Challenges and Trends of Implementation of 3D Point Cloud Technologies in Building Information Modeling (BIM): Case Studies

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ABSTRACT

Building Information Modeling (BIM) has gained wider acceptance in the Architecture/Engineering/Construction (A/E/C) industries in the U.S. and internationally. Capability of BIM technologies in early detection of spatial conflicts among various building systems and components concurrently designed by different design team members prior to construction has great potentials in reducing construction delays, loss of productivities, and overall construction costs. Recent advancements in 3D point cloud technologies such as 3D laser scanning can greatly augment BIM technology applications in the A/E/C industry by providing a rapid three dimensional capture of the built environment in great details and accuracy. This paper discusses the current approaches of implementing 3D point cloud data in BIM and virtual design and construction (VDC) applications during various stages of a project life cycle and the challenges associated with processing the huge amount of 3D point cloud data. Conversion from discrete 3D point cloud raster data to geometric/vector BIM data remains to be a labor-intensive process. The needs for intelligent geometric feature detection/reconstruction algorithms for automated point cloud processing and issues related to data management will be discussed. This paper also presents some innovative approaches for integrating 3D point cloud data with BIM to efficiently augment built environment design, construction, and management.

INTRODUCTION

Architecture/Engineering/Construction (A/E/C) industry has traditionally relied on 2-dimensional (2D) graphics to convey design and construction information. During the planning and design phases of a project, project development generally progresses with increasing details in a 2D format except for occasional 3D rendering of architectural concept models or 3D interior models for engineering study/simulation purposes (e.g., robotics, conveyors etc. for industrial process simulation or other dimension/clearance verifications). With segmented 2D representations of the 3D built environment and building information being partitioned in various discipline drawings, detection of design errors often is not an easy feat. Design errors and omissions not discovered until the field construction do not only cause project delays, cost overruns, decreased productivities for the contractors and lost revenues for the owners but also pose significant financial risks to the design firms. Similarly, for construction field supervisors and workers, being able to interpret the information from the 2-dimensional construction documents and synthetize the segmented plan views, elevation views, cross section views, and details mentally into a 3-dimensional representation of the project to detect constructability problems requires many years' training on the job and learned lessons.

The advent of building information modelling (BIM) and virtual design and construction (VDC) represented a quantum leap in the design and construction processes in the A/E/C industry. BIM and VDC differs fundamentally from the traditional 2D computer aided drafting (CAD) approach in terms of work flow and design technology as they are multi-dimensional (spatial and temporal dimensions) model-based processes where the model not only contains the geometric information of the building elements but also metadata information related to physical and functional properties of the elements such as material specifications, cost and schedule information, and other building lifecycle information. Better multiparty communication and understanding from 3D visualization is a BIM benefit rated most likely to improve return of investment (ROI) (McGraw-Hill 2009). In assessing ROI of BIM in construction, Giel and Issa (2013) noted that major benefits reported by construction companies included accelerated discovery of dimensional discrepancies, enhanced detection of 2D errors and omissions, and early detection of spatial conflicts among various building elements.

BIM has gained wider acceptance in the A/E/C industries in the U.S. and internationally. McGraw-Hill Construction's Smart Market Report in 2012 reported that industry-wide adoption of BIM in North America surged from 28% in 2007 to 49% in 2009 and to 71% in 2012 among the respondents to its surveys (McGraw-Hill 2012). Internationally, National BIM Survey (NBS) (2013) in UK showed that BIM adoption in UK has grown from 13% in 2010 to 39% in 2012 and 75% of the respondents agreed BIM is the future. The worldwide A/E/C industry trend of moving towards BIM and VDC for project delivery has provided momentum and opportunities for other innovative and state-of-art technologies being explored and integrated into the design and construction processes to augment BIM and VDC to fully employ the benefits of 3D-based design and construction.

AVAILABLE 3D POINT CLOUD ACQUISITION TECHNOLOGIES

Many technologies exist today to acquire 3D point clouds from a construction environment. Range-based technologies include 3D laser scanners (also known as terrestrial laser scanners) and time-of-flight (ToF) cameras. Accuracies of laser scanners at the present time are generally within 2 to 5 millimeters. 3D laser scanning has become a relatively matured technology and many commercialized systems are available such as Faro, Leica, Riegel, Topcon, Trimble, Zoller & Frohlich and others. Image-based point cloud technologies include close-range photogrammetry (requires a calibrated camera and a precision control frame to provide an accurate determination of the camera position, camera orientation, object point coordinates and calibration parameters) and Structure from Motion (SfM) method (uses a set of un-ordered and un-calibrated digital photographic images and processes them through a computer vision algorithms pipeline to reconstruct a 3D point cloud).

Much academic discussions exist as to which type of 3D point cloud technology is superior to others. 3D laser scanning technologies require time to set up the scanner unit and reference targets and each scan can generally take between less than five minutes and over fifteen minutes depending on the level of quality and resolution settings selected. Multiple scan set-ups are almost always required and the number of set-ups is dependent on the size of environment to be scanned and sometime it can take several days to obtain the point clouds for a complete coverage for large scale projects. As such, laser scanning technology has been viewed by some as requiring high capital expenditure and time-consuming for field setups and scans (Golparvar-Fard et al 2011, Skarlatos & Kiparissi 2012). In comparison, SfM-based image modelling methods can process ordinary photos that can be taken in a rapid and effortless fashion in a much short time frame however the successful reconstruction of the model and quality of point coverage are not always guaranteed. In comparing laser scanning to SfM method, Skarlatos & Kiparissi (2012) noted that for small and medium size objects and distance SfM seemed to have an advantage in terms of methodology and speed while on large scale objects laser scanning was better in terms of quality and processing time. In another similar comparative study, Golparvar-Fard et al (2012) found that in both laboratory and actual field experiments the accuracy of using image-based SfM modelling method was less than the point cloud generated by laser scanner. As being a passive light user, image-based 3D point cloud technology requires adequate lighting in the scene. The proper image exposure and clarity or noise levels of pixels in the images are highly dependent on the light input. Most of studies so far have been limited to daytime outdoor conditions or well-lid occupied building interiors where light conditions were not an issue. However, performance issues of image-based 3D point cloud technologies in non-optimally lit construction interior space with temporary lighting as typically existing during the construction stages were seldom evaluated. Range-based point cloud technologies are not affected by insufficient scene lighting conditions and can be operated in almost complete dark environments. In addition, the computer vision algorithms such as scale-invariant feature transform (SIFT) and multi-view stereo (MSV) behind the image-based 3D point cloud technology are very complex knowledge and not easy to understand for the average A/E/C industry users and therefore can be intimidating. For those reasons, Laser scanners despite the high initial capital expenditure costs have often been selected for actual production uses by point cloud data service providers. Regardless of the methods in which point clouds are acquired, the main interest to the end users is ultimately how this data can be employed to solve various business problems and how the data quality, resolution, and version history of the point clouds will affect such use.

IMPLEMENTATIONS OF 3D POINT CLOUD TECHNOLOGIES IN BIM

Planning and Design Phases. During the project planning and design stages, 3D point cloud technology can be used to quickly and inexpensively capture the surrounding environment in 3D and the obtained point cloud model can then be fused with proposed building BIM model to evaluate the potential impacts to the existing neighborhood and check for siting issues. Foster et al (2013) demonstrated on a high-rise building project in an urban downtown area that 3D point cloud coupled with BIM allowed the design firm to conduct line of sight and shadowing studies and produce a 3D visualization of the construction impact to get the appropriate approvals to move forward with the project.

Bidding and Construction Phases. Point cloud model of existing construction site conditions can be a virtual site/building survey tool to assist contractors to better prepare construction estimates and bid proposals by minimizing the risks of missing scope items and misjudging the field conditions. Traditionally it has always been a challenge to sufficiently depict the existing conditions in a two-dimensional survey where the existing features are often acquired manually and individually by using total station, GPS or other types of surveying equipment. Cost of surveys increases substantially when the required level of survey details increases. With point cloud technology the contractor would be able to extract dimensional information and make realistic decisions as to the amount and complexity of the work required. Point cloud models captured at various stages of the construction process integrated with the BIM can also allow the contractors and design firms to conduct quick design compliance verifications and assess impacts and develop resolutions when deviations from design occur. The same point cloud models captured during the construction can be compared to the 4D BIM on the same time scale to assess the construction schedule performance as to whether the project is behind, on or ahead of the planned schedule. Much research efforts have taken place in this area. Bosche et al (2010), El-Omari and Moselhi (2011), and Zhang and Arditi (2013) investigated laser scanning point cloud technology whereas Golparvar-Fard et al (2009) presented SfM-based approach for implementation with 4D BIM for construction progress monitoring. There has also seen increased uses of 3D point cloud technologies with 4D BIM for constructability analyses. Gilson and Mercure (2013) documented Connecticut Department of Transportation (CTDOT) I-95 New Haven Harbor Crossing project where 3D point cloud model of existing conditions was integrated into the Navisworks® 4D BIM simulation to check for constructability issues between three levels of existing highway ramps to be demolished and an historic building located just a few feet away.

Post-Construction Phase. One of the prevalent uses of 3D point cloud technologies at the present time is in the post-construction phase of a project. Project owners, recognizing the limitations of the existing 2D-based traditional as-built survey, are transitioning to point cloud based 3D as-built model documentation. The as-built point cloud models are then either converted to BIM models or stored away for future use. On projects constructed from BIM the as-built point cloud models are often used to update the construction BIM models. The acquired point clouds can be used for 4D constructability analysis of major equipment renewal/replacement during the facility management (FM) phase of the project life cycle where there is no longer adequate access when compared to during the construction phase. Additionally, on buildings/structures that undergo movements due to service load or geotechnical conditions, time-sequenced 3D point cloud captures of the structure/building have been used to produce before and after BIM models to analyze the causes of movements and monitor the patterns and magnitude of the movements.

CHALLENGES ASSOCIATED WITH IMPLEMENTING POINT CLOUD DATA IN BIM

Point Cloud Data vs. BIM data. Point cloud data is made of discrete point spatial coordinates (x,y,z) plus a point intensity value therefore a point cloud model only contains coordinate information. In comparison, a BIM model not only contains the geometric information but also includes a rich repertoire of functional, characteristics, and management data. Due to raster nature of the point cloud model, it is not as efficient as the vector-based model used in BIM. As such 3D point cloud model data files are generally very large and require substantial computer storage and computational load. Table 1 shows a sample list of type A/E/C laser scanning projects and the characteristics of the point cloud files.

Table 1. List of Sample Projects with Point Cloud Characteristics

Project Name	Project Type	Project Size (Story/ SF)	# of Scans	Raw file Size (GB)	# of Points	Working Pod Export Size (GB)	Field Man-hours	Point Cloud Reg. & Export Man-hours	Point Cloud Model. Man-hours
"X" Pump Station	Civil	3 / 4500	38	5.19	618,339,207	6.65 (at full resolution)	20	10	156.5
Mike's Habitat	Architectural /Assets Management	1 / 20,200	45	4.54	929,963,194	15.4	20	14	180
North Concessions Expansion	Architectural	5 / 59,500	31	4.63	112,987,322 at 1/2" spatial filter	1.8	10	8	37.5
Boiler	Industrial	1	10	1.31	436,978,820		10	6	80

Point Cloud to BIM Conversion. One of the driving forces behind the need for point cloud model conversion to BIM model is to produce printable 2D line drawings for construction field use. The raster nature of the point cloud is not suitable for producing construction plans and is not easily annotatable whereas in BIM the annotated typical floor plans, elevations, sections and details can be developed easily once the BIM model is complete. Due to the fact that the technology advancements and adoption at the construction field level are not at where it would be totally paperless and the majority of the construction field users are still accustomed to the traditional 2D paper-based construction documents, 2D paper-based plans will still be the mainstay on construction sites for the foreseeable future.

One of the biggest challenges facing today is with the point cloud to BIM conversion process which often is very time-consuming. As a point cloud model only contains geometric information, its conversion means not only recreating the vector-based geometric model but also creating the BIM metadata for scratch which can be a huge cost undertaking. Questions also arise on the idealization error resulted in the conversion process. The Point cloud data generally contains higher level of geometric details (attachment accessories, special features, architectural details, and geometric deviations) than a typical BIM model even at LOD (Level of Development) 500 and modeling such details would add tremendous amount of man-hours. As such, some of the high level of details will inevitably have to be forfeited during the conversion process. With its indiscriminative nature of reality capture, point cloud models often contain irrelevant or temporary features in the scene that would interfere with feature recognition operations during the modelling process. The conversion process is also affected by occlusions and partial point coverage issues (e.g. upper surfaces of overhead MEP system components under floor decks will be hidden from the laser scanners or cameras therefore will not have any point coverage). For these reasons, the conversion process is rarely fully automatic and often requires substantial time to manually extract geometric features. There are various commercial solutions (e.g., ClearEdge3D®, Kubit®, Geomagic®, Leica Cyclone®, Bentley Decartes®, LFM®, etc.) available to automate some of the feature recognition and modelling steps but they are currently limited to simple geometric shapes and objects (e.g., rectangular shaped windows and doors; straight circular pipes). Complex geometric shapes and objects commonly found in construction such as open web bar joists and computational curve based building façade would still require manual modelling efforts. With the continuous advancements in the computer vision research field, this challenge is anticipated to ease with more or more automatic intelligent feature recognition algorithms and modelling tools becoming available.

Data Management. On some of the large projects or facilities where frequent 3D point cloud captures are required to track the project progress or facility changes, conversion from point cloud to BIM model can be very cost-prohibitive and the benefit-to-cost ratio may not be favorable for such endeavor. Data management of point clouds from different locations and scan dates can be a huge task. Registration precision of conjoining a large number of individual sets of point clouds and error propagation can greatly affect the quality of the overall project/facility point cloud model and detract the confidence of the clash detection analyses.

CASE STUDIES

"X" pump station project. A point cloud model on an existing pumping facility was obtained with laser scanning technology and converted to a BIM model (see Figure 1). Some of high level of details such as bolts on pipe flanges and plug valve actuation stem contained in the point cloud model were omitted during the BIM object conversion process to reduce the modelling time. The lobe shaped motor drive components were manually modelled with composite shape geometry. A number of other features were omitted as well.

Volvo cars manufacturing facility. Volvo Cars Group has been using 3D scanning technology for plant installation verification for over 15 years. At their main manufacturing facility (> 1,000,000 SF) in Sweden, Volvo needed a highly accurate and current 3D model for the existing plant to virtually check for new equipment fit and assembly line transport movement clearance issues prior to plant changes which are constant in the auto industry to accommodate new model productions. Recognizing that creating an existing plant BIM model from thousands of scanned point clouds of different dates was not only a huge cost endeavor but also more importantly the lengthy time required to build such BIM model would render the model obsolete by the time it was finished. Instead, Volvo implemented a hybrid point clouds + 3D CAD model where the existing plant is represented in a point cloud model and any new equipment's 3D CAD model is then registered in the plant point cloud model. When an existing sub-assembly is to be relocated to other part of the manufacturing facility, point cloud for such sub-assembly would be segmented into a point cloud module and moved to the destination location in the plant point cloud model. The updated plant point cloud model is then used with the 3D models of the new vehicles/equipment for clash detection and virtual manufacturing analyses. In order to ensure the precise registration of the hundreds of incremental point clouds within the plant point cloud model, a factory coordinate infrastructure system was implemented which included a network of permanent laser target markers set at various locations of the plant. The (x,y,z) coordinates of the permanent laser targets were verified and balanced with high precision surveying equipment. With the factory coordinate system infrastructure, precise alignment of a new point cloud cell with the plan point cloud model was possible and the projected average distance error was within 2.6 mm. Today, this hybrid model is not only implemented at Volvo's main production plant but also at all of their assembly and component plants worldwide.

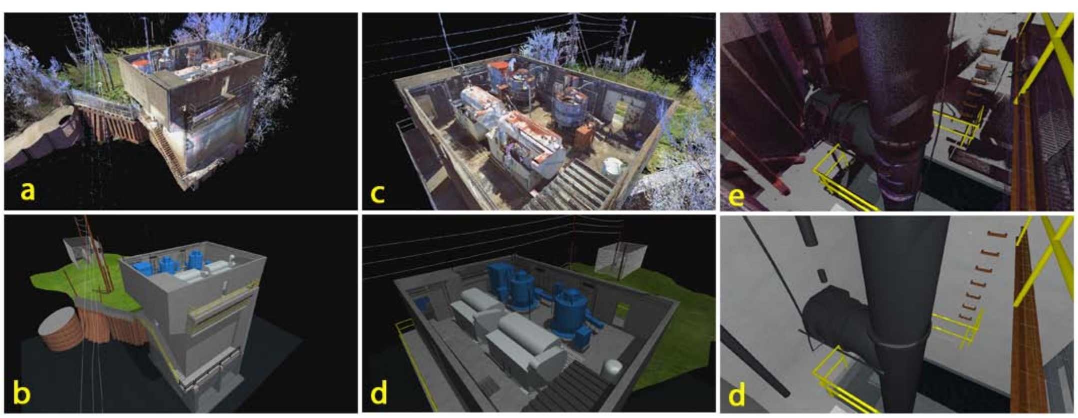

Figure 1. (a) Point cloud of the "X" pump station, (b) Converted BIM model, (c) motor center in point cloud, (d) motor center in BIM model, (e) intake shaft in point cloud, and (d) intake shaft in BIM model

CONCLUSIONS

This paper provides a review on the current state of practices of implementation of 3D point cloud technologies in building information modelling (BIM) and virtual design construction (VDC). Hardware-based and computer vision algorithm based 3D point cloud technologies are discussed as to their advantages and disadvantages for use on construction sites. 3D point cloud integration with BIM provides great benefits in facilitating the project planning and design and offer the contractors the visualization tools in improving the project performance. Challenges in 3D point cloud model to BIM model conversion process are discussed as at the present time this remains a labor intensive process where improvements are needed in the area of automated feature detection algorithms and tools. Challenges also exist in the area of data management and version control on projects that requires frequent 3D point cloud captures. Hybrid point cloud + BIM approach as discussed in Volvo case study offers an innovative approach on how point cloud technology can be useful in virtual design and construction in its native format.

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