A Survey of Applications With Combined BIM and 3D Laser Scanning in the Life Cycle of Buildings

Jingbin Liu, Dong Xu, Juha Hyyppä, and Yifan Liang

***Abstract*—The integration of building information model (BIM) with point cloud from 3-D laser scanner provides powerful assistance in a variety of applications in the life cycle of building. However, the adoption of BIM and 3-D laser scanning for applications in the whole life cycle of buildings has yet to be satisfactorily reviewed. There is a need to understand the current situation of applications with BIM and 3-D laser scanning and their combined methods. The authors summarized combined methods of BIM and 3-D laser scanning at first. Then. the work presented in this article provides summarization of applications in the life cycle of building. In addition, the impact of emerging technologies on applications also be discussed. In this review, articles were limited to those published over the last decade. Two patterns in the approach to integrate BIM and 3-D laser scanning are reviewed. Several domains of application namely construction progress tracking, building components quality control, construction site safety, structural health monitoring, rescue after the disaster, energy modeling and management and modeling for exist building are looked back. According to occurred time of these applications, this article divides them into two classes: applications in construction period and applications in maintenance period. Based on the observed limitations in the reviewed papers, the authors conclude some potential future research trend for these applications based emerging technology at the same time.**

***Index Terms*—Applications, building information model (BIM), life cycle of buildings, point cloud, 3-D laser scanning.**

I. Introduction

BUILDING information model (BIM) technology includes generation and management of digital representation of buildings covering whole life cycle from the engineering design to construction and maintenance [1]. Through the integration of data and BIM, engineering technicians can make correct decisions and efficient response to various building information at various stages.

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Jingbin Liu, Dong Xu, and Yifan Liang are with the State Key Laboratory of Information Engineering in Surveying, Mapping and Remote Sensing, Wuhan University, Wuhan 430079, China (e-mail: jingbin.liu@whu.edu.cn; dongxu_@whu.edu.cn; lyf0312@whu.edu.cn).

Juha Hyyppä is with the Remote Sensing and Photogrammetry at Finnish Geospatial Research Institute, FI-02430 Masala, Finland, and also with the Shinshu University, Nagano 390-8621, Japan (e-mail: juha.coelasr@gmail.com).

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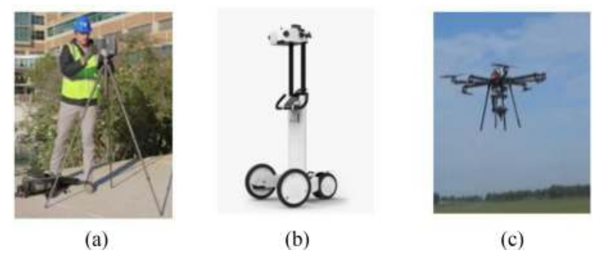

Fig. 1. Different categories of 3D laser scanner. (a) TLS: FARO focus70 image http://faro.com/ (b) MLS: Navvis M6 image https://www.navvis.com/. (c) ALS: geosun gAirHawkGS100H image http://www.geosun-gnss.com.cn/.

3-D laser scanning is a technology to obtain the surface properties of an object by emitting laser beams and receiving the reflected signals from the target. A 3-D laser scanner can capture the 3-D surface points of target object by 3-D laser scanning technology in an accurate and efficient manner. Thus, it has gradually become one of the main data sources for BIM [2]. 3-D Laser scanners can be classified into three categories based on their working platforms, namely terrestrial laser scanner (TLS), mobile laser scanner (MLS), and airborne laser scanner (ALS), as shown in Fig. 1 [3]. TLS is usually fixed on a stable tripod or observation pile, and it can achieve up a precision of several millimeters from one hundred meters range. Point cloud derived from TLS is usually used for progress tracking [4], struct health monitoring [5], [6], and 3-D reconstruction [7]. Although TLS provides data at the rate of about one million points per second, it generates complete point cloud of a building slower than MLS. The occlusions caused by the complex indoor environment and the inconsistent point cloud densities are major obstructions. In order to cover the whole building and to obtain consistent point density using TLS, construction managers have to make a scan plan and establish survey control-net, which are major time-consuming tasks [8]. In addition, multiple point cloud data sets resulting from each separate scan need to be merged together through the registration algorithm [9]. MLS does not require the registration steps in general. Some MLS systems, such as trolley-based system like M6 from Navvis, and backpack mobile scanner like bMS3D LD5+, can achieve point cloud of complete building efficiently. MLS has greatly increased scan efficiency and obtain more data coverage. The drawback of MLS is lower precision than TLS. TLS can obtain several millimeters accuracy, while MLS can only provide a few centimeters accuracy. Error sources include range measurement errors and errors due to positioning of the sensor [10]. Positioning using SLAM algorithms are prone to drift. They can lose tracking in feature-less zones, and will fail in zones with high similarity [11]. The efficiency of MLS is a considerable advantage. Due to the complexity of indoor environment, ALS is generally not used for data collection within buildings. It is widely used for data collection on a large scale [12]. But in theory autonomous obstacle-avoiding unmanned aircraft vehicle lidar could be used for such task and there are developments towards that [13]. Also, construction sites are today imaged with UAV photogrammetry resulting in point cloud similar to laser scanning [14], [15].

Several reviews have been properly conducted by focusing on some applications in the life cycle of buildings in the published literatures. For example, Rankohi *et al.* [16] investigated image-based modeling tools and techniques for construction project status comparison. Omar *et al.* [8] examined different technologies of automated and electronic construction data collection for construction progress tracking. Wong *et al.* [17] demonstrated a comprehensive review on digital technologies, e.g., BIM and Internet of Things, in facility management(FM) research. Xu *et al.* [18] described a full picture of pervasive sensing technologies adoption for FM. The above paper reviewed various technologies and sensors applied to some applications in the whole life of buildings. Although insightful these studies were, the adoption of BIM and 3-D laser scanning for applications in the whole life cycle of buildings has yet to be satisfactorily reviewed or discussed in past literacy.

3-D laser scanning is one of the most accurate and efficient methods for information of building. BIM is an efficient kind of data tools applied to engineering design, construction and maintenance. The integration of BIM and 3-D laser scanning play an important role in the whole life cycle of buildings. There is a need to understand the current situation of applications in the life of buildings using BIM and 3-D laser scanning including the following.

1) What are the methods of integrating 3-D laser scanning with BIM?
2) What are the applications in building life cycle using BIM and 3-D laser scanning?
3) What are the limitations of BIM and 3-D laser scanning technology in applications?
4) What will be the impact on these application areas with the development of technology (e.g., MLS)?

The work presented in this article provides summary of applications in the life cycle of building and reviews patterns in the approach to integrate BIM with 3-D laser scanning. In addition, the limitations of BIM and 3-D laser scanning technology in these applications and the impact of emerging technologies on these applications also be discussed. The rest of article goes as follows: Section II explains the research methodology; Section III introduces the methods of combining BIM and 3-D laser scanning; Sections IV and V review the applications in life of buildings using BIM and 3-D laser scanning; Section VI gives limitations and future trend. Finally, Section VII summarizes and concludes this survey.

II. Research Methodology

To ensure a comprehensive review of applications in the life cycle of building using BIM and 3-D laser scanning, Elsevier Scopus was used mainly and Google Scholar was used as supplement. The titles and keywords were used in the search progress as matching conditions to focus on the exact research topics. We used retrieval formula "[(TITLE (("point cloud" or "laser scan∗") and "BIM") or KEY (("point cloud" or "laser scan∗") and "BIM")) AND PUBYEAR $>$ 2009]"to conduct literature search. In addition, the language was restricted to English and only journal articles were selected.

There were 157 search results. Through reading the article's abstract and keywords, the 62 articles were screened out. These articles include 15 literatures that without 3-D laser scanning technology, 8 literatures that introduce related data acquisition technology, 5 reviews and 34 literatures that not focus on applications in the life cycle of building using BIM and 3-D laser scanning. The 95 literatures were selected. In the Table I list the article details. We can see that literatures are published on journals that involve remote sensing, automated construction, cultural Heritage and sustainable development. We also find that the more and more researchers focus on applications with combined BIM and 3-D laser scanning.

The applications involved domains are construction progress tracking, building components quality control, construction site safety, structural health monitoring (SHM), rescue after disaster, building energy modeling and management, and modeling for existing building. According to occurred time of these applications, this article divides them into two classes: applications in construction period and applications in maintenance period. The categorization of the reviewed paper according that is shown inFig. 2.

III. Methods of Combining 3-D Laser Scanning and BIM

In this section, two kinds of combined methods of BIM and 3-D laser scanning are concluded from reviewed articles' methodologies and implementation. The authors describe the basic steps for each method, and demonstrate how a method was implemented in various applications from reviewed articles.

A. Creation of BIM Model From Point Cloud

This is the basic way of integrating BIM and 3-D laser scanning technology. It is a necessary process for these applications that request BIM. 3-D laser scanning technology produces original data for BIM. In this step, in order to achieve different goals, there are some researchers focus on various data acquisition platforms and scan planning. Thomson *et al.* [10] investigates indoor MLS as a data collect device for BIM model creation over TLS through a series of fit-for-purpose experiments. Chen *et al.* [19] focus on research refer to scan-planning framework. After getting the point cloud of target building, modeling was followed. According to the degree of automation, three sorts of methods is reviewed. Table II gives the partial articles' details in brief.

Automatic modeling method is often used for regular elements, such as indoor structural components, mechanical, electrical, and plumbing (MEP) components and facade. At first, the whole point cloud is segmented into many elements (e.g., plane, column). The methods that include region growing-based methods [20], [21], model fitting-based methods [22] and feature

TABLE I
REVIEWED ARTICLES

	2010-2012	2013	2014	2015	2016	2017	2018	2019	2020	total
Automation in Construction		3	2	4	3	1		3	4	20
Remote Sensing				2				3	7	12
Applied Sciences (Switzerland)						1	1		5	7
Advanced Engineering Informatics				2	2	1	2			7
Journal of Computing in Civil Engineering			1		1		1	2	1	6
Sustainability (Switzerland)							1		4	5
ISPRS International Journal of Geo-Information						1		2	1	4
ISPRS Journal of Photogrammetry and Remote Sensing								2	1	3
IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing			1					1		2
Journal on Computing and Cultural Heritage								1	1	2
International Journal of Architectural Heritage						1			1	2
other		1	3	4		2	3	5	7	25
total		4	7	12	6	7	8	19	32	95

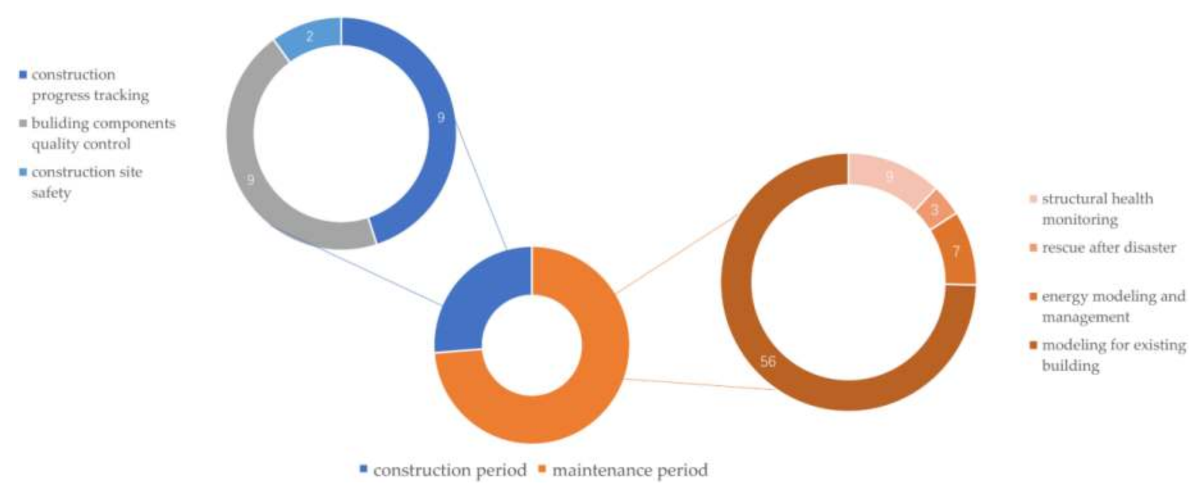

Fig. 2. Categorization of the reviewed papers. We see intuitively from the picture that the reviewed papers about construction progress tracking and building components quality control are main part in the construction period. The reviewed papers about modeling for existing building are main part in the maintenance period.

clustering-based methods [23] are usually adopted in this process. Then these elements are classified by rule-based methods [24]–[26], machine learning methods [27], [28] or deep learning methods [29], [30]. The above steps are not necessary for single object modeling, such as precast concrete elements [31]. The model parameters of the detected elements are estimated subsequently. Based on the parametric models, the complete BIM model is created after the data conversion.

Semiautomatic modeling method is usually chosen for the conditions that modeling of larger scene building [32], [33] or modeling with higher level of model details [34]. In the semiautomatic modeling methods, the model parameters of the regular elements are estimated automatically. Because specific requirements of modeling, these model parameters need to be transferred into software. Manual process with software is conducted subsequently.

Manual modeling method is adopted frequently for heritage buildings [35]–[37], which consist of heterogeneous, complex, and irregular components. There are currently no automatic software processes for the parametric design of the heritage buildings components. It is still a time-consuming manual process with commercial software.

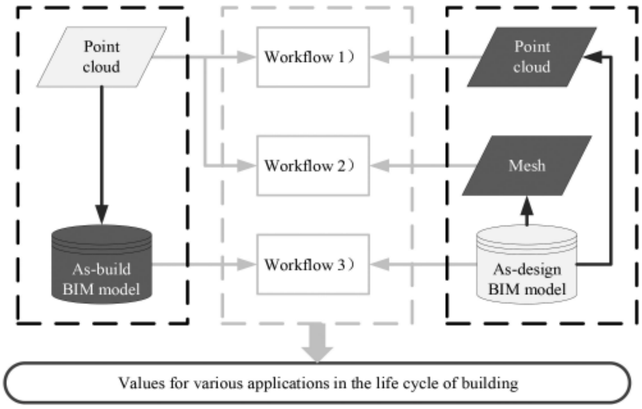

Fig. 3. Three workflows of comparing point cloud with BIM model. In short, workflow 1) is point versus point; workflow 2) is point versus mesh; and workflow 3) is BIM versus BIM.

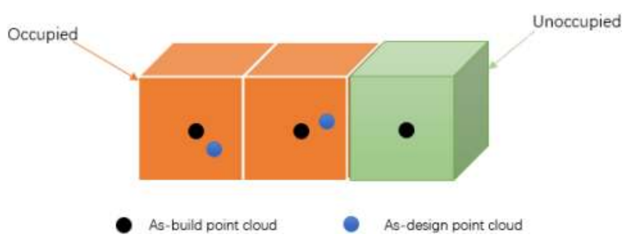

Fig. 4. Comparing between as-build scanning point cloud and point cloud from as-design BIM model. In the same voxel gird, there is a judgement to determine this voxel gird is occupied or unoccupied. If the voxel gird is occupied, the as-build scanning point in this voxel is matched with BIM model. Otherwise, the as-build scanning point belongs to Occlusion point cloud.

TABLE II
DIFFERENT MODELING OBJECTS AND THEIR CORRESPONDING PARTIAL PAPERS

The modeling object	Degree of automation	Partial papers
Heritage building	manual	[82], [83]
Indoor structure components	semi-automatic	[32]
	automatic	[24], [89][90]
Steel structure (e.g. bridge)	semi-automatic	[91]
	automatic	[92] [93]
Curtain wall/facade	automatic	[62][94] [95]
Indoor small components	semi-automatic	[34]
	automatic	[75] [96]
precast concrete elements	automatic	[31] [97]
MEP	automatic	[98] [99]
Railway tunnel	automatic	[26]
Interior of damaged building	automatic	[64], [65]

B. Comparing Between Point Cloud With BIM Model

Comparing as-build (as-damaged) point cloud from 3-D laser scanner with as-design BIM model is usually adopted in the several applications in the life cycle of building. Such as construction progress tracking, building components quality control and SHM. Several different workflows (as shown in Fig. 3) are adopted in this progress: 1) comparing as-build point cloud with point cloud from as-design BIM model; 2) comparing as-build point cloud with meshes from as-design BIM model; 3) comparing as-build BIM model with as-design BIM model. In the other words, workflow 1) and workflow 2) are comparing as-build point cloud with data that derives from as-design BIM model. Workflow 3) is comparing as-build BIM model that derives from as-build point cloud with as-design BIM model. In workflow 1) and workflow 2), aligning point cloud from 3-D laser scanner with BIM model is necessary. It is a basic step for matching each point with 3-D model object to achieve the goal of progress tracking or structural health monitor. The difference between workflow 1) and workflow 2) is that distinguishing methods in the step of matching each point with 3-D model object. Based step mentioned above, different applications have different subsequent processing step. Registration is not necessary in the workflow 3).

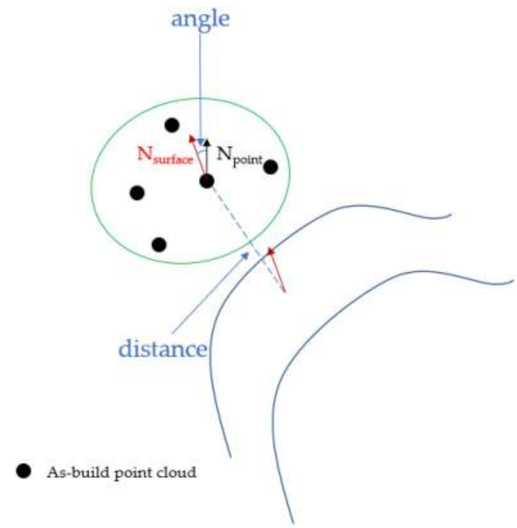

Fig. 5. There are two criteria to determine whether point belongs to the BIM model. The distance of point orthogonally on the surfaces of target building components. The angle between normal of point cloud and normal of surface.

TABLE III
DIFFERENT APPLICATIONS AND THEIR CORRESPONDING PARTIAL PAPERS

Application	Workflow	Partial papers
Construction progress tracking	1)	[11]
	2)	[39], [40], [46]
Building components quality control	2)	[50], [51], [54]
	3)	[31]
Structural health monitoring	2)	[59] [5]
	3)	[60] [61] [62]
Rescue after disaster	3)	[64] [65]

Workflow 1) compares as-build point cloud with point cloud from as-design BIM model. The first step is aligning point cloud from 3-D laser scanner with BIM model. Then the as-design point cloud with same resolution as as-build (as- damaged) point cloud is extracted. The detail of extraction method is presented in [38]. The both point clouds are down sampled into a voxel grid with a constant resolution. By comparing the attributes of each voxel of both point clouds to determine whether it is “occupied”

or "unoccupied." Based on the state of voxel, each point in the voxel can then be labeled as belonging to correctly building components. As shown in Fig. 4.

Workflow 2) compares as-build point cloud with mesh from as-design BIM model. The first step is aligning point cloud from 3-D laser scanner with BIM model. Then each point from as-build point cloud is matched with building components by judging relationship between point and mesh. There are several criteria to determine whether the point belongs to the target object. It includes the distance of point orthogonally on the surfaces of target building components [39], the angle between normal of point cloud and normal of surface [40] and so on. As shown in Fig. 5.

In workflow 1) and workflow 2), the matching process between points with 3d model objects is a basic but underappreciated step in their complete procedure. So, the matching approaches that adopted in reviewed papers are ordinary. Local shape descriptor can be adopted for the matching process. It encodes the geometric information of the local neighborhood around the selected point into a feature vector. Using local shape descriptor makes the matching process more robust to noise and occlusion. SHOT [41], RoPS [42], QLCI [43], and BSC [44] descriptors has good description performance. Matching process with local shape descriptor improves the accuracy of these applications.

Workflow3) compares as-build BIM model with as-design BIM model. The specific modeling methods are shown at Section III-A. Based on the existing as-build BIM model, this workflow achieves the purpose of progress tracking, quality control and structural health monitor by extracting the geometries of the model or analyzing using other commercial software.

IV. Applications in the Construction Period

According to reviewed papers, the main applications using BIM and 3-D laser scanning in the construction period are construction progress tracking, building components quality control and construction site safety.

A. Construction Progress Tracking

During the period of construction, due to some reasons (e.g., weather, delays in supply, human errors, human negligence), the actual state of the construction may deviate from the planned state. There is a need for construction managers to understand the current state of the project, (e.g., deviation from plan status or percentage of completed project). This need can be called progress control or progress tracking. Traditional progress tracking methods depend on a lot of manpower, which is error-prone and time-consuming. For construction managers, it is time-consuming to walk around the construction site to verify the progress in different activities (e.g., measure, take photos) and understand the status of the project. Over the years, there are more attentions have been paid on automating this process by using advanced computer technologies. Automated construction progress tracking that using BIM and 3-D laser scanning achieves deviation by comparing as-build building point cloud or model with as-plan model. There are two types of approaches currently being adopted in research into construction progress tracking. The key difference is whether there is a need to make assumptions about the shape. Aligning point cloud with BIM is their common initial step. After matching each point with BIM, model point cloud and occluding point cloud can be obtained (this progress refer to integration of laser scanning and BIM and details are showed in Section III-C). In the methods [40], [45], [46] that need shape assumptions, the point cloud of target object is extracted from the overall point cloud, and then is compared with the as-plan point cloud of target model obtained by simulation technology. So, as to obtain the current construction situation. The methods [38], [39], [47] that do not need shape assumptions directly compare the whole point cloud and the whole BIM model to obtain the current construction situation. The methods [48], [49] adopt a manual approach with software.

Turkan *et al.* [45] first presented an automated construction progress tracking which combines 3-D object recognition algorithms with 4-D BIM. Because it uses surface-based object recognition algorithms, it got a good progress tracking performance only in structural scenes (e.g., floor, columns and wall). Bosché *et al.* [46] proposed scan versus BIM processing system with some enhancements over previous researches for MEP components progress tracking. The work presented creates a novel way to finish progress control of other unstructured building components. Subsequently, Bosché *et al.* [40] promoted their approach by integrating the Hough transform-based circular cross-section detection approach with the scan versus BIM object recognition and identification framework of Bosché *et al.* [46]. The all above methods approached request assumptions about the shape of an element and density of the point cloud.

Zhang *et al.* [39] got the percentage of completion by comparing number of points on the face of original 3-D model and contractive 3-D model. The state of each point depends on the distance from the point to the face. Rebolj *et al.* [47] identified state of building components by computing the surface coverage of building components. The points that close to surface of building elements are projected orthographically onto three rasterization orthogonal planes. And coverage of the element was archived by combining the results of all three projections. Chen *et al.* [38] proposed a point-to-point comparison method for automated deviation detection. At first, BIM model was converted to as-plan point cloud format by uniformly sampling points from mesh model. The as-built point cloud was similarly down-sampled to be at the same resolution as the as-plan point cloud. The deviation of building elements between the BIM and laser-scanned point clouds can be obtained by discern difference in the same voxel. The above methods are more general, which allow to identify any element of building with different quality point cloud when possible.

B. Building Components Quality Control

Building components quality control is an important part of the construction process to prevent rework. To achieve this goal, traditional tools, such as plumb and gauges are still widely used, and more advanced equipment including hand-held laser rangefinder and total station are available. These new measurement techniques result in better precision than conventional ways. However, they are still laborious and time intensive. The reason is that their performance heavily relies on sampling techniques. For example, the total station is used to measure the verticality of a wall, and only a few points at different heights along a vertical line spaced horizontally (sparsely) are measured. The risk of this kind of local measurement is that the locations with large differences may not be found, which may lead to the wrong conclusions of the surveyors. In addition, it can be considered that human participation increases the risk of measure error. 3-D laser scanning can achieve dense and accurate measurements without the need for human interaction. The integration of BIM and 3-D laser scanning shows effective and reliable work in the reviewed papers. In the reviewed papers, these themes include surface regularity control [50], quality inspection for MEP modules [51] and quality control for precast concrete elements [31], [52]–[54]. Some researchers focus on practical application in specific case [55], [56].

Bosché *et al.* [50] presented an approach that integrates TLS and BIM to automate floor flatness control significantly. The proposed system relies on the scan versus BIM [46], and applies specified dimensional control procedures to the floor data. Guo et al. [51] presented an automated quality inspection technique for MEP modules that in the steel frame. The method presented registers point cloud with BIM model by aligning steel frames with each other's at first and identifies different types of elements (e.g., pip, ventilation duct, cable tray) by shape fitting algorithm. The disadvantage of this method is several parameters of shape fitting algorithm need to be manually determined. Wang *et al.* [54] proposed a method that inspects the dimensional quality of the side surfaces of precast concrete elements. The method aligns the point cloud of a precast concrete elements with the BIM model by boundary of precast concrete elements. It finds the locations of shear keys and archive the dimensions difference. Kim *et al.* [52], [53] proposed similar processing workflows for inspecting quality of precast concrete elements. Different from the above methods, Wang *et al.* [31] extracted the geometries of precast elements from the precast concrete elements model and inspected quality of them. The paper investigates a method for automatic creation of BIM model of precast concrete elements, which enables more accurate and efficient quality assessment.

C. Construction Site Safety

Construction site safety continues to be among the top concerns in the construction industry. There are no fewer than 600 Chinese construction workers died each year (due to excavation, scaffolding, shoring systems, e.g.,) in 2010–2017. To ensure the safety of workers, safe work conditions should be provided, in addition to supply safety education and personal protect equipment. The researches focus on construction safety using 3-D laser scanning and BIM can offer a valuable aid to decrease death of workers.

Wang *et al.* [57] presented a method that semi-automatically identifies fall and cave in construction sites and provides the required fall protection equipment. It visualizes the excavation pits, and the required protective safety equipment in BIM model according to existing occupational safety and health standards. Teizer *et al.* [58] proposed an overview of sensing technology available for temporary resource tracking at construction sites and provided the status quo of research applications by highlighting exemplary case. Automatic resource tracking information extraction from sensors can provide extra safeguard related to the safety of construction worker.

V. Applications in the Maintenance period

In the maintenance period, the main applications using BIM and 3-D laser scanning are SHM, rescue after disaster, energy modeling and management, and modeling for existing building.

A. Structural Health Monitoring

The purpose of SHM is to monitor, analyze and identify various loads and structural responses of the target structure during its service period. It aims to realize the evaluation of its safety status, and provide support for the owners to make structural management and maintenance decisions. Displacement is an important index for structure state evaluation. The traditional contact measurement equipment that measures displacement includes dial indicator, pulling-type displacement sensor and linear variable differential pressure sensor. In this kind of conventional methods, the sensor contacts the measuring point of the target structure. The displacement of the contact point is caused when the structure is displaced, and the sensor measures the change of the position of the contact point. Then, we can realize the displacement measurement. Noncontact displacement measurement methods usually include global positioning system (GPS), laser Doppler instrument, total station and computer vision. Although GPS, laser Doppler instrument and total station have a high measure precision, their sampling frequency of measurement is low. It is difficult to achieve a wide range of high precision measurement of structural displacement. 3-D laser scanning can achieve dense and accurate measurements without the need for disproportionate human interaction and time. Some papers using directly point cloud derived from laser scanner for SHM. The others extracted the geometries from BIM model which derive form laser scanner to evaluate structural safety status.

Chan *et al.* [59] proposed a conceptual framework to improve the reliability and efficiency of bridge asset management practices through the integration of BIM and advanced sensors technologies. The adoption of 3-D laser scanning technology improved 50% efficiency and retrench 40% of cost as against the traditional approach in Yongxin Floodgate Pumping Station Project in China. Ham et al. [5] presented a structural safety diagnosis method using 3-D laser scanning and BIM. In the case analysis, the point cloud and the BIM model were compared and analyzed to determine the degree of deformation of pipe rack. The above approaches achieve the goal of SHM by comparing point cloud with BIM. In this progress, the key factor for automation is registration between data drive from laser scanner with BIM model. However, there are room for improvement in the degree of automation and efficiency of registration.

Banfi *et al.* [60] proposed a new methodology, which is able to simplify the creation process of a historical bridge model and share related multimedia data into a database for SHM. Rolin *et al.* [61] presented a complete geometrical modeling methodology for the finite-element analysis (FEA) of historical buildings and it was applied for studying the structural performance of the spire of the Senlis cathedral, France. Patil *et al.* [62] presented an approach which combines 3-D laser scanning, BIM, and FEA, to evaluate the structural integrity of a curtain wall. A similar process is proposed in the article [63]. Modeling for existing building is a requisite step in the all above papers. The difference of their framework is that FEA software was used in [60] and [61] to analyze structural issues. The FEA can provide additional information for continuous inspections. The visualization and sharing of SHM data achieve more focus in [62].

B. Rescue After the Disaster

Postearthquake, the damage quantity and location of the collapsed building is unknown. In order to make effective response to disaster recovery (e.g., search, rescue, and damage assessment,), search and rescue teams have to figure it out the location of damaged buildings and their condition. Remote sensing technology (such as airborne or terrestrial laser scanning technology) is very suitable for collecting the information of earthquake affected areas. By comparing the scan data of the intact building before the earthquake with the data collected after the earthquake, the location and damage characteristics of each building can be obtained. Providing aforementioned information of building can guide search and rescue teams to minimize their risk and accelerate operations.

Bloch *et al.* [64] presented a capable method of providing detailed information about the damaged building. The method puts the BIM of the pre-event building in a collapse simulation engine to create possible damage patterns of the building. After the earthquake, 3-D laser scanning technology is used to capture as-damaged point cloud. Then each possible damage pattern from the database is analyzed and compared with the as-damaged point cloud. Zeibak-Shini *et al.* [65] developed an algorithm based method presented by Bloch *et al.* [64] and tested for the case of reinforced concrete (RC) frames with masonry infill walls. The algorithm identifies the RC frames that in the as-built BIM. And it gets an initial estimate of the locations and orientations of the structural frame members in the as damaged point cloud based the result of the previous step. The above methods create possible damage patterns of the building at first and match them with as-damaged laser scanning data. If you want to get good results, you need to make sure that the candidate damage patterns of the building in the database is plenty (some parameters must be set carefully enough). Ma *et al.* [66] proposed an approach to edit as-damaged BIM models and presented a laser scanning emulator to generate point cloud that is similar to a real laser scanning on site according to aforementioned models. The accurate data from synthesizing technology fills the hole in the scarcity of data from buildings that have suffered real earthquake damage.

C. Energy Modeling and Management

Assessment and repair for building energy efficiency require a lot of information. However, the building model established by traditional CAD software contains limited information. Therefore, assessment of building energy efficiency requires a large amount of manual data input. As a result, the analysis of building energy consumption tends to become an additional work after the architectural design, which is difficult to influence the previous architectural design. Even if the design is optimized according to the analysis results, it is still a time-consuming and laborious process with low efficiency. BIM provides a design model with extremely complete design information. Provided the model has achieved the necessary and credibility detail, energy-saving design and repair for buildings can be realized.

Lagüela *et al.* [67] proposed a methodology for the automatic generation of textured as-built models. It starts with data acquisition and continues with geometric and thermographic data processing. Aims to automatic obtain textured 3-D models, an automatic registration strategy of thermographic and RGB images with a point cloud is adopted. Otero *et al.* [68] developed a semi-automatic determination of the indoor 3-D geometry of a building for y energy experts. Vilarin *et al.* [69] presented a working methodology for the automatic generation of as-built models including shade surfaces that can be adopted to solar analysis. It gives the great assistance for energy consumption of the building. Celis *et al.* [70] developed an integrated system for the energy inspection for buildings. It will propel effective rehabilitation actions towards the reduction of the CO_2 discharge and convert those buildings with high energy-saving potentiality into zero-consumption buildings. Marzouk *et al.* [71] presented a framework to obtain equipment maintenance information for water treatment plants by using BIM and 3-D laser scanning.

D. Modeling for Existing Building

The growing applications with BIM in the life of building is propelling an increase in demand for creating as-build models for existing building. To create BIM model of buildings, traditional methods usually use commercial software, such as CAD, Revit and 3-Ds max. The BIM model is built up manually according to design data or measure data that roots in conventional measuring methods. The process of manual modeling is time-consuming. And provided CAD data is not available, it is necessary to use 2-D discrete point data that obtained by means such as total station to construct CAD base map, which is also time intensive. Moreover, since the total station collects single point, it is difficult to measure the irregular structures, and even cannot accurately map them. 3-D laser scanner has become a common technology to acquire complete point clouds in many engineering projects due to efficiency and high precision. Many studies have focused on automatic generation for BIM models of existing buildings with 3-D laser scanning data. The reviewed papers refer to indoor modeling (indoor structure and other small components), components of railway and historical buildings.

The indoor structure modeling focus on the geometric modeling for indoor structures. This progress usually includes several steps: plane segmentation, boundary detection; building components classification; and data conversion in the reviewed paper. There is rule-based building components classification method in Wang *et al.* [72], Thomson *et al.* [73] and Jung *et al.* [32]. The difference of their indoor structure modeling approaches is automation degree of data conversion step. Jung *et al.* [32] proposed a more practical semi-automatic methodology for efficient as-built BIM creation with respect to large indoor environments. While Wang *et al.* [72] and Thomson *et al.* [73] presented automatic methodology, which are not suitable for large scenes. Xiong *et al.* [74] presented a method is different from the above papers. He used machine learning method to automatically label building components as walls, ceilings, or floors. Deep learning technology is gradually adopted in this domain. Chen *et al.* [29] proposed a data-driven deep learning framework to automatically detect and classify building elements from a laser-scanned point cloud scene

Some papers also focused on modeling for other small components in the room. Valero *et al.* [34] presented a TLS data-processing pipeline that aims at semantic 3-D modeling for furniture s in the office and home. Adán *et al.* [75] developed an approach to recognize the smaller objects (e.g.,sockets and switches) that are commonly located on walls by processing dense colored 3-D points provided by TLS.

In recent years, heritage (Historic) BIM (HBIM) has been applied with great advantage within the scope of management of heritage sites and buildings. To create elaborate HBIM, the reviewed papers provided workflows both with BIM software in different heritage building case. Sztwiertnia *et al.* [16] focused on the case of the so-called Wang Temple in Karpacz, Poland. León-Robles *et al.* [15] propose a framework and a model for stone arch bridge. Godinho *et al.* [76] described the development process of a BIM model that constitutes a digital resource for the management of the National Palace of Sintra, Portugal. Due to the unstructured nature of historic buildings, the automated modeling method cannot be well applied in the process of modeling. There are some other similar works [77]–[81]. The above workflows are all based on BIM software, such as Revit [82] and ArchiCAD [83]. HBIM works does not necessarily are not found when using methods depicted in Section III-A Cultural heritage mapping in 3-D is one of the oldest applications for laser scanning.

VI. Limitations and Future Trend

Sections IV and V mainly discuss the applications in the life of buildings using BIM and 3-D laser scanning. This chapter focuses on the using limitations of the technologies in these applications and the impact of the emerging technologies on these applications.

There are common limitations in the all reviewed applications.

1) Data collection efficiency is low. There is only a station scene, not a complete scene in many papers experiment. Using TLS to collect all construction site data is time-consuming in practice. At first, we must carry out the control network by using total station. And then collecting point cloud station by station using TLS.
2) Application accuracy requirements are not clear. Different applications require different data accuracy. For example, in the process of quality control, the data precision is often required to be higher, while in the energy modeling applications, the data is not strictly required to be as high as above demand.
3) The method is not sufficiently automatic. Such as requiring manual input of multiple parameters, achieving goals with commercial software and more restrictions on the original data.

At present, the emergence of some new technologies makes it possible to solve the above limitations. Both high-precision point cloud and collection efficiency are needed. The effect can be achieved by optimizing the scanning plan [19], [84], [85]. But provided the precision request of point cloud is not very high, we can use MLS [24], [33] to collect data.

According to our survey that different applications request different scanning accuracy. A framework that creates accuracy corresponding relationship between data with various applications need to be proposed. It has quantitative requirements for various applications. The accuracy of point cloud can help decide whether the obtained data is suitable for the specific application. The most efficient data acquisition method that directs to the application can also be selected according to the framework.

Deep learning technology can reduce the parameter setting process. It is useful for automation in applications in the life cycle of building life. Some papers [86]–[88] focus on automatic registration based deep learning. We can use these methods in the workflow of comparing point cloud with BIM. In addition, modeling for unusual shapes building that cannot be described by parameterized methods can also adopt deep learning technology to address labor-consuming problem.

For various kinds of applications, there are some different demands that need to be addressed. In the construction progress tracking domain, a more general approach without any assumptions about the shape of a building component is needed. In the building components quality control domain, several millimeters precision is required to detect poor quality components. The noise of point cloud needs to be filtered out, because high precision request of the application. A more robust and more accurate noise point filter approach is needed. In the construction site safety domain, continuous construction site observation plays an important role. TLS has a long observation period and large observation range. While multipleline lidar (e.g., velodyne VLP16) has a short observation period and restricted resolution. The fusion of their data may work out the continuous construction site safety observation. In the SHM domain, the complete point cloud of buildings is necessary. Scan from multiple viewpoints needs to be stitched together automatically. In the rescue after the disaster domain, damage patterns may be predicted by deep learning that based the accurate data from synthesizing technology. In the energy modeling and building modeling, approaches for irregular object modeling need more attention, which is a challenge that must be overcome in the process of modeling automation. Based synthetic point cloud data, the data-driven deep learning framework may play a crucial role.

To accomplish goals of various applications in the life cycle of building, researchers should have an extensive knowledge background in construction, remote sensing, image processing, deep learning, and some related technologies. Future research programs need to focus on developing more automatic and more robust algorithms. In addition, researchers need to keep be curious about emerging hardware. New hardware often makes big changes in these applications of building.

VII. Conclusion

This article summarizes combined methods of 3-D laser scanning and BIM at first, and provides comprehensive review of applications in the life cycle of building. In addition, the limitations in the reviewed papers and impact of emerging technologies on applications also be discussed. A total of **95** related papers over the last decade are reviewed. The authors summarized two combined methods of 3-D laser scanning and BIM. Then authors analyze these various applications based on combined technology in the life of buildings: construction progress tracking; building components quality control; construction site safety; SHM; rescue after disaster; energy modeling and management; and modeling for existing building. Based on the observed limitations in reviewed papers, the authors conclude some potential future research trend for these applications-based emerging technology at the same time.

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Jingbin Liu received the Ph.D. Degree from Wuhan University, Wuhan, China, in 2008.

From 2008 to 2016, he was a Specialist Research Scientist with Finnish Geospatial Research Institute (FGI, formerly known as Finnish Geodetic Institute). He is a Professor in positioning and navigation with State Key Laboratory of Information Engineering in Surveying, Mapping and Remote Sensing, Wuhan University, Wuhan, China. His interest areas include indoor and outdoor positioning, smartphone navigation, indoor mobile mapping, and GNSS/INS/SLAM integration technology.

Dong Xu received the B.S. degree in surveying and mapping engineering from China University of Mining And Technology, Xuzhou, China, in 2017, and the M.S. degree in surveying and mapping engineering in 2019 from Wuhan University, Wuhan, China, where he is currently working toward the Doctoral degree.

His research interests include laser scanning and data processing.

Juha Hyyppä received the M.Sc., Dr.Ing., and Dr.Sc. degrees, all with honors, from Helsinki University of Technology, Helsinki, Finland, in 1987, 1990, and 1994, respectively.

He is currently a Professor of remote sensing and photogrammetry, Finnish Geospatial Research Institute, Director of the Centre of Excellence in Laser Scanning Research, laserscanning.fi, and a Distinguished Professor, Shinshu University (Japan). His references include 30 years experiences in research team leadership, coordination of more than ten international science projects, and author of more than 200 ISI Web of Science listed papers. He has focus on laser scanning systems, their performance and new applications, especially related to mobile, personal and ubiquitous laser scanning and their point cloud processing especially to forest information extraction.

Yifan Liang received the B.S. degree in surveying and mapping engineering from China University of Mining And Technology, Xuzhou, China, in 2017. He is currently working toward the doctoral degree at Wuhan University, Wuhan, China.

His research interests include laser scanning and data processing.