An Overview of Approaches for automated intelligent Building Information Modeling

Bastian PLASS, Germany

1. INTRODUCTION

The construction industry plays a key role in Germany. Within the last years the economic importance of the construction industry refers to the constant development of the total volume (Statistisches Bundesamt 2019b) and also by the related increase in employment (Statistisches Bundesamt 2019a). In a European comparison 2017 and with a total construction volume of 327 billion EUR Germany was in the first place ahead of France, Great Britain and the Netherlands in sixth place (Hauptverband der Deutschen Bauindustrie 2020). Approximately 2/3 of the efforts are caused by existing buildings (BBSR 2019). Challenges facing a new generation of surveyors and civil engineers can be described by rapid urban growth, the associated housing shortage and the requirement for innovative mobility concepts. Those objectives clash with a highly interdisciplinary and fragmented industry struggling with stagnant productivity due to numerous problems such as time overrun, cost overrun and waste generation (Hussin et al. 2013). The low digitalisation index of the construction industry is identified as the major reasons of these deficits by several studies (McKinsey & Company 2018).

In this context Building Information Modeling (BIM) describes an instrument to assist the building sector in its digital transformation. It is supported and promoted both by international working groups and national institutions (EU BIM Taskgroup 2017; BBSR 2019). The usage of BIM aims at optimizing the value chains in architecture, engineering and construction (AEC) industry. Cooperative planning processes with all parties involved and the maintenance of a digital, multidimensional model over the entire life cycle of a building faces the loss of data and knowledge leading to the above-mentioned effects. With BIM the construction process can be planned virtually in order to avoid incorrect decisions in real project loop, to prevent media disruptions, intransparency, redundant data sources and to establish missing communication lines (Kaden et al. 2019).

Buildings can be classified by type of use (e.g. residential, commercial, public), age (e.g. new construction, existing building) and owner (e.g. private owner, public owner). Those different conditions influence the application and advantages of BIM which is not limited to new constructions by managing such projects digitally from scratch. In recent years the percentage of new construction volume in public engineering has shown an increasing trend but is low in comparison to projects on existing buildings. Ensuring building functionality to increase energy efficiency and to extend their remaining useful life both residential and non-residential construction are dominated by investment in modernisation and energy-related renovation (BBSR 2019). A strategic planning of modernisation, refurbishment but also conversion or extension actions requires existing documents such as construction papers or a model of the current condition (as-built) which are usually not available and have to be obtained repeatedly. This case offers optimisation potential and shows the importance of as-built documentation, that must be created and archived after a construction work. Hence the scope of BIM is not limited to new construction engineering but is crucial in case of existing buildings. In addition to AEC industry the documentation of cultural heritage is an emerging field of application (Rocha et al. 2020) which defines different requirements for data acquisition and digital data modeling.

As-built documentation is characterised by a mainly manual process to achieve a BIM Model from a measured abstraction of an object (Son et al. 2015; Volk et al. 2014; Hichri et al. 2013). This workflow is called Scan-to-BIM and leads to the demand for efficient and preferably automated methods which are subject of current research. As experts in spatial data acquisition and data modeling surveyors should have a strong desire bringing its expertise to the emerging world of BIM and thus contribute to revolutionise an entire industry.

2. DEFINITION OF BIM

According to the international standard Building Information Modeling (BIM) is defined as „shared digital representation of a built object […] to facilitate design, construction and operation processes to form a reliable basis for decisions" (ISO 2016). A digital, semantically enriched, object-oriented and parametric building model provides its backbone. In a limited perspective little or lonely BIM refers to a virtual building model that serves as a central information repository for a single task. In contrast, big or social BIM can be seen as a paradigm for collaboration of an entire industry in which the model behaves as a central information hub. Thus the life cycle of a building, from planning and execution to operational use, can be digitally displayed and made available to all stakeholders (Kaden et al. 2019; Jernigan 2008).

In this paper BIM is used in narrow context (little BIM). The Scan-to-BIM method is currently being investigated for documentation purposes or for constructional measures on existing buildings. In a large number of practical and theoretical application studies challenges are described (Volk et al. 2014; Sistani 2017), workflows are defined (Rocha et al. 2020; Bassier et al. 2017; Bonduel et al. 2017; Pătrăucean et al. 2015) and methods are tested (Bosché et al. 2015; Freimuth and König 2019; Xiong et al. 2013; Yang et al. 2017). Objective of Scan-to-BIM process is to restore building information as efficiently as possible in a reverse engineering process (Valero et al. 2011). Based on a detailed 3D discretisation of the building by imaging measurement systems a "digital twin" can be created or updated in a currently still manual and error-prone process (Son et al. 2015; Volk et al. 2014; Hichri et al. 2013; Tang et al. 2010). Because of the average age of buildings in Germany, that can be dated before the emergence of the BIM method, as-built BIM creation (Figure *1*) is the most common application.

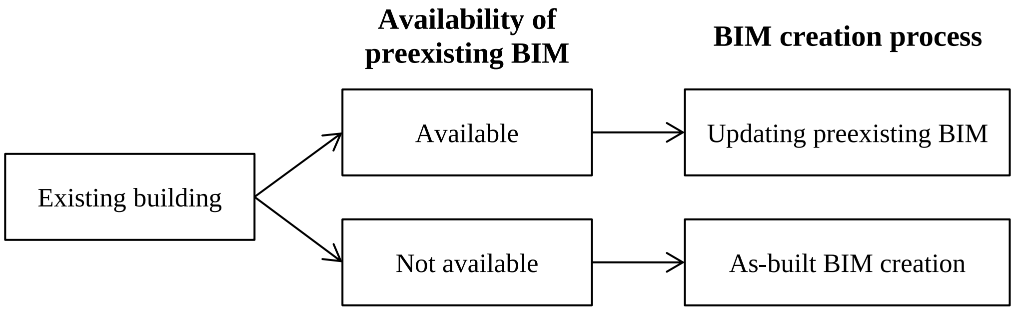

Figure 1: Scan-to-BIM processes regarding availability of preexisting models by Volk et al. 2014

The ”digital twin” is characterised by geometry, semantic attributes and topological relations (Eastman 2008) which are still created manually from 3D point cloud. Depending on the application specific requirements are defined for BIM models which concerns both accuracy and depth of information. The US-american specification ”Level of Development” (LoD) is curcial for this. The LoD is divided into a geometric (”Level of Geometry”, LoG) and a semantic (”Level of Information”, LoI) part (BIM Forum 2019). Known from computer graphics and virtual reality the ”Level of Detail”, used to describte the geometrical precision of buildings, has the same meaning as LoG. As-built BIM models are encoded with the highest LoD 500 (VDI 2552), include a realistic geometry and the information content required for the intended application. The model requirements must be related to the data collection methods. In this respect the ”Level of Accuracy” (LoA) defines an additional specification (USIBD 2016).
While methods for data acquisition are established and versatile the automated processing of the resulting 3D point cloud in context of Scan-to-BIM is a challenge that has not been solved yet (Bassier et al. 2019). An fundamental step and subject of current research is the identification of individual, regular structural elements such as floors, ceilings and walls in a semantically segmented 3D point cloud (Leoni et al. 2019; Bassier et al. 2017, 2016; Thomson and Boehm 2015; Xiong et al. 2013).

3. SCAN-TO-BIM WORKFLOW

Since the emergence of BIM in the AEC industry several workflows for as-built documentation have been proposed. Each use case is characterised by different challenges, so a generic workflow could not be defined. To build a BIM model of an existing building from scratch numerous sources of information are required. The geometry represents the first step for creation of the stock reference which is attributed and enriched with element-specific properties afterwards. Finally, it is necessary to establish the topological relations between the individual building elements (Macher et al. 2015; Hichri et al. 2013; Barbosa 2018) in order to exploit the full potential of BIM. Current research focuses on the automated generation of the geometric as-built stock reference based on a 3D point cloud (Stumm et al. 2017; Son et al. 2015; Macher et al. 2015).

3.1 Data Acquisition

Data Acquisition is the beginning of Scan-to-BIM workflows. Point clouds are a set of coordinates in 3D space which can be measured using various technologies. A dense 3D point cloud provides all information required for the geometric as-built stock reference. Cost and time factors, environmental conditions and LoD requirements during as-built documentation limit the list of potential measurement methods (Volk et al. 2014). Photogrammetry, laser scanning or a combination of both are major data capturing techniques which are relevant in Scan-to-BIM research (Rocha et al. 2020; Son et al. 2015; Volk et al. 2014; Hichri et al. 2013; Nguyen and Le 2013).

3.1.1 Photogrammetry

Photogrammetry is a non-contact method to obtain geometrical information of an object using image measurement techniques. First, the building is captured with a parametrically stable camera model by taking numerous images in different orientations. In the second step object features such as position, size and shape are determined. The processing of any number of image measurements is called bundle triangulation. To reconstruct the object individual images can be linked together using corresponding image points (Luhmann 2018).
Photogrammetric methods can be used for fast terrestrial and UAV-based data acquisition even for objects that are difficult to access and which are extended. Those images provide a high density of spatial information and accuracy potential. The main weaknesses and error potentials of such passive methods can be addressed to both insufficient object illumination and reflective or transparent surface characteristic. These restrictions have to be excluded by additional equipment (Kern 2003).

3.1.2 Laserscanning

Terrestrial Laserscanning is the most common used data acquisition method for Scan-to-BIM processes (Stumm et al. 2017; Volk et al. 2014). Based on electro optical, reflectorless distance measurement with a deflected beam in horizontal and vertical direction an object surface can be scanned pointwise. By measuring the distance and direction of the reflected laser beam the 3D coordinates can be calculated to the position of the scanning unit. Imaging scanners additionally captures the intensity of the incoming pulse in order to colour the point cloud in grayscales. According to the complexity of the object or items in the field of view numerous viewpoints may be required whose point clouds must be registered using identical points. Laserscanning units generate a detailed abstraction of objects in a range up to several kilometres depending on the measurement method (phase-based or time-of-flight). The major disadvantage of this active method is the distance-related beam divergence, step size (angular resolution), dependence of surface reflectivity and the random scanning principle as well as the associated time-consuming processing with regard to edges and corner points (Kern 2003).

Photogrammetric or laser-based data acquisition is highly influenced by the requirements of the BIM model. A high LoD is synonymous with a large data acquisition and data processing effort. The more unbiased single points describe an object the more accurate those can be modeled (inner accuracy). In addition, the outer accuracy (LoA) becomes particularly important in the area of big BIM in order to overlay different models or for interacting with their environment.

3.2 Data Processing

The processing of the raw data obtained from photogrammetry or laserscanning is non-trivial and a significant step in the Scan-to-BIM processes that require the knowledge of surveyors.

3.2.1 Photogrammetry

Transforming the photogrammetrically captured single images into a dense 3D point cloud is a semi-automatic process. The calculation of a multi-image set is based on the measurement of tie points in each image. Algorithms such as SIFT (Lowe 2004) can automate this work. Each object point is described in an image by a single pixel with radiometric information. Creating a dense 3D point cloud of the object from the multi-image set requires numerous rays for each object pixel. The configuration of the rays is crucial for the quality of the 3D coordinate and thus the BIM model to be created from them. An interpretation of the residuals, statistical accuracy and reliability of data is mandatory to identify distortions or geometrical imaging errors (Luhmann 2018).

3.2.2 Laserscanning

After each scan a 3D point cloud is already available. If one object is captured by several scans a registration process is required to transfer them into a uniform spatial reference system. Depending on the characteristics of environment and object, registration can be point-based via targets or feature-based as a best-fit (Kuhlmann and Holst 2017; Vosselman and Maas 2011). With the purpose to achieve an automated point cloud processing an accurate registration is essential (Lorenczat and Bergholz 2019). After registration the accuracy should be evaluated via check points (Kern 2003).

Apart from acquisition method the result is an unstructured 3D point cloud. Those has to be checked against gaps, georeferenced by control points, cleaned from outliers manually and thinned before modeling systematically. In case of occlusions a densification of the point cloud afterwards is still possible. With regard to the requirements from LoD and LoA the statistical accuracy should be evaluated.

3.3 Data Modeling

BIM-compliant data modeling refers to the creation of geometric building elements including their semantic information and topological relationships to neighbouring elements. Modeling in an unstructured 3D point cloud is a manual, time-consuming and error-prone procedure with a lack of automation (Son et al. 2015; Volk et al. 2014; Hichri et al. 2013; Tang et al. 2010). Research in this field of application is still in its infancy. First steps towards are limited to geometric as-built modeling from a structured point cloud without any semantics or topology (Volk et al. 2014).

One possible approach in BIM modeling is the semantic segmentation of an unstructured 3D point cloud in order to filter it, to limit the space of possibilities and thus enabling object recognition. The modeling of geometric primitives such as planes, cylinders, spheres or cones can be solved semi-automatically but with need of significant user input. This is why only rough elements are subject of this application yet. Supplementing planar (boundary representation, B-Rep) or solid shapes (constructive solid geometry, CSG) with semantics and topology cannot be solved automatically (Rocha et al. 2020; Bassier et al. 2019; Barbosa 2018; Chai et al. 2016; Pătrăucean et al. 2015; Volk et al. 2014; Tang et al. 2010).

4. AS-BUILT BIM APPROACHES

Scan-to-BIM research is concerned with the development of several approaches to automate the process of as-built documentation. Four basic approaches are distinguished: heuristic approaches, approaches based on context, approaches based on ontologies and approaches based on prior knowledge (Hichri et al. 2013; Tang et al. 2010).

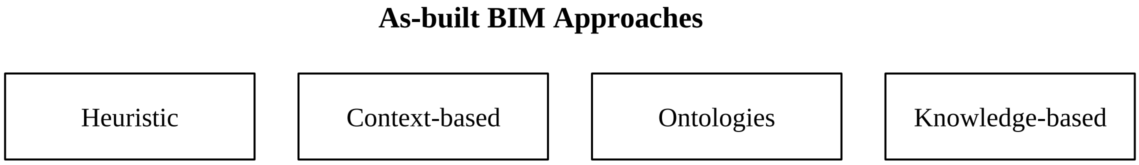

Figure 2: Scan-to-BIM approaches, classified into four main categories by Hichri et al. 2013

Heuristic approaches typically are defined by an initial segmentation of the thinned point cloud followed by a specification of several conditions and finally an object recognition. **Approaches based on context** proceed in a similar way. In order to create and intersect levels based on context knowledge, e.g. about the room, a voxelisation is executed initially which reduces the point cloud density. The **approach based on ontologies** is another possibility which is inspired by the concept of semantic web. They use prior knowledge for selective recognition of objects in point clouds. Latest results are available in Ponciano (2019) from i3mainz research lab. Each of these previously mentioned approaches is based on significant user knowledge about environment or object geometry. The modeling **approach based on prior knowledge** differs from previous. The user knowledge is not generic but available as an “as-planned” BIM. For deformation or difference analysis the point cloud can be compared with the entities of the existing model (Hichri et al. 2013). Numerous methodologies for segmentation and object recognition are proposed in the literature based on the mentioned approaches.

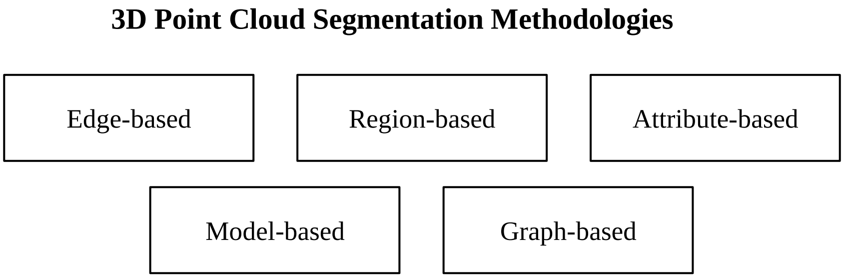

Figure 3: Summary of point cloud segmentation methods by Nguyen and Le 2013

According to *Figure* 3 point cloud segmentation can be summarised in five methodologies. **Edge-based methods** detect boundaries of point cloud groups by intensity gradients in order to segment regions. **Region-based methods** obtain isolated point regions by setting up a specific amount of points which is extended continuously until a criteria or threshold is reached. **For attribute-based methods** an algorithm calculates robust features for point regions. **Model-based methods** use mathematical representations to segment regions and **graph-based methods** transfer the point cloud into a tree, consists of nodes and paths between, for using neighbourhood relationships to partial structuring.

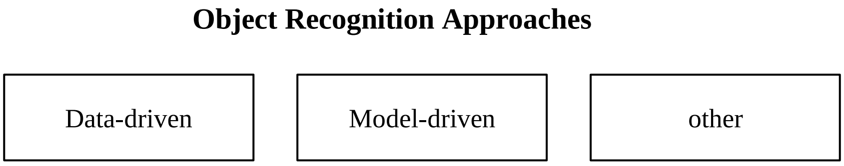

Figure 4: Summary of object recognition approaches by Volk et al. 2014

In heuristic and context-based approaches object recognition is attached directly to point cloud segmentation. Three approaches, seen in Figure *4*, are distinguished by Volk et al. (2014). **Data-driven object recognition** can be divided into feature-based, geometry-based, material-based and statistical methods that deduct geometries according to the respective source of information. **Model-driven approaches** (knowledge-based or context-based) are reliant on prior knowledge such as modeled entities of an "as-planned" BIM. Manual creation of object for as-built BIM is state-of-the-art and considered in **others** (Volk et al. 2014, 2014; Chen and Cho 2019).
Within the scope of research studies on automation different approaches are combined. While Bonduel et al. (2017) progress manually, Bassier et al. (2017) and Chai et al. (2016) suggest an more innovative approach. Using a SVM the point cloud is segmented. Next, object recognition is performed model-based by calculating features for building elements using SIFT and Hough-Transformation as well as comparing them with a component library. Using RANSAC the geometrical creation of building elements is executed. Model-driven influences can also be identified in Thomson and Boehm (2015). In this project plane geometries are fitted under instructions using RANSAC and then clustered according to Euclidean methods. Chen and Cho

(2019) apply k-means clustering and region growing technique for point cloud segmentation. Object recognition is performed by feature correlation of a manually selected point cloud area that is representative for a given building element. In the studies mentioned above the used point clouds represents simple and regular designs such as school rooms or factory floors. Machine Learning (ML) or Deep Learning (DL) is still in its infancy due to the lack of large training databases (Chen and Cho 2019). Guo et al. (2019) presents several DL methods for point cloud processing. DL is currently applied as proven ConvNets for image processing of floor plans, panoramic scans or room images (Zhang et al. 2020; Zeng et al. 2019; Kreyenschmidt 2019; Quintana et al. 2017).

5. DISCUSSION AND FUTURE NEEDS

As-built BIM are outlined as semantically enriched 3D CAD models. The demand on such is significant as construction documents in most cases do not correspond to the as-built (Barbosa 2018). This challenge is faced by Scan-to-BIM research which rely on laser scanning for collecting as-built data and manually to semi-automated algorithms for data analysis. For many algorithms processing an unstructured point cloud is currently an impossible task. The challenges are mainly caused by artefacts, noisy data, clutter, occlusions that avoid unambiguous object recognition and the size of the original point cloud limiting reasonable computing effort. Regarding the above mentioned deficits in data acquisition manual approaches are justified. Prior human knowledge is necessary to understand the meaning of elements in virtual space in order to achieve respectable results with primitive geometries. An additional challenge is the compliance with geometric requirements such as orthogonality between floors and walls which is often not presented in existing or historical buildings.

The advantages of BIM are not only based on the geometrical stock reference. Research activities require an extension by success factors such as semantics, topology (Sistani 2017) and irregular geometries. The untapped potential of DL should be explored and adapted more intensively on point clouds. Valuable references could be provided by relevant studies from automotive research especially on topics like autonomous driving. In addition, the influence of point cloud density and registration accuracy on the results of automated processes need to be investigated. More, there is a lack of uniform quality evaluation (Bonduel et al. 2017; Thomson and Boehm 2015) for comparison of as-built models from different scenes in order to achieve objective quality characteristics and metrics and thus to increase the overall model accuracy. Finally, the continuing popularity of Volk et al. (2014) in this area shows the stopped progress despite growing demand.

The Scan-to-BIM result should not be restricted to the visible elements. In order to locate and extrude internal supply and discharge lines (e.g. electricity, water, gas, telecommunications), more BIM-attended data acquisition methods should be developed. A survey of the synergy of imaging and penetrating sensors or investigations into integration of classical blueprints is recommended.

6. CONCLUSION

This paper presents an overview of Scan-to-BIM processes. Popular data acquisition techniques and processing paradigms are presented and current challenges in automating process stages of 3D point clouds are described. The identification of geometries, semantics and topology is essential in BIM process. Numerous approaches are able to obtain rough geometries automatically from point cloud data but still with a large amount of user input. Due to increasing importance of BIM in AEC industry and cultural heritage documentation the demand for automated methods is growing rapidly. ML is a promising tool whose potential and also its limitation must be evaluated in future research in this domain.

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BIOGRAPHICAL NOTES

Bastian Plaß works as a research associate in the Building Information Modeling and Machine Learning domain at the Mainz University of Applied Sciences. He obtained his master's degree in Mainz too and gained more experiences in the broad range of Machine Learning at the German Aerospace Center (DLR) in Oberpfaffenhofen and the Fraunhofer Society for Advancement of Applied Research in Freiburg. Since October last year he is PhD student in a cooperative promotion with the Technical University of Darmstadt.

CONTACTS

Bastian Plaß M.Sc.
Institute for Spatial Information and Surveying Technology
i3mainz, Mainz University of Applied Sciences
Lucy-Hillebrand-Str. 2
55128 Mainz
GERMANY
Tel. +49 6131 628 1496
E-Mail: bastian.plass@hs-mainz.de
Website: https://i3mainz.hs-mainz.de