platforms for 3D point cloud data processing to explore its interoperability (integration) with BIM systems.

Despite the multiple applications of laser scanning alongside BIM in the current research, most studies focused on the process after the point cloud data exportation, with little attention being given to the acquisition of the data itself. In (Tang et al., 2010; Tang et al., 2011; Hichri et al., 2012), the authors divide the process of creating as-built BIM using laser scanning in three steps: data acquisition; data processing; and BIM integration. However, in most cases, the first two steps are simply briefly discussed, with the focus on BIM modelling; similarly, in (Wang et al., 2015), the authors present a methodology for the automatic extraction of BIM components from point cloud data, with the methodology starting after the point cloud data has been acquired (Sanhudo, Ramos, Martins, Almeida, Barreira, Simões, and Cardoso, 2020). Finally, in (Wang, et al. 2015) and (Lagüela et al., 2013), the authors respectively, propose methodologies that fuse laser scanning, infrared thermography and BIM for energy analysis. The focus of both articles fall on the processes after the acquisition of the point cloud, although Lagüela et al. (2013) identify the need for three scan station positions, referring to important aspects for the registration of the acquired scans (Sanhudo, Ramos, Martins, Almeida, Barreira, Simões, and Cardoso, 2020).

Based on the systematic review, a significant number of research papers about point cloud from 3D laser scanners have been published in the past decade. However, most of the earlier publications have been about point cloud applications in the industrial and manufacturing sector. It has only been recently that point cloud applications have gained momentum in the construction industry. Therefore, the literature search was mainly focused on the last five years, corresponding to the period where much interest in the automation of construction processes has been focused. An attempt to summarize the evolution of research in 3D point cloud and 3D laser scanning through a systematic review from academic papers published from 2015 to 2020 is undertaken.

3. Materials and Methods

This paper has been developed based on a 3 step methodology: Systematic Review; Field Survey (Point Cloud Model development), and Framework proposal. A systematic review of literature is adopted in order to identify knowledge gaps which is further supported by a field survey. The survey was conducted using a 3D laser scanner which was followed by point cloud processing and BIM integration. The proposed framework was then developed from the knowledge and data acquired from both methods. The hardware and software with well-documented interoperability were chosen for the field survey. The Trimble TX8 laser scanner was used for the point cloud data acquisition, as it allows for simple surveying with a high degree of accuracy. Realworks and Autodesk Revit, were utilized to provide a greater understanding of the acquired point clouds and their relationship with BIM modelling. The details of the methods are discussed in the ensuing sections.

3.1. Systematic Review

The systematic review aims to provide a thorough analysis of the applications of 3D point cloud data in the construction industry. Furthermore, it attempts to summarize the evolution of research in 3D point cloud and 3D laser scanning from academic papers published from 2015 to 2020. Following the review of different applications, discussions are provided regarding how to properly acquire and process point cloud data to fulfil the needs of construction applications.

The papers were obtained from selected peer-reviewed academic journals and databases. These include Science Direct, Emerald, Ebsco and Google Scholar. The search term used for literature search related to the acquisition and processing of point clouds were '3D Laser Scanning' + '3D Pont Cloud'. The '3D Laser Scanning' + '3D Pont Cloud' and 'Scan to BIM' search terms yielded results for Science Direct, Ebsco and Google Scholar and nothing for Emerald. A second attempt was undertaken whereby the term "abstract" was affixed to the terms '3D Laser Scanning' + '3D Pont Cloud' and 'Scan to BIM' to form '3D Laser Scanning' + '3D Pont Cloud' + 'abstract' and 'Scan to BIM' + 'abstract' which yielded results from Emerald. To facilitate understanding, the search results will be summarised in Tables 1, 2, 3 & 4 for Science Direct, Ebsco, Emerald, and Google Scholar respectively.

Table 1. Science Direct Results

	Using '3D laser scanning' + 'point clouds' as a search term		
	Journal	**Year**	**Papers**
1	ISPRS Journal of Photogrammetry and Remote Sensing	2019, 2017	2
2	Automation in Construction	2019	1
3	Journal of Cultural Heritage	2018	1
5	Measurement	2015	1

6	Pattern Recognition	2015	1
	Using 'Scan to BIM' as search term		
1	Journal of Building Engineering	2020	1
2	Advanced Engineering Informatics	2018	1
		2016	1
3	Automation in Construction	2017	1
		2016	1
		2015	2
4	Procedia Engineering	2017	1
5	Simulation Modelling Practice and Theory	2015	1

Based on Table 1, a total of 15 research papers published from 2015 until January 2020 were identified. These results are from a combination of '3D Laser Scanning' + '3D Pont Cloud' and then 'Scan to BIM' in the Science Direct search engine.

Table 2. Ebsco Results

	Using '3D laser scanning' + 'point clouds' as a search term		
	Journals	**Year**	**Papers**
1	Sensors	2017	2
		2015	4
		2019	1
2	Journal of Cultural Heritage	2018	1
		2015	1
		2019	1
3	Pattern Recognition	2018,	1
		2015	1
4	International Journal of Distributed Sensor Networks	2018	1
5	IEEE Transactions on Geoscience & Remote Sensing	2016	3
6	Journal of Sustainable Forestry	2019	1
7	Geomechanik und Tunnelbau	2017	1
8	Automation in Construction	2019	1
		2018	1
9	International Journal of Pattern Recognition & Artificial Intelligence	2015	1
10	Remote Sensing	2019	2
		2016	1
		2017	1
11	Journal of Coastal Research	2016	1
12	ISPRS Journal of Photogrammetry & Remote Sensing	2018	1
		2019	1
		2016	1
13	Instrumentation, Mesures, Métrologies	2018	1
14	ISPRS International Journal of Geo-Information	2019	1

15	Computers & Geosciences	2017	1
16	International Journal of Remote Sensing	2016	1
		2015	1
17	International Journal of Agricultural & Biological Engineering	2016	1
18	Engineering Geology	2015	1
		2019	1
19	Geomatics & Information Science of Wuhan University	2015	1
20	International Journal of Pavement Engineering	2017	1
21	International Journal of Applied Earth Observation & Geoinformation	2016	1
22	Journal of Computing in Civil Engineering	2016	1
23	Bulletin of Engineering Geology & the Environment	2016	1
24	International Journal for Light & Electron Optics	2015	1
25	Archives of Photogrammetry, Cartography & Remote Sensing	2015	3
26	Advanced Engineering Informatics	2018	1
27	Journal of Applied Geodesy	2015	1
28	Measurement	2015	1
29	International Journal of Production Research	2017	1
30	Mathematical Problems in Engineering	2018	1
31	Journal of the Institute of Science & Technology	2018	1
32	Landslides	2018	1
33	Annals of Botany	2018	1
34	Computer-Aided Design & Applications	2019	1
35	Computer-Aided Design	2015	1
36	Estuarine Coastal & Shelf Science	2018	1
37	Ecology & Evolution	2018	1
38	Agricultural & Forest Meteorology	2019	1
39	Computers & Electronics in Agriculture	2017	1
40	Geophysical Research Abstracts	2019	2
41	Engineering Structures	2016	1
	Using 'Scan to BIM' as search term		
1	Remote Sensing	2019	3
2	Advanced Engineering Informatics	2018	3
		2017	1
		2016	1
		2015	1
3	Automation in Construction	2019	2
		2018	3
		2017	4
		2016	1
		2015	1
4	Simulation Modelling Practice & Theory	2015	1
5	Journal of Architectural Education	2019	1

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6	Computer-Aided Civil & Infrastructure Engineering	2017	1
7	Journal of Computing in Civil Engineering	2016	2

Based on Table 2, a total of 88 research papers published from 2015 until January 2020 were identified. These results are from a combination of '3D Laser Scanning' + '3D Pont Cloud' and then 'Scan to BIM' in the Ebsco search engines.

Table 3. Emerald Results

	Using the term '3D Laser Scanning' + '3D Pont Cloud' + 'abstract'		
	Journals	**Year**	**Paper**
1	International Journal of Building Pathology and Adaptation	2018	1
2	Journal of Facilities Management	2019	1
3	International Journal of Intelligent Computing and Cybernetics	2019	1
4	Built Environment Project and Asset Management	2017	1
5	Engineering, Construction and Architectural Management	2019	1
6	Sensor Review	2017	1
7	Assembly Automation	2019	1
	Using 'Scan to BIM' + 'abstract' as a search term		
1	Journal of Facilities Management	2019	1
2	Built Environment Project and Asset Management	2017	1
3	Structural Survey	2016	1

Based on Table 3, a total of 10 research papers were identified published from 2015 until January 2020. These results from a combination of '3D Laser Scanning + '3D Pont Cloud' + 'abstract' and then 'Scan to BIM' + 'abstract' in the Emerald search engines.

Table 4. Google Scholar Results

	Using '3D laser scanning' + 'point clouds' as search term		
	Journal	**Year**	**Papers**
1	Pattern Recognition	2015	1
2	Automation in Construction	2019	1
3	European Journal of Remote Sensing	2016	1
4	Sensors	2017	1
5	Applied Mechanics and Materials	2015	1
6	American Journal of Engineering Research	2018	1
7	IEEE Access	2018	1
8	Revista de la Facultad de Ingeniería U.C.V	2017	1
9	Bulletin of Surveying and Mapping	2017	1
10	Computer Science	2016	1
11	Journal of Shandong University of Technology	2017	1
12	Metal Mine	2017	1
13	Nonferrous Metals Science and Engineering	2017	1
14	Journal of Wuhan University of Technology	2017	1

15	ISPRS Journal of Photogrammetry and Remote Sensing	2019	1
16	Construction Management and Economics	2015	1
	Using "Scan to BIM" as search term		
1	Automation in Construction	2015	1
2	The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences	2019 2017	3 1
3	Advanced Engineering Informatics	2018	1
4	Architectural Engineering and Design Management	2019	1
5	Architecture and Civil Engineering	2016	1
6	Virtual Archaeology Review	2019	1
7	Geo Business	2015	1
8	European Real Estate Society	2019	1
9	Construction Research Congress	2018	1
10	Remote Sensing	2019	2

Based on Table 4, a total of 16 research papers published from 2015 until January 2020 were identified. These results are from a combination of "3D Laser Scanning +3D Pont Cloud" and then "Scan to BIM" in the Google Scholar search engines.

Given that the aim of the systematic review was to understand the evolution of research in 3D point cloud and 3D laser scanning, it is imperative to investigate trends in various disciplines and areas of applications. To gain insights into the application of 3D laser scanning in the different domains, a word cloud was generated from all the articles obtained using '3D Laser Scanning' + '3D Pont Cloud'. The result is presented in Figure 1.

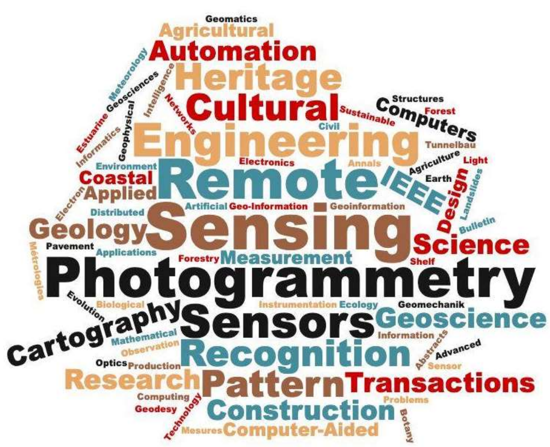

Figure 1. Word cloud from the 4 databases obtained using the search terms '3D Laser Scanning' + '3D Pont Cloud'

Based on Figure 1, the result shows that the application of laser scanning in 'construction' as a discipline is very limited. This can be seen at the bottom of the point cloud above. For example, The European Journal of Remote Sensing and The American Journal of Engineering Research discuss the density and the size of point cloud data in the natural environment with the focus on forest and vegetation. Furthermore, IEEE Access and sensors explore point cloud data, its intensity and use in tunnel inspections. Moreover, Applied Mechanics and Materials and Revista de la Facultad de Ingeniería

U.C.V focus on the methods of processing point cloud data using software such as Geomagic and Cyclone for diagnostics and registration. Nonferrous Metals Science and Engineering also focused on point cloud data processing, while Computer Science discussed the display speed of point cloud data for visualisation purposes. Metal Mine proposed a method to automatically extract boundary features of a surface from the point cloud data. Finally, Automation in Construction, Pattern Recognition, and Construction Management and Economics overlap with the results from Science Direct.

The word cloud in Figure 1 shows that the literature focuses on the technical side of 3D point cloud and 3D laser scanners as the main journals are on remote sensing, photogrammetry, and sensors, while published papers in the construction field is limited.

To gain insights into the application of 3D laser scanning, a word cloud was generated from all the articles obtained using 'Scan-to-BIM', as shown in Figure 2.

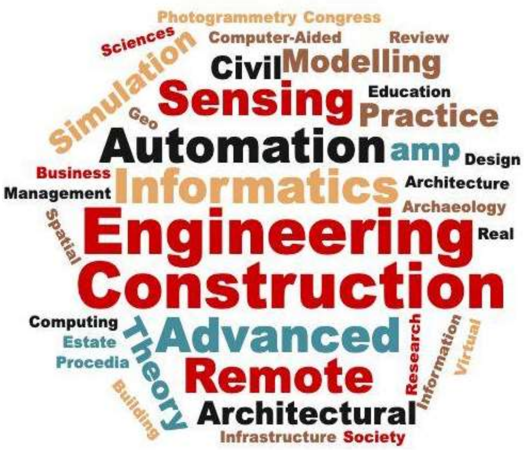

Figure 2. Word cloud from the 4 databases obtained using the search term: "Scan-to-BIM"

It can be inferred from Figure 2 that 3D laser scanning applications are quite common in construction practice as a process. In addition to the findings that emerged from the systematic review presented and discussed in Tables 1, 2, 3 &4 and Figures 1 &2, a detailed examination of the articles also revealed some interesting results. This include: Automated processing of point cloud data based on material and colour, which identifies topologies (building elements) based on texture, intensity value, and RGB colour space that aims to identify the spatial relationships between building elements and their surface properties (Wang and Kim, 2019). Additionally, Xiong's et al. work attempts to automatically identify walls, floors, ceilings, and any significant rectangular openings (e.g., doorways and windows) (Xiong, Adan, Akinci and Huber, 2013). All this can lead to imprecise quality assurance and progress estimates, which was mentioned by Chen and Cho (2019) as concerning visibility issues in Scan to BIM applications. Additionally, the relationship of point cloud intensity, the processing and the quality of data (Fryskowska and Stachelek, 2018).

3.2. Field Survey: point-cloud model develpoment

The following field survey is the core of the 'proof-of-concept' approach used for this study and was imperative to describe the case study building and the technologies used in data acquisition and analysis. The Headington Hill building, a historic mansion built in

1824, and is located on the Oxford Brookes University Campus in Oxford, UK. The main reason for selecting the building lay in the historical value of the asset and the rich detail level on the external and internal envelope of the building. The uniqueness and the appropriate scale of the building allowed the collection of sufficient data from the scans to examine the feasibility and accuracy of the 3-D laser scanning device. The aerial view is presented in Figure 3.

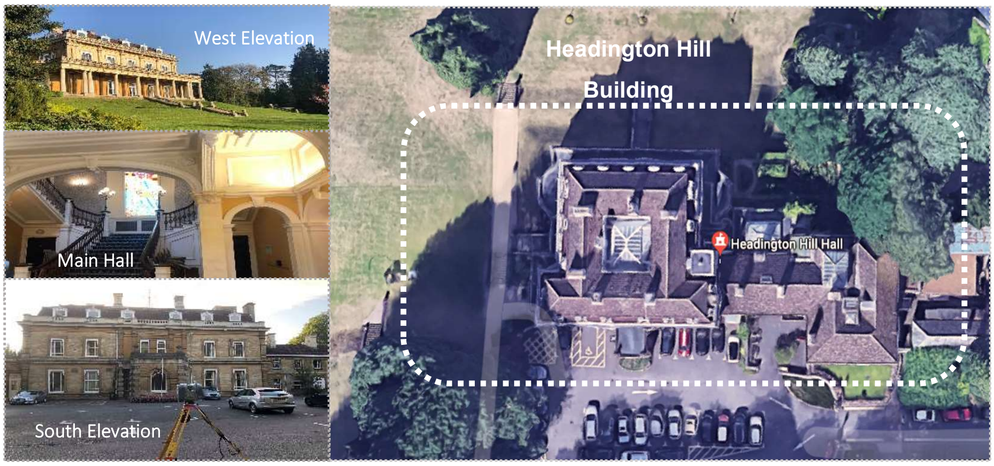

Figure 3. 3D model and aerial view of Headington Hill Building

The main surveying equipment used was 3D laser scanner, Trimble TX8 mark. The key technical specifications of Trimble TX8 are listed in Table 5.

Table 5. the technical specifications of Trimble TX8 Laser Scanner

Scan Parameter	Trimble TX8 Specifications
Maximum range (m)	120 m
Minimum range (m)	0.6 m
Field of view (degree)	360°X317° degree
Scanning Speed	1Milion point/second
Scan Duration (seconds)	60 second
Scan Accuracy (mm)	<2 mm noise or error on most surfaces
Laser beam dimeter (mm)	6-34 invisible
Data Storage	USB Flash Drive

The Trimble TX8 provides high resolution scans with performance range of 1 million points/second, with an integrated HDR camera that colorizes the scans. The device provides 360°X317° view range, capturing high-resolution scans up to 120m from the station point. The applications of the Trimble TX8 in the built environment includes urban studies, documentation of historic buildings, quantity surveying, construction, quality control, and building maintenance purposes.

Data from the Trimble TX8 was processed though the Trimble RealWorks software. It provides a complete solution to efficiently register, analyse, model and create deliverables using data from virtually any source. Revit, one of the leading BIM authoring software used for the 3D design of projects, was also used in the project and can also be used for other applications such as visualisation, generation of schedules, and quantities.

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Having examined the case study building to accomplish this 'proof-of-concept' method, the following framework will be examined. See Figure 4.

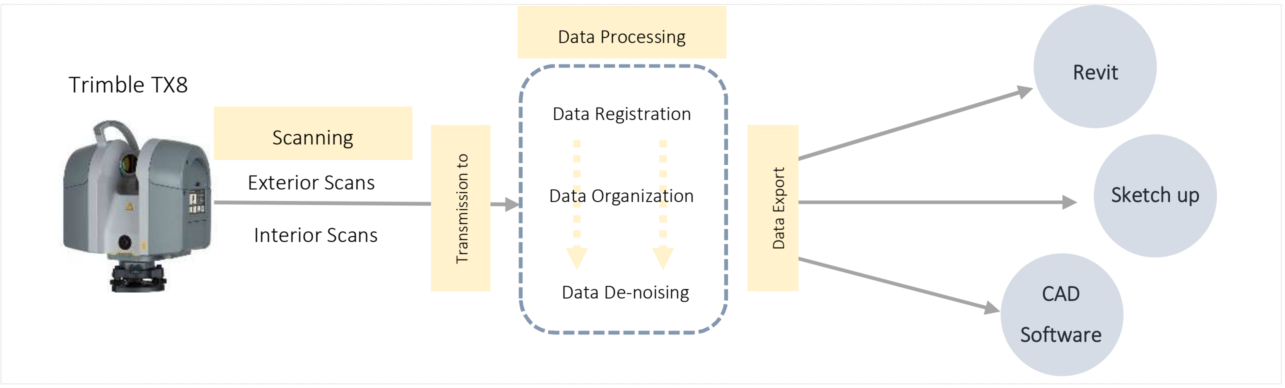

Figure 4. Cloud-data Examination Framework

The first step was to capture the building data using the Trimble TX8. This involves exterior and interior scans with different characteristics in term of station point distance, number of cloud points, level of detail and level of accuracy. The scanning strategy was based on the positioning of the scanning device to capture the external envelope of the building and formulate a coherent 3-D model through capturing the external elevations of the building from various stations with different angles, distances, and heights. The interior scanning strategy was based on scanning the internal spaces of the building in separation, then merging the scanned spaces into a single model that represents the internal envelope of the building. Interior scans are classified by floor level and involves a number of scans that shape the 3-D model of the floor. Common spaces with double floor heights were scanned from various points and floor levels to formulate a unified cloud model that illustrates the spaces without the duplications of cloud points.

3.2.1. Scanning Process

The surveying was conducted in two phases, one each for the exterior envelope and interior spaces of the building. Phase 1 was conducted through five station points surrounding the exterior elevations to shape a comprehensive field of view and enable the device to identify and integrate the external surfaces. Figure 5 shows station points location on site. Station A and station B cover the western elevation, while station D, C, E cover eastern elevation. Station A, C together cover southern elevation and station E covers the apparent part of the northern elevation. The station points were placed in different distances from the nearest building surface. Station A was 15.5 m away from the nearest surface, while station C was 6.5 m away from the nearest surface. Station D recorded the farthest distance of 22.5 m. The variation in point distances relates to the desired angle, field of view of the scans and the existing site situation, limits, and obstacles.

Figure 5. External scanning points placement on the Headington Hill building site

Noticeably, the distance between the station point and the nearest building surface affected the cloud points number of each scan. The cloud points acquired from station A scan was at a distance of 1.5M, while cloud points of station C and E were 11M and 34M respectively. Table 6 demonstrates the distances of the stations along with the acquired cloud points from each station.

Table 6. list of acquired cloud points of external scans along with station points distances

Station	Distance from nearest building surface (meters)	Cloud Points
Station A	15.5 m	1,035,939
Station B	20 m	1,178,415
Station C	6.5 m	1,428,007
Station D	22.5 m	1,072,529
Station E	13.6 m	1,389,529

Phase 2 was conducted in two stages, stage one focused on the ground floor of the building where 7 station points were utilized to obtain cloud data for the main hall, common areas, and rooms. Stage two focused on the first floor where 5 station points were placed to scan the main hall ceiling, major staircase, and upper floor common areas to integrate these scans with the ground floor cloud data. Figure 6 shows the distribution of the station points on the ground and first floor levels of the building. It is of note that scans were only conducted on accessible areas of the building.

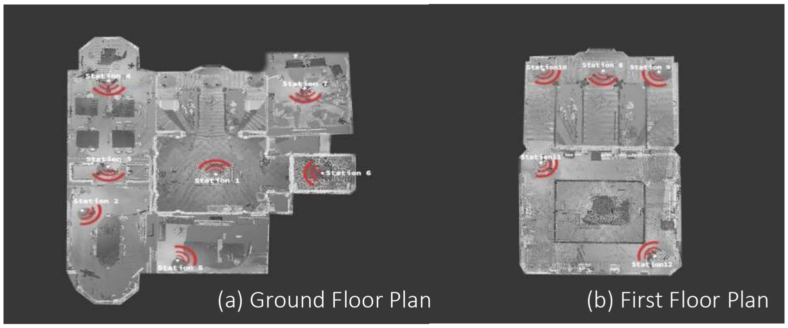

Figure 6. Headington Hill building plan: (a) ground floor plan; (b) first floor main hall plan

Although, the distance variations between the surfaces and station points in exterior scanning affected the cloud points density, this effect appeared less in interior scanning because of the similarity of distances from the nearest internal surface making the point cloud much denser and more more complex than the external scans. See Table 7.

Table 7. lists acquired cloud points of internal scans along with station points distances

Station	Distance from nearest building surface (meters)	Cloud Points (millions)
Station 1	3 m	1,879,252
Station 2	4.5 m	1,864,804
Station 3	2.5 m	1,865,083
Station 4	3.5 m	1,857,055
Station 5	4 m	1,861,777
Station 6	2 m	1,843,463
Station 7	3.5 m	1,873,135
Station 8	5 m	1,875,792
Station 9	5 m	1,878,262
Station 10	5 m	1,835,489
Station 11	4.5 m	1,894,394
Station 12	4.5 m	1,895,844

3.2.2. Exporting Scanning-data: Trimble TX8 to Trimble Realworks

This step involves importing the captured data from a USB flash in the TX8 into a point cloud processing software, which in the case of this study is Trimble Realworks.

3.2.3. Point Cloud Processing

The scanned stations acquired through survey were processed in a software compatible with Trimble TX8 scanner namely, Trimble Realworks software. Data processing was conducted in three stages; stage 1 related to cloud data registration, while stage 2 involved filtering registered data and stage 3 was concerned with investigating the resulting cloud model. Each stage will be discussed in more detail in the ensuing sections.

3.2.3.1. Point Cloud Registration

The first step in processing cloud data is registering the cloud stations acquired throughout the surveying process. The registration process was conducted through two phases, phase 1 refers to external scans while phase 2 focuses on internal scan registration. Station registration is based on two methods, either cloud-based registration (clouds registered according to surfaces matchings or proximities) or target-based registration (clouds registered according to a selected reference plane, sphere or object). Cloud-based registration was utilized in registering the cloud points, the registration was conducted through two stages. Stage 1 concerned with an automatic registration of cloud points based on surface matching by which cloud points were identified, and registered. Automatic cloud registration specifies properties of each cloud station such as point density, station height, matching errors, cloud point number and cloud stations clashes. Figure 7 illustrates the results of automatic cloud points registration.

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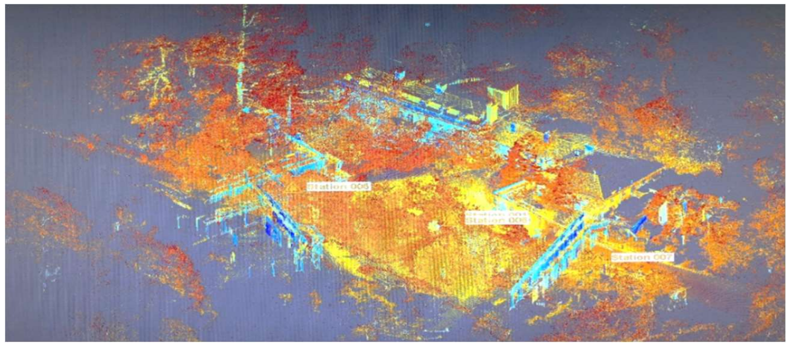


Figure 7. Automatic Point Cloud Registration

Automatic cloud registration (stage 1) defines and registers cloud station points, surfaces, and volumes, therefore, these cloud stations appear as distinguished clouds merged according to proximities of station surfaces. The resulting cloud stations necessitate another stage of registration (stage 2) to organize, assemble, and establish an integrated cloud model. Stage 2 focuses on manual cloud registration. In this stage registered cloud stations were adjusted and organized to achieve full surface matching. Manual cloud registration methods are based on selecting a reference cloud station and a moving cloud station where the latter can be moved, rotated, and adjusted to match shared surfaces of the reference cloud station. Manual registration provides a surface matching test between the two stations, where matching test result with acceptable low error (usually <10mm), can be merged in a single registered station. Figure 8 shows manual registration process.

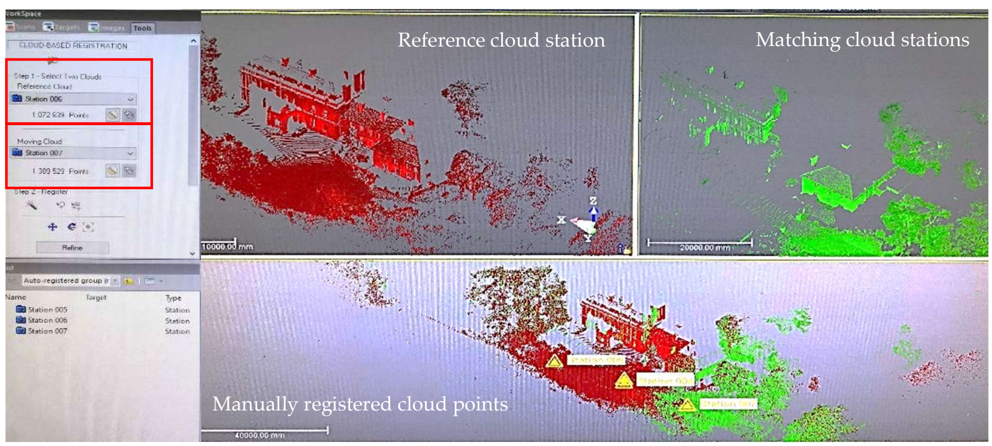
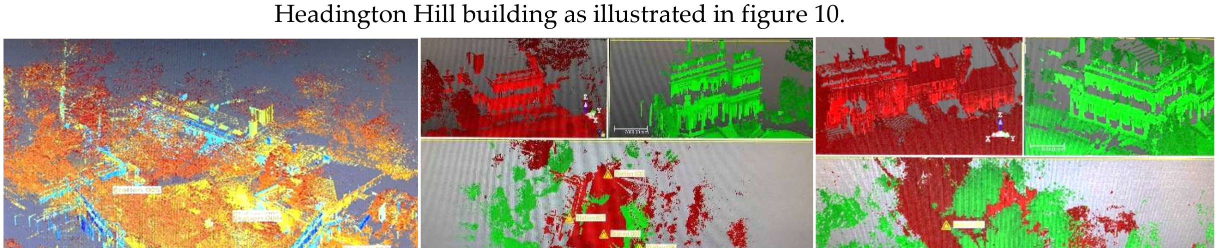


Figure 8. Manual Registration Process

The manually registered station can be later merged with other stations through the same process of manual registration. In this case, the manually registered station represents the reference cloud station and remaining cloud stations represent moving stations. Figure 9 illustrates point cloud registration stages, including the automatic cloud registration (stage 1) and manual cloud registration (stage 2).

Manual cloud registration was conducted on all the cloud stations, as a result, a coherent model with complete matching stations and low error level (less <10mm) was created. The resulting cloud model represents a collection of separated station scans for the Headington Hill building as illustrated in figure 10.



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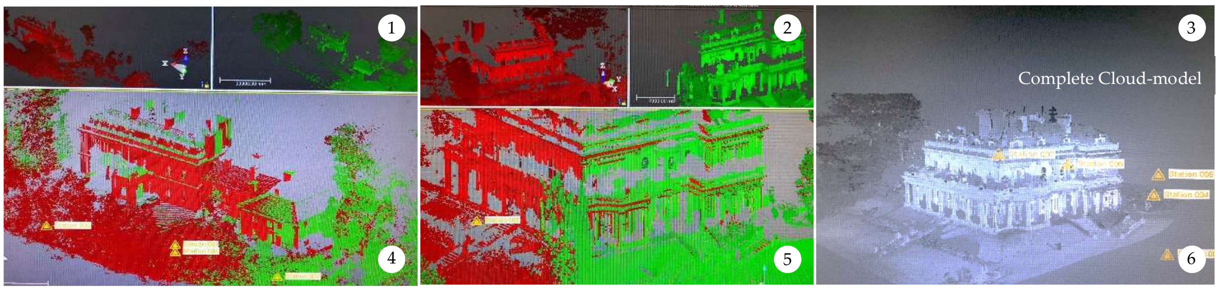

Figure 9. Point Cloud Registration stages: (1) automatic registration; (2,3,4,5,6) manual registration

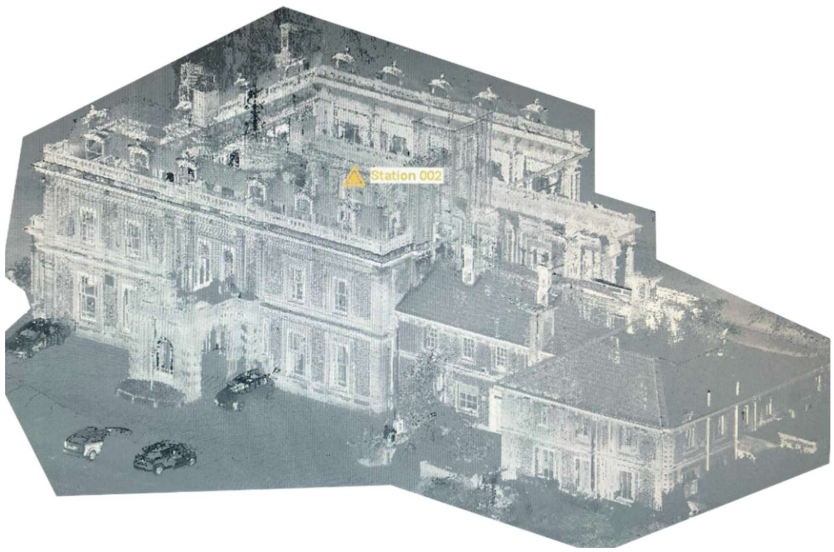

Figure 10. Headington Hill building exterior cloud model

3.2.3.2. Point Cloud De-noising

3-D laser scanners capture and scans all physical objects that appear in the field of view during the scanning process. For instance, the Trimble TX8 captures all existing objects on site such as moving objects, plants and trees, neighbouring buildings, and the surrounding environment.

All these objects add massive points to the cloud, complicating the cloud model and point cloud production due to the extensive point number resulting from unwanted objects. Some objects create barriers and visual obstacles to the model, and therefore require visual treatment to produce a clear, understandable cloud model. De-noising refers to the process of excluding undesirable physical objects captured during the scanning process. In this paper, the purpose of point cloud de-nosing was to:

- Reduce cloud points through eliminating undesirable objects, neighboring buildings, unrelated visual context to ease and reduce time required to process scanned clouds.

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- Extract visual barriers overlaying building elevations, interior spaces, and surfaces to obtain a clear, functional field of view.
- Decrease cloud model complexity and focus on cloud model components.

The de-noising process was conducted through two methods provided by the Trimble Realworks software as the following:

- Regional de-noising: enables eliminating large areas such as surrounding environment and neighboring buildings.
- Segmental de-noising: enables eliminating single objects, undesirable existing elements on site and visual barriers.

Figure 11 presents exterior and interior cloud model of Headington Hill building prior de-nosing the cloud model and after implementing de-noising methods.

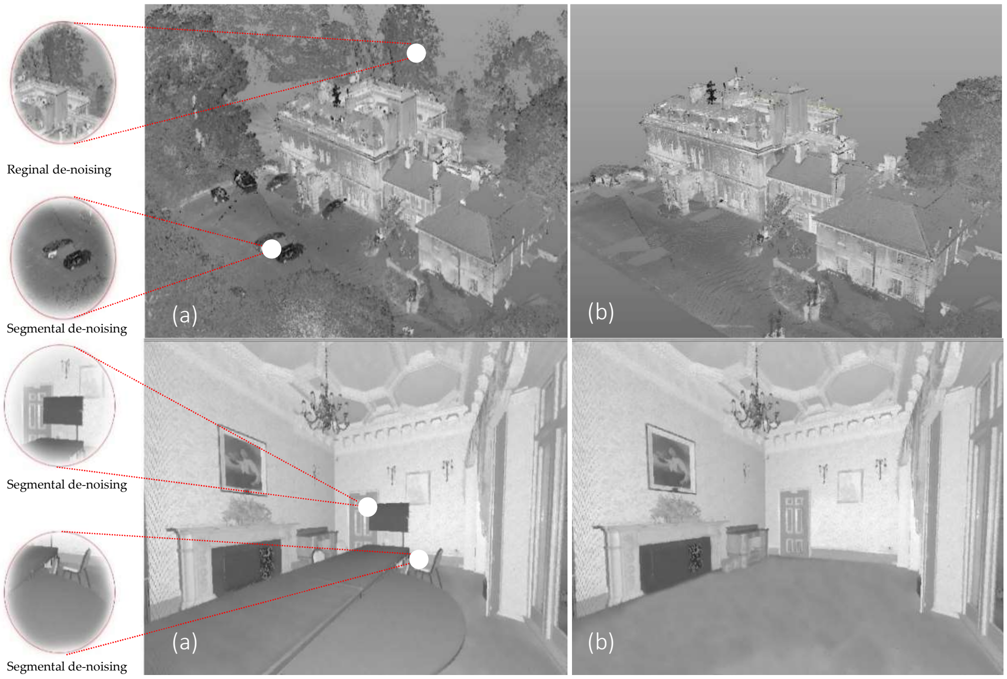

Figure 11. Point cloud de-noising: (a) prior de-noising; (b) after de-nosing

Point cloud de-noising decreases complexity, volume of cloud model through eliminating the un-desirable physical object. Exterior cloud de-noising in the case study showed higher points reduction due to the massive points acquired from various elements on site, while interior cloud de-noising showed lower points reduction due to contextual limits of interior scans. Table 8 lists cloud points prior and after cloud de-noising as well as redacted points from each cloud model.

Table 8. Cloud points prior and after cloud de-noising

Cloud Model	Cloud points prior de-noising	Cloud points after de-noising	Redacted points
Exterior Model	8,224,818	4,093,981	4,130,837
Interior Model	52,278,405	50,127,390	2,0151,015

3.2.3.3. Point Cloud Investigation

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After registering and de-noising cloud stations, the acquired cloud model was investigated by set of tools provided in the Trimble Realworks software. The aim of the investigation was to test reliability and accuracy of the resulting cloud model. Point cloud investigation was conducted for two main principles in 3-D laser scanning, the first principle related to the tools and options of measuring cloud models as well as accuracy of the measurement. The second principle related to the penetrability of laser beams through building elements.

Realworks software provides various measurement tools including basic measurement means such as horizontal and vertical measurement as well as advanced tools such as angular, plane, and geometry measurements. Points in the cloud formed reference points for measurement, where, in a distance between (5mm-10mm) a point was tangible as reference of measurement. Selected reference points were connected with another tangible point to generate the readings. In Figure 12, main hall elements were measured, noticeably areas with low intensity of points showed errors in measurement between (10mm-20mm), while areas with high intensity of points showed accurate readings. The reason of various measurement readings lay in the intensity of scanned points on different surfaces, where Areas with higher number of points showed more accurate readings.

Figure 12. Inveistigation of the main hall elements of Headington Hill building

Another aspect of the investigation was testing penetrability of the Trimble TX8 laser beams through various surfaces. Trimble TX8 generates laser beams with diameters of 6-10-34mm based on the distance from the nearest surface. Laser beams penetration through building elements such as walls, ceilings, structural elements was limited due to material specifications of these elements. The building facade was included large stones blocks with thickness of up to 600 mm that forms the external façade of the building. The nature and specifications of the external walls as well as internal walls, ceilings, and structural elements obstructed laser beams penetration. Figure 13 illustrates penetrability of laser beams through different surfaces, (b) represents laser penetration in the glass roof of the main hall, noticeably laser beams penetrate through low point intensity areas as showed in the points test, (c) represents laser penetration through the roof structure of the main hall, the points test shows limited penetration and high reflection of laser beams. As a result, the penetrability test has indicated that opaque materials with high point intensity reflect laser beams, while transparent materials with low point intensity are penetrated by the beams. The Point cloud investigation has indicated a relationship between scanned point intensity, accuracy of measurement readings, and penetrability of laser beams. Surfaces with higher points intensity showed accurate readings and high reflectivity for laser beams, while surfaces with lower point intensity showed minor errors in reading and higher penetrability for laser beams.

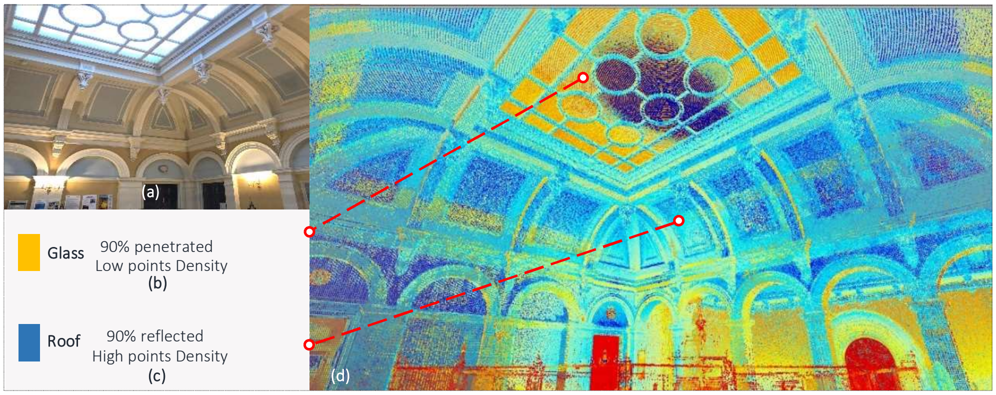

Figure 13. (a) original photograph; (b) main hall glass roof; (c) main hall roof structure; (d) penetrability test

3.3. Cloud Model Integration with BIM

The point cloud process generated a unified, integrated cloud model which was a result of linking and merging several point clouds. The created cloud model was integrated with BIM applications by exporting cloud the model to CAD software, then applicable BIM strategies were investigated on the model. Trimble Realworks provides two main methods of integrating cloud model with BIM applications. The methods of exporting cloud model are listed below:

- Built-in Plugin: a plugin provided by Trimble Realworks enables direct export of cloud model to SketchUp software.
- Cloud Export: a method enables exporting cloud model to other file formats compatible with various software.

Trimble Realworks enables exporting a cloud model in various file formats. Table 9 lists commonly used file formats in CAD software, as well as, exporting availability in Trimble Realworks along with compatible software for these formats and format integration with BIM applications.

Building on Table 9, all other file formats that can allow interoperability between the software involved in the 3D printing process are presented in Table 10.

Table 9. key file formats in CAD with exporting availability of these formats in Trimble Realworks

File Format	Availability	Compatible Software	BIM Applications
DWG	Available	AutoCAD Suite, Revit	Required
DXF	Available	AutoCAD Suite, Revit	Upon request
IFC	Not available	Revit, Costx, Navisworks	Required
SKP	Built-in plugin	SketchUp, 3ds Max, Revit	Upon request
OBJ	Available	3ds Max	Upon request
KMZ	Available	Google Earth	Upon request

FBX	Available	3ds Max, AutoCAD Suite	Upon request
PDF	Not available	Adobe Acrobat, AutoCAD Suite	Upon request
DGN	Available	AutoCAD Suite, Revit	Upon request
ACIS	Not available	AutoCAD Suite	Upon request

Table 10. Interoperable file formats between different 3D printing related software systems

		3D-laser scanner	Software	File in (input to software)	File out (output from software)
Point Cloud based software	3D laser scanner dependant software	Trimble TX [Data output format (RWP)]	Trimble Realworks	RWP, XYZ, E57, LAS, LAZ, ZFS, RSP, FLS, DP, PTX, PTS	E57, ASC, LAS 1.2, LAS 1.4, LAZ, POD, PTS, PTX, TZF, BSF, KMZ, DWG, DXF, DGN, FBX, OBJ
		FARO [Data output format (FLS)]	FARO Scene	FLS, XYZ, CVS, COR, CPE	PTC, PTX, PST, XYZ, DXF, IGES, VRML, E57
		Leica [Data output format (PTX and PTS)]	Leica Cyclone	XYZ, PTS, PTX, LAS, E57, ZFS, DP	XYZ, PTS, PTX, E57, DXF, PCI/CWF, DBX, gbXML
	3D laser scanner non dependant software		LiDAR360	LiData, las, laz, asc, neu, xyz, pts, csv, ply	LiData, las, laz, asc, neu, xyz, pts, csv, ply
			PolyWorks	IGES, STEP, DXF, JT, OBJ, PLY, POL, STL, VRML 2.0	IGES, STL, DXF
			PointCab	dp, e57, asc, fws, lsproj, fls, las, laz, lsdx, lse, dae, 3ds, ifc, stl, mpc, ply, ptg, ptx, rps, pvtp, vtp, xyz, zfs, .zfprj	dwg, dxf, dae, 3ds
	BIM Based tools		Autodesk Recap	ASC, CL3, CLR, E57, FLS, FWS, ISPROJ, LAS, PCG, PTG, PTS, PTX, RDS, TXT, XYB, XYZ, ZFS, ZFPRJ, DXF, DWG	RCS, RCP, PCG, PTS, E57, DXF, DWG
			Autodesk Revit	DWG, RVT, DXF, gbXML, RCP, DWF	DWG, DXF, gbXML, FBX, DGN, ACIS, IFC
			Bentley	POD, OBJ, SHP, DXF, DWG, ESRI, E57, ZFS, LAZ, LAS, FLS, FWS, XYZ, PTS, PTX, PTZ, TXT, LWO, CL3, BIN, RSP, 3DD	POD, PTS, XYZ
			ArchiCAD	DWG, IFC, 3DS, 3DM, SKP, KMZ, STL, PDF, DXF	PDF, DWF, DXF, DWG, DGN
	Web-based visualisation		FARO SCENE WebShare		rcp, pod, xyz, e57
			Leica Pegasus		

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	Flyvast	LAS, LAZ, XYZ, PTX, PLY, OBJ	FLY, dxf, shp
	Voxxlr	IFC, Dxf, e57, pts, ply, las, laz	

Noticeably, Trimble Realworks lacks the ability to export cloud model in the IFC file format (Industry foundation classes) which is commonly utilized in exchanging BIM models. The absence of the IFC file format requires third-party software, in this case Revit, to generate IFC file formats for cloud models to integrate with specific software such as Costx, Navisworks that are essential for implementing BIM strategies.

The resulting case study cloud model was exported in DWG file format and imported into the Revit software that is commonly used for BIM applications. In Revit, the cloud model was recognized as a 3D asset formed by millions of points, these points were visible but intangible (not solid or physical). Revit generated horizontal, vertical sections for the model as well as elevations, 3-D navigation. Figure 14 (a&b) illustrate the eastern elevation as well as the cross section of the main hall of Headingtion Hill building, as shown below.

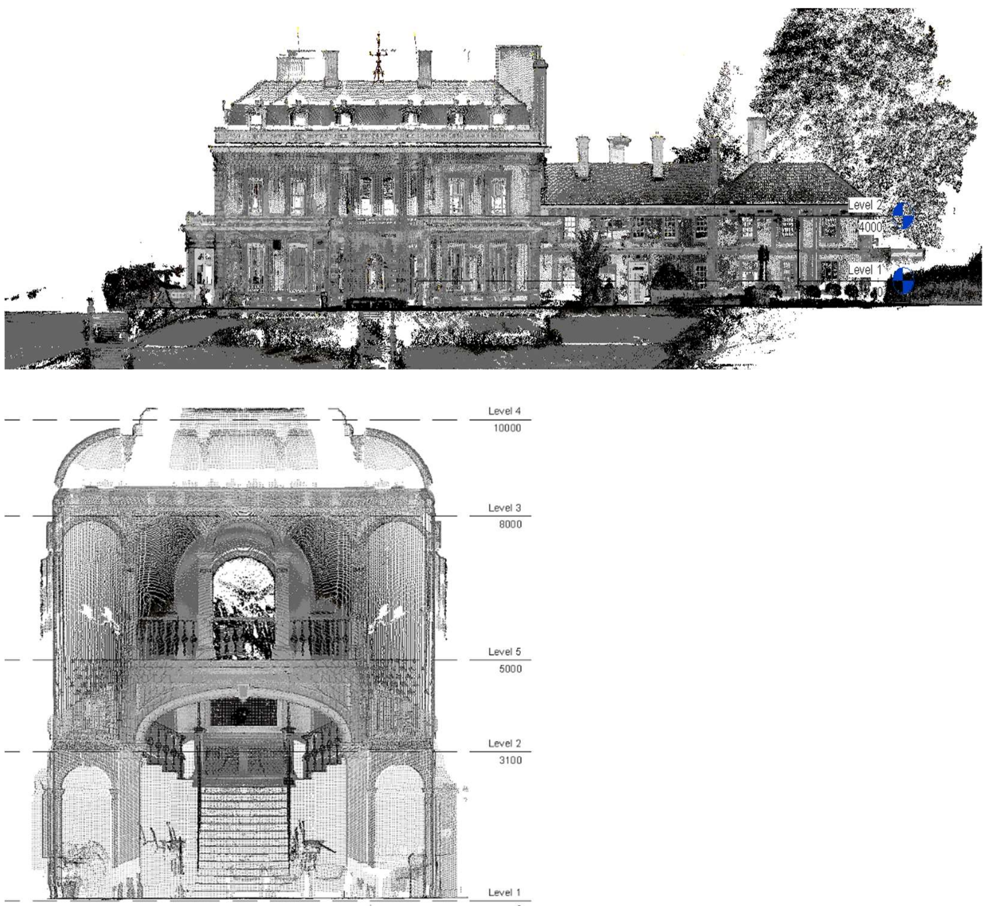

Figure 14. (a) Eastern elevation of Headington Hill Building; (b) Cross-section of the main hall

Generating drawings from the cloud model was the first step in attaining cloud model integration with BIM applications. The resulting drawings can be utilized in documenting the historical building. Furthermore, the drawings were measurable, accurate and exportable to other BIM software programs. Revit was only considered a third-party

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software in this study by which IFC formats were established from the cloud model and enabled complete integration with other BIM applications such as Costx which is a specialist program in quantity take-off. Hence, material quantities in the building can be calculated, investigated, and analysed. Another possible application, is the use of structure analysis software which analyses the physical condition of the building and indicates defect points in the structure. Such data can be used in rehabilitating historical buildings or renovating external or internal envelopes and for documentation purposes of historic buildings. Also, the IFC cloud model data is crucial for the facility management of buildings. Additionally, BIM applications can expand to cover maintenance issues in the build environment. The acquired IFC model can be used in the maintenance process. Regular and advanced maintenance activates to be modeled and tested in the cloud model before implementation. Figure 15 demonstrates BIM applications of cloud models using third-party software.

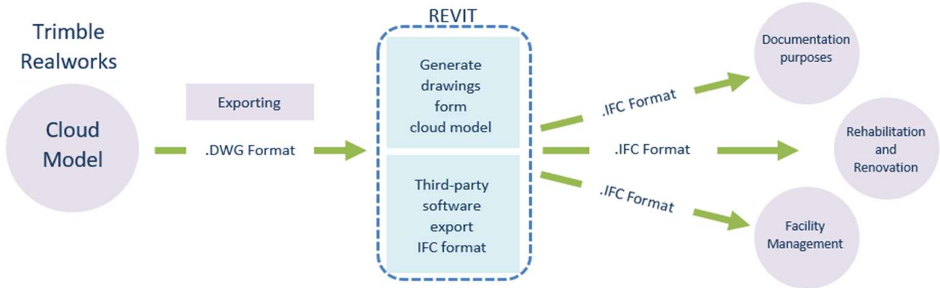

Figure 15. Cloud model integration with BIM applications

4. Findings and Discussion

This study has yielded 3 main findings. Firstly, despite the multiple applications of laser scanning alongside BIM in the existing research, most studies focus on the process after the point cloud data exportation, with little attention being given to the acquisition of the data itself. Therefore, it becomes imperative to further examine the data acquisition phase. Additionally, to ensure the direct communication or exchange of data in the scanning workflow, software and hardware requirements, and their interoperability within the BIM system have been examined and presented in Table 10.

Secondly, the intensity of point cloud data before and after the de-nosing process varies significantly for exterior 3D point cloud models compared to the interior. The de-noising process of the case study has shown that for the exterior, the number of point clouds was decreased by 50%, while for the interior there was a reduction of less than 1%.

Lastly, the penetrability of laser beams through various surface materials depends on the surface material of various building components such as walls, columns, and windows. For example, stone used for exterior walls showed a much higher penetration rate compared to glassed surfaces. This could be interpreted incorrectly for auto detection of various building elements or surfaces based on the intensity of surface material as it was in this case where the colour of the arcade space was the same as the glass roof.

5. Conclusion

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This study has examined the applications of 3D laser scanners in construction. A systematic review and a proof-of-concept method were used in this study to shed light on various factors influencing the use of laser scanner and their integration into BIM. It was found that, despite the recent interest in 3D laser scanners, research on its applications are still lagging in the construction field compared to other disciplines. Furthermore, it emerged that most studies have seldom focused on the data processing phase. Also, this study has found that issues with intensity quality of point cloud data vis-à-vis the position of 3D laser stations revealed through de-noising. Lastly, the study revealed issues around the penetrability of laser beams through various surface materials. As this is a crucial issue for automated detection of various building elements that could be used for automated progress monitoring and detection of discrepancy in construction. These findings reveal the need for further exploratory research to be conducted in the field of 3D laser scanning applications in construction practice.

6. References

1. Bosché, F., Ahmed, M., Turkan, Y., Haas, C.T. and Haas, R., 2015. The value of integrating Scan-to-BIM and Scan-vs-BIM techniques for construction monitoring using laser scanning and BIM: The case of cylindrical MEP components. *Automation in Construction*, *49*, pp.201-213.
2. Díaz-Vilariño, L., Frías, E., Balado, J. and González-Jorge, H., 2018. Scan planning and route optimization for control of execution of as-designed BIM. *International Archives of the Photogrammetry, Remote Sensing & Spatial Information Sciences*.
3. Campi, M., di Luggo, A. and Scandurra, S., 2017. 3D modeling for the knowledge of architectural heritage and virtual reconstruction of its historical memory. *The International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences*, *42*, p.133.
4. Chan, D.W., Olawumi, T.O. and Ho, A.M., 2019. Perceived benefits of and barriers to Building Information Modelling (BIM) implementation in construction: The case of Hong Kong. *Journal of Building Engineering*, *25*, p.100764.
5. Cheng, L., Chen, S., Liu, X., Xu, H., Wu, Y., Li, M. and Chen, Y., 2018. Registration of laser scanning point clouds: A review. *Sensors*, *18*(5), p.1641.
6. Fassi, F., Fregonese, L., Ackermann, S. and De Troia, V., 2013. Comparison between laser scanning and automated 3d modelling techniques to reconstruct complex and extensive cultural heritage areas. *International archives of the photogrammetry, remote sensing and spatial information sciences*, *5*, p.W1.
7. Fröhlich, C. and Mettenleiter, M., 2004. Terrestrial laser scanning–new perspectives in 3D surveying. *International archives of photogrammetry, remote sensing and spatial information sciences*, *36*(Part 8), p.W2.
8. Fryskowska, A. and Stachelek, J., 2018. A no-reference method of geometric content quality analysis of 3D models generated from laser scanning point clouds for hBIM. *Journal of Cultural Heritage*, *34*, pp.95-108.

 doi:10.20944/preprints202101.0331.v1

9. Göçer, Ö., Hua, Y. and Göçer, K., 2016, October. A BIM-GIS integrated pre-retrofit model for building data mapping. In *Building Simulation* (Vol. 9, No. 5, pp. 513-527). Tsinghua University Press.
10. Guidi, G., Russo, M. and Angheleddu, D., 2014. 3D survey and virtual reconstruction of archaeological sites. *Digital Applications in Archaeology and Cultural Heritage*, *1*(2), pp.55-69.
11. Ham, Y. and Golparvar-Fard, M., 2015. Mapping actual thermal properties to building elements in gbXML-based BIM for reliable building energy performance modeling. *Automation in Construction*, *49*, pp.214-224
12. Hichri, N., Stefani, C., De Luca, L., Veron, P. and Hamon, G., 2013. From point cloud to BIM: a survey of existing approaches.
13. Jalaei, F., Zoghi, M. and Khoshand, A., 2019. Life cycle environmental impact assessment to manage and optimize construction waste using Building Information Modeling (BIM). *International Journal of Construction Management*, pp.1-18.
14. Kim, M.K., Wang, Q., Park, J.W., Cheng, J.C., Sohn, H. and Chang, C.C., 2016. Automated dimensional quality assurance of full-scale precast concrete elements using laser scanning and BIM. *Automation in Construction*, *72*, pp.102-114.
15. Lagüela, S., Díaz-Vilariño, L., Armesto, J. and Arias, P., 2014. Non-destructive approach for the generation and thermal characterization of an as-built BIM. *Construction and Building Materials*, *51*, pp.55-61.
16. Lagüela, S., Díaz-Vilariño, L., Martínez, J. and Armesto, J., 2013. Automatic thermographic and RGB texture of as-built BIM for energy rehabilitation purposes. *Automation in Construction*, *31*, pp.230-240.
17. Larsen, J.K., Shen, G.Q., Lindhard, S.M. and Brunoe, T.D., 2016. Factors affecting schedule delay, cost overrun, and quality level in public construction projects. *Journal of Management in Engineering*, *32*(1), p.04015032.
18. Maalek, R., Lichti, D.D. and Ruwanpura, J.Y., 2019. Automatic recognition of common structural elements from point clouds for automated progress monitoring and dimensional quality control in reinforced concrete construction. *Remote Sensing*, *11*(9), p.1102.
19. Nocerino, E., Menna, F. and Remondino, F., 2014. Accuracy of typical photogrammetric networks in cultural heritage 3D modeling projects. *International Archives of the Photogrammetry, Remote Sensing & Spatial Information Sciences*, *45*.
20. Omar, H., Mahdjoubi, L. and Kheder, G., 2018. Towards an automated photogrammetry-based approach for monitoring and controlling construction site activities. Computers in Industry, 98, pp.172-182.
21. Pärn, E.A. and Edwards, D.J., 2017. Conceptualising the FinDD API plug-in: A study of BIM-FM integration. *Automation in Construction*, *80*, pp.11-21.
22. Pica D. & Abanda F.H. (2019) Emerging BIM-3D-Laser Scanning Integration in Construction Practice. In: The 11th International Conference (CITC-11), Construction in the 21st Century, September 9-11, 2019, London, UK
23. Remondino, F., 2011. Heritage recording and 3D modeling with photogrammetry and 3D scanning. *Remote sensing*, *3*(6), pp.1104-1138.

24. Sanhudo, L., Ramos, N. M., Martins, J. P., Almeida, R. M., Barreira, E., Simões, M. L., & Cardoso, V. (2018). Building information modeling for energy retrofitting–A review. *Renewable and Sustainable Energy Reviews*, *89*, 249-260.
25. Shalabi, F. and Turkan, Y., 2017. IFC BIM-based facility management approach to optimize data collection for corrective maintenance. *Journal of performance of constructed facilities*, *31*(1), p.04016081.
26. Tang, P., Anil, E.B., Akinci, B. and Huber, D., 2011. Efficient and effective quality assessment of as-is building information models and 3D laser-scanned data. In *Computing in Civil Engineering (2011)* (pp. 486-493).
27. Tang, P., Huber, D., Akinci, B., Lipman, R. and Lytle, A., 2010. Automatic reconstruction of as-built building information models from laser-scanned point clouds: A review of related techniques. *Automation in construction*, *19*(7), pp.829-843.
28. Wang, Chao, Yong K. Cho, and Changwan Kim. "Automatic BIM component extraction from point clouds of existing buildings for sustainability applications." *Automation in Construction* 56 (2015): 1-13.
29. Wang, Q. and Kim, M.K., 2019. Applications of 3D point cloud data in the construction industry: A fifteen-year review from 2004 to 2018. *Advanced Engineering Informatics*, *39*, pp.306-319.

30. Wierzbicki, D., Kedzierski, M. and Fryskowska, A., 2015. Assesment of the influence of uav image quality on the orthophoto production. *The International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences*, *40*(1), p.1.
31. Wu, W., Chen, C., Cong, Y., Dong, Z., Li, J., Li, S., Dai, W. and Yang, B., 2019. LOW-COST WHEELED ROBOT-BORNE LASER SCANNING SYSTEM FOR INDOOR AND OUTDOOR 3D MAPPING APPLICATION. *International Archives of the Photogrammetry, Remote Sensing & Spatial Information Sciences*.
32. Xiong, X., Adan, A., Akinci, B. and Huber, D., 2013. Automatic creation of semantically rich 3D building models from laser scanner data. *Automation in construction*, *31*, pp.325-337.