Comparative analysis of technologies and methods for automatic construction of building information models for existing buildings

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ABSTRACT: Building Information Modelling (BIM) provides an intelligent and parametric digital platform to support activities throughout the life-cycle of a building and has been used for new building construction projects nowadays. However, most existing buildings today do not have complete as-built information documents after the construction phase, nor existed meaningful BIM models. Despite the growing use of BIM models and the improvement in as-built records, missing or incomplete building information is still one of the main reasons for the low-level efficiency of building project management. Furthermore, as-built BIM modelling for existing buildings is considered to be a time-consuming process in real projects. Researchers have paid attention to systems and technologies for automated creation of as-built BIM models, but no system has achieved full automation yet. With the ultimate goal of developing a fully automated BIM model creation system, this paper summarises the state-of-the-art techniques and methods for creating as-built BIM models as the starting point, which include data capturing technologies, data processing technologies, object recognition approaches and creating as-built BIM models. Merits and limitations of each technology and method are evaluated based on intensive literature review. This paper also discusses key challenges and gaps remained unaddressed, which are identified through comparative analysis of technologies and methods currently available to support fully automated creation of as-built BIM models.

1 INTRODUCTION

BIM intends to develop the process and use of a computer generated model to simulate the planning, design, construction and operations and maintenance of a building (Azhar, 2011). The resulting building information model not only focuses on creating a simple 3D model but a data-rich, object-oriented, intelligent and parametric digital representation of the building to support diverse activities throughout the life-cycle of the building. This smart model providing an intelligent platform could extract and analyse the whole construction project achieving various users' needs, such as energy simulation, structure analysis, and construction plan, etc.

Buildings can be classified into three types according to their ages: new buildings, existing buildings and heritage buildings. The majority of existing buildings and heritage buildings constructed before the BIM was introduced do not have initial or updated BIM models. With the development of the BIM platform today, the industry has started to use BIM-based tools for new construction projects, and furthermore the emphasis related to the BIM research also include operational phase and maintenance phase or even retrofitting/refurbishment phase of existing buildings. As shown in Figure 1, process (1) stands for creating a BIM model for new building from the design phase through the retrofitting phase, while process (2) presents creating an as-built BIM model for existing buildings.

Missing or incomplete building information is one of the main reasons leading to manage existing building projects with low-level efficiency. During the operations and maintenance phase or the retrofit phase, uncertain recognition of existing building documents and inaccurate assumptions about the condition of the building might result in unintended errors or even accidents. Since the BIM is accepted to act as a digital platform with comprehensive building information, it also should be applied to operate and manage existing buildings. In reality, however, there are a lot of challenges in creating BIM models for existing buildings due to, for example, 1) Missing or lacking complete or effective building documents; 2) the whole process of creating an as-built BIM model needs efforts, costs and time. Skilled workers are also necessary to successfully complete the process (Figure 1).

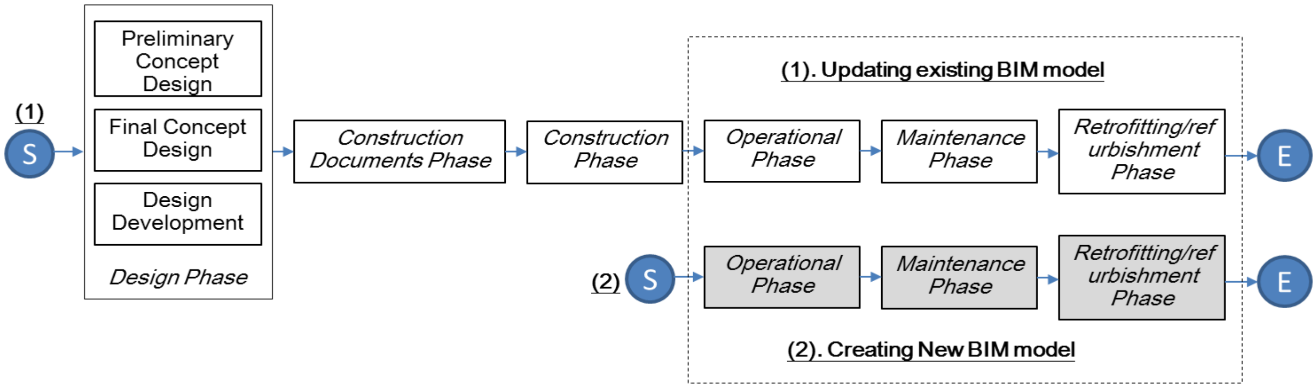

Figure 1 Comparison existing buildings and new buildings of BIM model creating process in LC

Considering that it is a time-consuming and costly manual process to create an as-built BIM model, research has concentrated on how to make the process fully automatic. On one aspect, a BIM model is not a simple 3D geometry model, but each component is registered and connected with their building information. On another aspect, building elements hidden behind another elements are hard to identify from the actual building (e.g. pipeline systems are always settled under the decoration layer) (Volk et al., 2014). Hence, it is indeed a difficult research problem to automatically create existing building models, which has been investigated by many research groups over the last 30 years, while the industry has not gotten enough breakthroughs so far (Nagel et al., 2009). These difficulties have been mentioned by many researchers before and some of the key difficulties are summarized as following:

a) Redundant efforts and resources are needed. As we create an as-built BIM model, both geometry information and building information are required. Sometimes it is not easy to collect all necessary data. Extra time and effort are the must (Arayici, 2008);
b) Complex processes of input data and reconstructed models (Nagel et al., 2009);
c) Extra data errors and inaccuracies; There exist uncertainties in interpretation and an additional verified process is needed (ibid).

In recent decades, there are a lot of contributions in this area. This paper mainly focuses on comparing and analysing technologies to create as-built BIM models. In the following sections of this paper, data capturing and building surveying technologies applying in real projects are explained. Data processing technologies and object recognition approaches are also compared and summarized in the second part, followed by describing as-built BIM modelling. Based on the knowledge and lessons learnt in this study, research conclusions and future work are described in the last chapter.

2 COMPARISON AND ANALYSIS OF CURRENT TECHNOLOGIES & METHODS

Creating an as-built BIM model can be differentiated between for new and for existing buildings, as the degree of difficulty, the quality of building information and the availability and functionality requirements of building information are varied from each other (Volk et al., 2014). For new buildings, according to various requirements of designers and owners, the BIM model is created in an interactive way using BIM-based design authoring applications (e.g. Revit, ArchiCAD) in the design phase. For existing buildings, however, there are two different scenarios. If there exists an initial BIM model of the target building, it is only required to update the model with missing and newly-created building information in the construction or operation phases, and correct inaccurate information. If there is no existing model, a new BIM model needs to be created by directly gathering all the information from the actual building and available resources such as drawings and specifications documents.

Automated as-built BIM creation means achieving a streamline, which starts with an input (e.g. point clouds/images/video/others) and ends up with the as-built BIM model, while the whole intermediate processes apply semi-automated or automated techniques saving effort & time and improving efficiency (Figure 2).

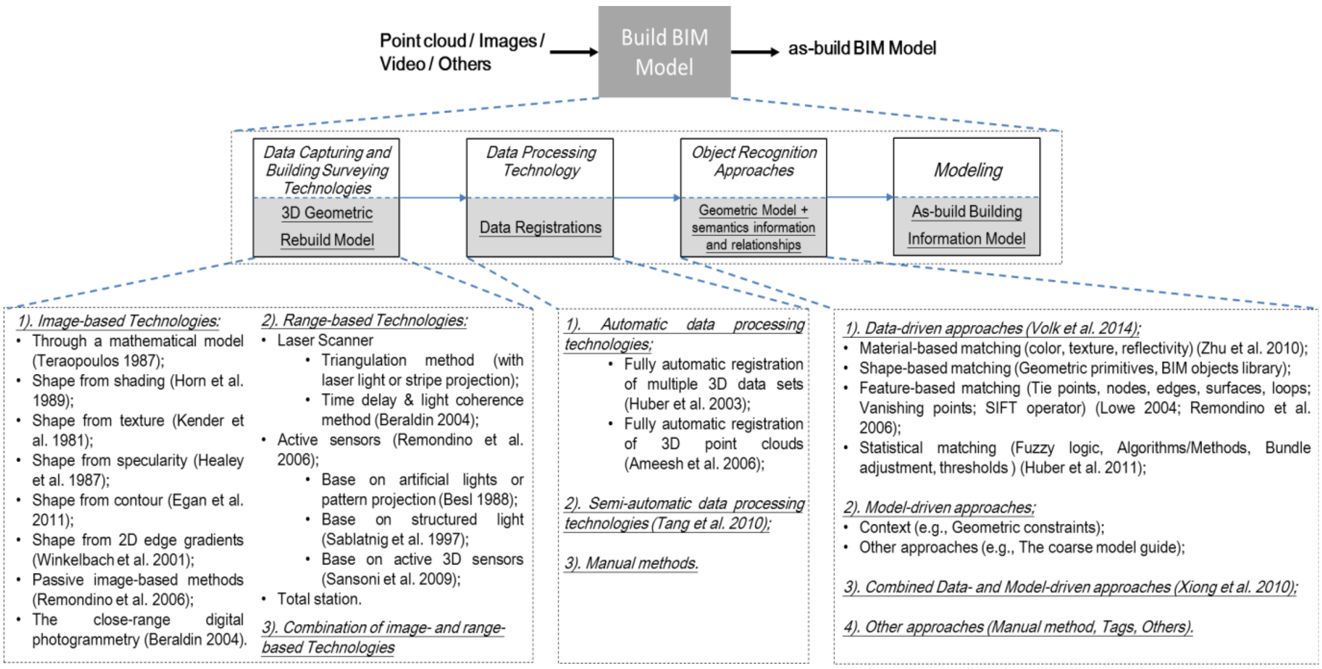

Figure 2 Technologies and processes of reconstructing as-built BIM model

As shown in Figure 2, creating an as-built BIM using different technologies can be divided into four main steps: 1) data capturing step in which various building surveying technologies can be chosen and 3D geometric models are created; 2) data processing step in which all measurements from the 1st step (e.g. point clouds) are combined and registered into one representation in a global coordinate system; 3) object recognition step in which the 3D geometric models in the global coordinate system are complemented by semantic information and objects also are given relationships with each other; 4) modelling the as-built BIM model step in which the primary partial information model will become a semantically rich BIM. In this model, every object has its meaning and information. Further, the whole process and primary goal should be gained at reasonable time and cost.

2.1 *Data Capturing and Building Surveying Technologies*

Creating a 3D geometry model of an existing building is a process of applying data capturing and building surveying technologies to measure and to capture existing objects and/or around environments, and then choosing reasonable software or techniques to get a complete 3D model. Data capturing technologies can be divided into contact based and non-contact based technologies. Considering that 3D geometry models are usually produced using non-contact based technologies in recent years, this paper concentrates on discussing this type. They can be further classified into three sub-categories: image-based, range-based, and comprehensive technologies, as shown in Table 1. Image-based technologies depend on geometry or surface characteristics of building elements. For example as shown in Figure 2, accurate 3D geometry models are created from shading, texture, and contour of buildings from their images, while range-based technologies obtain 3D models directly from the actual building according to geometric information of buildings with high accuracy (such as laser scanners or total stations). However, generally the cost of the range-based technologies is higher than the image-based technologies.

Hence, it is usually not an easy task to choose a suitable technology. There are a lot of factors that should be taken into consideration. When researchers evaluate and confirm a reasonable data capturing and building surveying technology, important specifications and factors affecting the decision should be determined. GSA (2009) has mentioned about some of these factors including project requirements (e.g. measurement uncertainty, resolution, and level of detail), project schedule, time, and costs. Based on discussions and prior research, we have identified eight factors in the decision process as following:

a) Degree of automation (1. automatism of the whole correspondence process; 2. meeting project requirements) (Kandil et al., 2014);
b) Applicability to free-form objects and fitting for BIM transformation (Mian et al., 2005);
c) Accuracy (reducing errors and level of details) (ibid);
d) Efficiency with respect to time (ibid);
e) Robustness to the range image resolution and surface sampling (ibid);
f) Robustness to dealing with adjacent views (Volk et al., 2014);
g) Data Volumes (ibid);
h) Cost (ibid).

Table 1 summarizes the results of evaluating some technologies currently available by these eight factors. The use of laser scanners shows promising properties of creating a complete 3D model, but needs relative large data volumes and high cost.

The table also shows that any single technology is not possible to meet all the requirements. So combination of different technologies is the comprehensive way to overcome and supplement limitations of each individual technology (Volk et al., 2014). Photogrammetry and laser scanning have often been used together to capture complex or large objects of a building. In this way, a complete and detailed 3D model data can be obtained efficiently. For example, Liu et al. (2012) used a laser scanner and a camera to build a 3D model in only achieving incomplete as-built data condition.

In real projects, it is not always practical to scan all the information of a building in the light of laser scanning. Besides, the image-based technology is difficult to deal with irregular surfaces and cannot provide the model automatically. So the most logical and effective method is: the basic outlines (e.g. the building surfaces) are captured by image-based technologies (e.g. photogrammetry) and the details are modeled through range-based one (El-Hakim et al., 2002).

2.2 *Data Processing Technology*

Data processing technology aims at transferring the image-based and range-based geometry data in its local coordinate system to the global coordinate system, as the initial data are expressed from different kinds of data capturing methods in their local coordinate frames. All of the data should go through this transformation process to be presented in the common global coordination system. This process is also known as registration as shown in Figure 2 (Tang et al., 2010). Some automatic data processing technologies have been available. For example, Ameesh et al. (2006) developed a technique, which could register three dimensional (3D) point clouds automatically. This comprehensive technique is established basing on the two related Extended Gaussian Images (EGIs) in the Fourier domain and taking advantages of harmonic transforms. It could fully automatically transfer point clouds with little overlap. Huber et al. (2003) also introduced an automatic method to register multiple 3D model data. This registration algorithm tries to transfer the input data into surface meshes through a surface matching engine. However, they are still a manual or semi-automatic process.

Table 1 Summary and comparison of data capturing technologies
(Furukawa et al. 2009; Nagel et al. 2009; Tang et al. 2010; Volk et al. 2014)

Data Capturing Technologies	Types of Technologies		Characteristics of Technologies 1	2	3	4	5	6	7	8
Non-contact Technologies	Range-based Technologies	Total Stations	M	M	M	M	M	M	H	M
		Laser Scanning (e.g. terrestrial/airborne laser scanners, LADAR, LiDAR)	Y	Y	Y	M	Y	M	H	H
	Image-based Technologies	Photogrammetry	M	N	M	Y	M	M	M	L
		Videogrammetry	M	N	Y	M	M	M	M	M
	Other Technologies	Pre-existing information (e.g. photo, geometry)	N	M	Y	Y	N	N	M	M
		Tagging (e.g. RFID, Barcodes)	M	N	M	Y	Y	Y	L	M
Contact Technologies	Manual Technologies	CMMs Callipers Others	N	N	M	N	N	N	L	L

*Y stands for fully satisfying all the requirements; M stands for marginally satisfying the requirements (1-6) and the medium level for data volume and cost (7 and 8); N stands for dissatisfying the requirements;
*H and L stand for high and low, respectively;
*LADAR: Laser Detection and Ranging; LiDAR: Light Detection and Ranging; RFID: Radio-frequency Identification; CMMs: Coordinate Measuring Machines.

2.3 *Object Recognition Approaches*

The third step is to recognize building components and connect them with their building information. For example, object recognition approaches need to recognize classes of objects, such as recognizing all the window objects with various height, width, etc. As shown in Figure 2, object recognition approaches can be divided into four types: data-driven, model-driven, combined data- and model-driven approaches, and others. Data-driven approaches recognize objects and sort building information based on their captured data. As shown in Table 2, these methods can be mainly classified into feature-based matching, shape-based matching, material-based matching and statistical matching, while model-driven approaches require the predefined structures to extract building information (Volk et al., 2014). These approaches always rely on the architectural information or context. Table 2 also summarizes disadvantages and advantages of the approaches that are the most commonly used ones nowadays. However, comprehensive methods (i.e., combined data- and model-driven approaches) have also been applied in order to integrate different methods and overcome disadvantages of each approach. For instance, Xiong and Huber (2010) used building context to create semantic 3D models of indoor environments. Despite the efforts, manual identification is still one of the most common options in the practice.

The statistical matching method is considered to have higher geometric accuracy. In particular, the fuzzy theory has been highly chosen by many researchers as a natural representation framework for real-world concepts (Lee et al. 2009). The fuzzy theory is also recognized as a promising method applied in object recognition approaches. Kim et al. (2009) tried to achieve real-time object recognition by using neuro-fuzzy to control workload-aware task pipelining.

Table 2 Summary and comparison of object recognition approaches
(Zhu et al. 2010; Lowe 2004; Volk et al. 2014; Huber et al. 2011; Tang et al. 2010; Lee et al. 2009)

Object Recognition Approaches		Types of Approaches	Advantages	Disadvantages
Data-driven Approaches	Feature-based matching	Tie points, nodes, edges, surfaces, loops Vanishing points SIFT operator	Flexible (allowing for large image variations); Automatically extracted and matched features;	Unsuitable for similar elements detection; Redundant information (too much for 3D model); High requirements during this process;
	Shape-based matching	Geometric primitives Segmentation, cell decomposition BIM objects library Images/videos	Divided into explicit shape, implicit shape and relationship representations (Explicit one is suitable to describe free-form objects); Implicit one can describe geometric needs accurately for building BIM model;	Explicit method sometimes may lead to mix up the volumetric objects and surface ones; Implicit one is not well suited for algorithms, which use for automatically recognise objects;
	Material-based matching	Colour/Texture Reflectivity	Being suitable for collecting information of structural elements;	Unable to identify correctly structural element (e.g. these elements connected each other or made of the same material);
	Statistical matching	Fuzzy logic Algorithms/Methods (FEM, LSM) Bundle adjustment Thresholds	Higher geometric accuracy; Being independent from the shape of components;	Complex images fitting should be achieved manually; Semi-automatic;
Model-driven Approaches	Context	Constraints	Full automation; Being reliable and accurate for create building models.	High requirements (e.g. feature detection and closely spaced images).
	Other Technologies	The coarse model guide		

*SIFT: Scale-invariant feature transform; FEM: Finite element method; LSM: Least square method.

2.4 *Creating As-built BIM Models*

Creating an as-built BIM model aims at: firstly, the representation of the BIM model can match and express geometric components accurately, which contain individual surfaces and volumetric shapes. Secondly, the geometric components of the BIM model also need to be labeled with an object category. Furthermore, relationships among different components should be described clearly. For instance, walls must be connected to slabs at the bottom (Volk et al., 2014). If the as-built building data comes from data capturing and building surveying, it requires the building information in details and with high accuracy as well. The "level of detail" (LoD) is an effective method to describe the information richness and the level of accuracy based on the primary goal of the construction project (Leite et al., 2011). When we create building information models, the LoD defines the quality and integrality. We also use it to verify the accuracy of an as-built BIM model, when different methods are chosen to construct the BIM model.

As mentioned earlier, it takes a significant amount of time and effort to build an as-built BIM model in real projects. It often needs several months even for highly skilled modelers to build a BIM model for an existing building just with common size, which will depends on the requirements and details about the project model (Tang et al., 2010). Figure 3 lists examples of the software applications commonly used in the practice, which output BIM models or CAD models. Although the

Potomodeler claims to generate 3D models based on images taken from a typical camera, it does not achieve fully automated process of creating as-built BIM models.

Some researchers intended to reduce time depending on pre-existing information, as the preexisting information of a building can predigest the whole BIM construction process and it provides a reference for further progress. However, it is still needed to gain extensive attention and deeper research on this topic. An automatic or semi-automatic system is necessary and imperative to improve efficiency of building as-built BIM models for existing buildings.

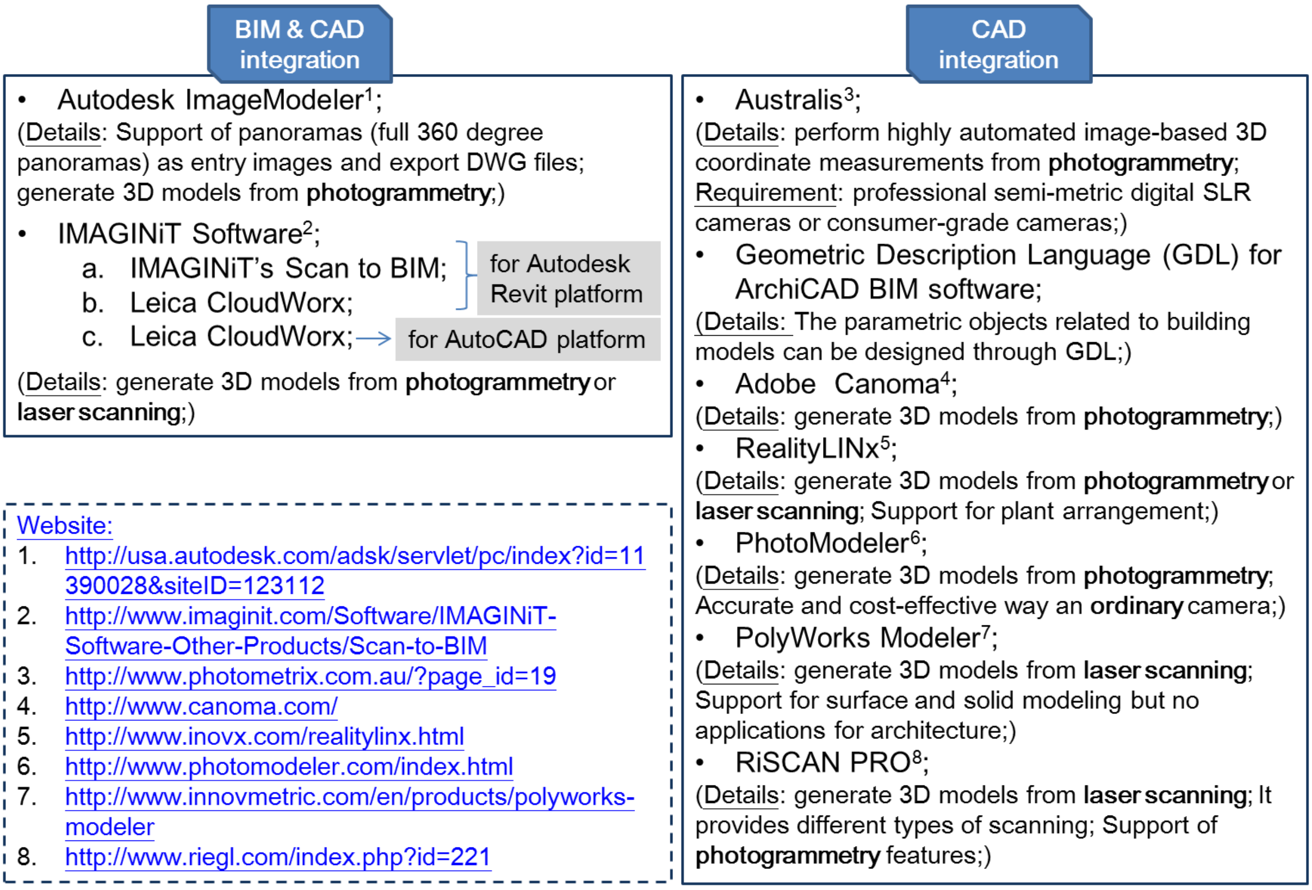

Figure 3 Summary of capturing and modeling software with respect to BIM or CAD integration

3 OVERVIEW OF SEMI-AUTOMATIC OR AUTOMATIC METHODS OF CREATING BIM MODELS FOR EXISTING BUILDINGS

The creation of an as-built BIM model focuses on surveying the geometry and surface of an existing building, improving this collected information into a primary semantically rich model and finally achieving a building information representation referring to LoD. In Chapter 2, the process of creating automated or semi-automated as-built BIM has been introduced and four steps of this streamline with existing techniques & methods within the relevant fields are also compared and analysed (Figure 2).

This chapter has twofold aspects: 1) to list the state-of-the-art systems for creating as-built BIM models; 2) to evaluate their merits and systems for automating the process and to put forward the possibility and main gaps to achieve fully automating the process.

3.1 *State-of-the-art of Creating As-built BIM Models*

Nagel et al. (2009) developed a two-step BIM model construction process. The process starts from 3D geometry models, which can be generated from different methods, such as laser scanning or photogrammetry. Then, they choose CityGML as an intermediate layer transferring geometry models to CityGML building models. The last step is to create IFC (Industry Foundation Classes) building models from CityGML. Since there are considerable gaps between the pure 3D geometry model and the as-built BIM model, it is difficult to achieve a fully automated creation process directly. In order to simplify the overall process and to increase the flexibility and operability, Nagel and his research team proposed the system. However, limitations include: 1) formalizations for CityGML or IFC are needed; and 2) the optimal and suitable data interpretation is also an issue.

Brilakis et al. (2010) proposed a framework combining video capturing and laser scanning technologies for automated as-built BIM creation. A 3D geometry model is first created through recording the geometry information and generating semantically needful components (e.g. columns and beams) as well. Then, fulfilling relationship definitions and fitting object recognition algorithms achieve as-built BIM construction. The main contribution of this research is reducing redundant tasks automatically and allowing for concurrent modelling processes.

Murphy et al. (2013) devote on Historic Building Information Modeling (HBIM). The HBIM is a smart library of parametric objects for historic buildings, which matches point cloud and image data. These parametric objects were created depending on Geometric Description Language (GDL), which is a kind of programming language embedded in the ArchiCAD, a commercial BIM authoring application. The final HBIM would automatically create cut sections and 3D models. However, it is still under development for real projects.

Kandil et al. (2014) provided a case study in which they captured a progressive history of a renovation project using a laser scanner and a camera to develop a complete as-built BIM model. However, the difficulty may concentrate on how to integrate different information sources.

There are also some researchers who have tried to start from a category of buildings or environmental components. For example, Livny et al. (2010) provided the tree reconstruction method and it can automatically rebuild multiple tree models directly from laser scanning data.

3.2 *Analysis*

Current as-built BIM creation processes are time-consuming and costly, and even sometimes the as-built BIM model may be considered to be meaningless and counteract the benefits for civil infrastructure projects, when comparing with effort and time. Although many systems have been proposed and developed, it is still a long way to achieve automated as-built BIM creation for existing buildings. The main research areas needed to be concentrated on and addressed include:

a) How to choose suitable capturing technologies with relatively low cost;
b) How to model complex structures;
c) How to easily distinguish the target building from surrounding extra environments;
d) How to represent models automatically using volumetric components rather than surface representations; and
e) How to transfer the input data effectively during data processing phase.

The whole papers described show promising opportunities of automated as-built BIM creation in future, but required more automated and intelligent way to achieve this goal.

4 CONCLUSION AND FURTURE WORK

It is beneficial to create an as-built BIM model for existing buildings as the as-built BIM models can help improve data management, support decision makings, increase management accuracy in the post-construction phases, and facilitate operations and maintenance of the building. However, current methods and technologies of creating as-built BIM models mainly depend on human effort. Although data may be collected automatically from diverse sources and methods such as laser scanners or camera, integration of the raw data, recognizing building objects and building logical relationships between the objects are all performed manually. In this paper, we began with the introduction of the streamline of creating an as-built BIM model. Four steps have been compared and analyzed in details, which contain data capturing, data processing, object organization and BIM model creation. Then, we focused on surveying and comparatively analyzed potential techniques and currently promising systems to automatically create as-built BIM models. Both promising opportunities and challenges are also discussed in this paper.

5 REFERENCES

Ameesh M, Patterson A and Daniilidis K (2006) Fully automatic registration of 3D point clouds. *Computer Vision and Pattern Recognition*, 2006 IEEE Computer Society Conference **1**.

Arayici Y (2008) Towards building information modelling for existing structures. *Structural Survey* **26(3)**: 210-222.

Azhar S (2011) Building information modeling (BIM): Trends, benefits, risks, and challenges for the AEC industry. *Leadership and Management in Engineering* **11(3)**: 241-252.

Beraldin JA (2004) Integration of laser scanning and close-range photogrammetry-the last decade and beyond. *In International Society for Photogrammetry and Remote Sensing*.

Besl PJ (1988) Active, optical range imaging sensors. *Machine Vision and Applications* **1(2)**: 127-152.

Brilakis I, Lourakis M, Sacks R, Savarese S, Christodoulou S, Teizer J and Makhmalbaf A (2010) Toward automated generation of parametric BIMs based on hybrid video and laser scanning data. *Advanced Engineering Informatics* ***24*****(4):** 456-465.

Egan E J, Todd J T, and Phillips F (2011) The perception of 3D shape from contour textures. *Journal of Vision* **11(11)**: 48-48.

El-Hakim S and Beraldin JA (2002) Detailed 3D reconstruction of monuments using multiple techniques. *Proceedings of the International Workshop on Scanning for Cultural Heritage Recording-Complementing or Replacing Photogrammetry*, 58-64.

Furukawa Y, Curless B and Seitz SM (2009). Reconstructing building interiors from images. *Proceedings of the International Conference on Computer Vision (ICCV)*, 80-87.

GSA (2009) GSA BIM Guide For 3D Imaging, version 1.0 **3**, http://www.gsa.gov/bim: U.S. General Services Administration (GSA).

Healey G and Binford TO (1987) Local shape from specularity. *Proceedings of the 1st IEEE International Conference on Computer Vision*, London, UK, 151-160.

Horn BKP and Brooks MJ (1989) Shape from Shading. *MIT Press*, Cambridge, Massachusetts.

Huber DF, and Hebert M (2003) Fully automatic registration of multiple 3D data sets. *Image and Vision Computing* **21(7)**: 637-650.

Huber D, Akinci B, Oliver AA, Anil E, Okorn BE and Xiong X (2011) Methods for automatically modeling and representing as-built building information models. *Proceedings of the NSF CMMI Research Innovation Conference*.

Kandil A, Hastak M and Dunston PS (2014) Developing as-built building information model using construction process history captured by a laser scanner and a camera. *Bridges*, **10**.

Kender JR (1981) Shape from Texture. *Carnegie Mellon University*, AAT 8114629.

Kim JY, Kim M, Lee S, Oh J, Oh S and Yoo HJ (2009) Real-time object recognition with neuro-fuzzy controlled workload-aware task pipelining. *IEEE micro* ***29*****(6)**: 28-43.

Lee J, Kuo JY and Xue NL (2001) A note on current approaches to extending fuzzy logic to object-oriented modeling. *International Journal of Intelligent Systems* ***16*****(7)**: 807-820.

Leite F, Akcamete A, Akinci B, Atasoy G and Kiziltas S (2011) Analysis of modeling effort and impact of different levels of detail in building information models. *Automation in Construction* ***20*****(5)**: 601-609.

Lowe D G (2004) Distinctive image features from scale-invariant keypoints. *International Journal of Computer Vision* **60(2)**: 91-110.

Liu X, Eybpoosh M and Akinci B (2012) Developing As-built building Information Model using construction process history captured by a laser scanner and a camera. *Proceedings of Construction Research Congress 2012: Construction Challenges in a Flat World*, West Lafayette, USA.

Livny Y, Yan F, Olson M, Chen B, Zhang H and El-Sana J (2010) Automatic reconstruction of tree skeletal structures from point clouds. In *ACM Transactions on Graphics (TOG)* **29(6)**: 151-159.

Remondino F and El-Hakim S (2006) Image-based 3D Modelling: A Review. *The Photogrammetric Record* **21(115)**: 269-291.

Mian AS, Bennamoun M and Owens RA (2005) Automatic correspondence for 3D modeling: an extensive review. *International Journal of Shape Modeling* **11(2)**: 253-291.

Murphy M, McGovern E and Pavia S (2013) Historic Building Information Modeling–Adding intelligence to laser and image based surveys of European classical architecture. *ISPRS journal of photogrammetry and remote sensing* **76**: 89-102.

Nagel C, Stadler A and Kolbe TH (2009) Conceptual requirements for the automatic reconstruction of Building Information Models from uninterpreted 3D models. *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, **38(3-4/C3)**.

Sablatnig R and Menard C (1997) 3D reconstruction of archaeological pottery using profile primitives. *Proceedings of the International Workshop on Synthetic–Natural Hybrid Coding and Three-Dimensional Imaging*, Rhodes, Greece, 93-96.

Sansoni G, Trebeschi M and Docchio F (2009) State-of-the-art and applications of 3D imaging sensors in industry, cultural heritage, medicine, and criminal investigation. *Sensors* **9(1)**: 568-601.

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)**: 829-843.

Teraopoulos D (1987) On Matching Deformable Models to Images.

Volk R, Stengel J and Schultmann F (2014) Building Information Modeling (BIM) for existing buildings—Literature review and future needs. *Automation in Construction* **38**: 109-127.

Winkelbach S and Wahl FM (2001) Shape from 2D edge gradient. *Proceedings of the 23rd DAGM Symposium on Pattern Recognition*. Springer, Berlin. Lecture Notes in Computer Science **2191**: 377-384.

Xiong X and Huber D (2010) Using context to create semantic 3D models of indoor environments. *Proceedings of the British Machine Vision Conference (BMVC).*

Zhu Z and Brilakis I (2010) Concrete column recognition in images and videos. *Journal of Computing in Civil Engineering* ***24*****(6)**: 478-487.