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The Need for Convergence of BIM and 3D Imaging in the Open World

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Abstract — Two types of technologies that are rapidly (exponentially) impacting the Architecture, Engineering, Construction, and Facilities Management (AEC/FM) industry are: Building Information Modelling (BIM) and 3D imaging technologies. The latter is currently mainly represented by laser scanning, but is being rapidly complemented with photogrammetry (both terrestrial and aerial), ground-penetrating radar (GPR), as well as their integration with other technologies such as infrared imaging, GPS, and RFID. While these two types of technologies individually offer significant performance improvements in all parts of the sector, it is their integration that promises to provide the most benefits. Integrated, the two types of technologies would form a cyber-physical system that would deliver bi-directional interoperability, allowing seamless coordination between the virtual worlds captured in the BIM model and the real world construction. Yet, it is interesting to note there are very few software solutions that enable the joint visualisation and manipulation of 3D imaging and BIM data/information. Furthermore, none of those solutions are based on the combined use of open standards and tools, thereby limiting the extent to which researchers can develop and test new solutions to increase the value of both BIM and 3D imaging technologies. This clearly demonstrates the need for an open source software platform (based on open source standards and tools) supporting the management and processing of BIM and 3D imaging data, particularly point clouds, for facility lifecycle management.

The paper first builds a case for the need for such a solution, identifying critical Virtual-to-Real, Real-to-Virtual and Virtual-vs-Real applications. A novel open, web-based core software platform is then proposed that utilises the open standards IFC and E57 for real-time bi-directional interoperability between BIM models and 3D imaging data (especially point clouds). Finally, it is revealed how such a system can be developed and grown over time from industry contributions through an open source initiative.

Keywords — BIM, 3D Imaging, Open Source, Software

I INTRODUCTION

Effectively controlling a facility during its entire life cycle demands automated and rich information flows. These flows require the establishment of cyber-physical systems delivering bi-directional interoperability between the physical facility and its counterpart virtual Building Information Modelling (BIM) model \cite{1, 2}. For example, during the construction stage the provision of real-time quality control against the as-designed BIM model ensures smooth construction processes and increases the promise to the owner that what is constructed is what has been designed.

Already, research and practice have demonstrated the value of on-site mobile devices and Radio Frequency Identification (RFID) technology to provide a unique link between physical and virtual objects \cite{3, 4}. Motamedi et al. \cite{5} have shown tracking of task and material during construction utilising RFID technology and open standard BIM models, i.e. Industry Foundation Classes (IFC) BIM models. In fact, current cyber-physical systems rely heavily on RFID technology as it provides a valuable means of identification of physical objects, that is creating the links between the real objects and their virtual counter-parts. However, RFID does not permit the acquisition of information about those objects, such as their as-is geometry. As a result much human intervention remains required updating BIM models, e.g.
manually through mobile devices [6]. Major advancements in reality capture technologies and new object recognition algorithms are going to allow automated recognition of geometric properties of physical objects and their comparison to their counter-part objects to in the virtual worlds (BIM models) via an object-based distributed relational database. These technologies could thus help address the limitations of current cyber-physical systems. In fact, they would work even better in combination with RFID (and GPS), as already demonstrated in [7] [8].

Successful implementation of BIM requires the smooth, reliable, and fast exchange of digital data. The data may be produced and subsequently employed in various software packages, which raises concerns regarding data interoperability, specifically the readability and corruption of data. In 2004, The US National Institute for Standards and Technology (NIST) highlighted that the cost of inadequate interoperability in the US capital facilities industry amounted to an estimated $15.8 billion per year. This issue requires achieving industry-wide consensus on the development and usage of data formats and exchange protocols that ensure lossless communication. This has been proving difficult due to the vested interests of various leading software providers in their proprietary formats that natively promote their own software solutions. Nonetheless, some progress has been achieved in the establishment of open data and process formats for BIM, e.g. the IFC and Construction Operations Building information exchange (COBie) formats. With respect to reality capture data formats, several open formats exist (e.g. XYZ, PTX). But, the main recent achievement is the e57 format [9] uniquely documented in the ASTM E2807 standard [10] that is an industry standard for the exchange of 3D imaging data.

This paper first shows how BIM and reality capture technologies are rapidly converging. It then argues that, an important vehicle to enable and accelerate this convergence is not only open formats for data exchange, but an open and free software platform that integrate means to concurrently manage, visualize and process BIM and reality capture data. The paper then reports on early considerations on how such a platform could be developed using existing open solutions.

II BACKGROUND ON BIM AND REALITY CAPTURE TECHNOLOGIES

a) Building Information Modelling (BIM)

BIM is a n-dimensional (nD) integrated practice process for the Architectural, Engineering, Construction and Facilities Management (AEC/FM) industries that consists of dimensional domains for all stakeholders to be part of the collective whole [11]. A BIM model is utilised to digitally and collaboratively model and manage the entire construction project life-cycle from briefing through to design, construction, operation and maintenance, and finally renovation or demolition. More officially, the UK BSI in 2009 defines BIM as, “a suit of technologies and processes that integrate to form the system, which is a component-based three dimensional (3D) representation of each building element”. BIM has been described to be ‘not an evolution, but a revolution’ to the AEC/FM industries. While the roots of BIM can be traced back to the 1970’s, it is only the development of powerful and ubiquitous personal computers (and now mobile devices) that has made the dream finally possible and the approach implementable in practice.

b) Parametricity, Semanticity, and Unicity

3D BIM affords users parametricity, semanticity, and unicity. The “I” in BIM is the crux of the process. Information/data is embedded into the virtual model begins to define its parametricity. BIM data models are designed to have entity relationships with other models of the same type or of different types. These models are instances of well-defined parameters, i.e. IFC classes, which allow a systematic approach to classify all model object information. The model’s semantic feature (semanticity) ensures that it can be queried to extract valuable information, e.g. how many doors of type A in this building? IFC Model View Definitions (MVD’s), like COBie for FM data handover, is an example of how each stakeholder extracts valuable distinct model semantics from parametric models.

BIM models are in fact virtual object-oriented representations of the actual unique products to be manufactured and installed utilising specifications derived from the parametric content within. The model’s unicity prevents errors resulting from duplication of data. A Global Unique Identifier (GUID) is what makes Door A unique from Door B when they are the same proprietor, size, shape, etc.

Semantically-rich BIM models accessible and populated by all project stakeholders underpins the collaborative process promoted by BIM. The (semantic) parameters within ensure that any change to the BIM model is automatically taken into account in other portions of the BIM model that depend on it, e.g. removing a 3D door from the BIM model (IfcDoor class) also removes it from the schedule of doors and 2D construction document views. Further interoperability can also be employed like removing the 3D door is reflected in the (4D) schedule, and because the door is removed the (5D) cost and (6D) energy information would also be
changed because of the IFC ‘parametric’ link within the background database. O’Keeffe et al. [12] discuss interoperability such as this in further detail.

c) As-Designed, As-Built, and As-Is

Theoretically, the BIM model of a project is for gathering and structuring all data and information relating to the asset over its entire life cycle. The BIM model should thus be a record of the state of the asset at each life stage. This leads to distinguishing the as-designed BIM model, i.e. the virtual representation of the asset after design and prior to construction, from the as-built BIM model (Fig. 1), i.e. the virtual representation of the asset after construction and prior operation, from the as-is BIM model (Fig. 2), i.e. the virtual representation of the asset during its operational stage. It is important to highlight that the wide majority of the developments in and uptake of BIM are in relation to the as-design BIM model, with some efforts in and only limited uptake of solutions in relation to generate as-built or as-is BIM models.

d) 3D Data

3D geometric data is at the core of BIM models (so much so that people have long thought that a 3D model was a BIM model). In fact, the (semantic) 3D geometric model typically acts as the main medium for structuring and navigating all the other data contained in a BIM model. Furthermore, 3D data is undeniably central to many important activities surrounding the construction and operation of a built asset. For example, constructability often relates to accurate and reliable 3D design data, and structural analysis using finite element analysis also requires sufficiently accurate 3D data about the asset’s structure. Furthermore, construction works require sufficiently accurate detailed 3D data and are controlled through a wide range of dimensional quality controls, and structural health monitoring also requires detailed geometric data about the as-is state of an asset to be compared with prior states.

e) Reality Capture / 3D Imaging for Life-Cycle Management

Dimensional quality control and structural health monitoring require accurate and reliable 3D information/data from the asset’s BIM model. They also require the capturing of accurate and complete as-is 3D data of the asset.

Traditional dimensional measurement methods employed in the AEC/FM sector have been so time-consuming and resource-hungry that they have impeded sound operation of the applications above. This observation, along with technological progress, has led to the development and now rapidly increasing usage of new reality capture or 3D imaging solutions. These are literally revolutionizing dimensional surveying in the sector. Three technologies can be particularly highlighted and are rapidly presented in the following: laser scanning, photogrammetry, and ground-penetrating radar.

Laser scanning, essentially terrestrial but also available in aerial setups, has been a significant step forward from total stations. Contrary to total stations, laser scanners are not aimed at acquiring individual 3D points, but capturing the entire 3D (depth) geometry of the environment surrounding the scanner, from 0.5m away up to 2kms for certain scanners. The key transformation resulting from the introduction of laser scanning is that the speed, accuracy, and density of the measurements it provides is extending the practice of dimensional surveying from a process based on point measurement only, to a process based on both point and surface measurement. A limitation of laser scanners is that they can only acquire data with line of sight and perform best when it is stationary. This means that the scanner has to be moved to numerous locations and the data subsequently co-registered. Car-mounted mobile laser scanners address this issue, but at the cost of inferior data accuracy. Another important limitation of laser scanning has been its cost that typically ranges from £25k to £80k for terrestrial scanners. Yet, the value of laser scanning is so significant that the market for laser
scanning services has been increasing exponentially over the last decade and is anticipated to reach $4 billion by 2018 [13].

While an older 3D imaging technology, photogrammetry has only recently been considered for wider application within the AEC/FM sector. This is explained by the fact that digital cameras are now widely available, very portable, and relatively cheap. Photogrammetry enables 3D measurements from multiple pictures of a scene, employing the optical flow principle. The first systems delivered sparse 3D measurements, but new systems can now deliver high-quality dense 3D reconstructions, in the form of coloured 3D point clouds [14]. The main advantage of photogrammetry over laser scanning is the hardware cost, i.e. cameras are relatively cheap. However, the output quality of photogrammetry is much less predictable as it varies with factors such as lighting conditions and the type of materials of reconstructed surfaces, e.g. shiny surfaces are challenging. Additionally, like laser scanning, photogrammetry only works with line of sight.

f) The value of integrating 3D as-planned and as-is Information/Data

BIM and 3D imaging technologies are rapidly penetrating the AEC/FM sector. In fact, the two technologies significantly overlap as 3D imaging is about the acquisition of 3D data, and BIM is built around a (semantic) 3D model that structures life-cycle information about the asset. This convergence, although theoretically obvious, is only slowly occurring in practice due to the fact that both technologies are quite new to the AEC/FM. Two areas of convergence are distinguished: Scan-to-BIM and Scan-vs-BIM. While AEC/FM actors have already developed interest in the former with solutions already commercialized, the latter is still emerging but has tremendous potential value.

Scan-to-BIM refers to the process of creating a semantic 3D BIM model from 3D point cloud data acquired through 3D imaging, i.e. laser scanning, photogrammetry, GPR, etc. Since the almost entirety of the current built environment does not have any existing digital BIM model, the push for employing BIM for improving operation, renovation, or refurbishment of those assets requires an initial step of acquiring its current 3D state and generating that semantic 3D (BIM) model from it, i.e. Scan-to-BIM. This obvious need has led numerous researchers and now commercial organisations to develop and sell various solutions to semi-automatically generate semantic 3D BIM models from 3D data (mainly acquired through laser scanning). Examples of commercial solutions include: EdgeWise MEP by ClearEdge 3D, Kubit PointSense (now Faro), or Trimble Realworks. Research is also being conducted in academia that aims to further automate current processes. Recent reviews of the state of the art in as-built modelling (i.e. Scan-to-BIM) can be found in [15, 16].

In contrast, Scan-vs-BIM (Fig. 3 and 4) refers to the process of comparing 3D imaging data acquired from an existing asset or construction site to an already existing 3D BIM model of that environment [17]. This process would normally be based on the registration, i.e. alignment, of the 3D imaging data within the coordinate system of the 3D BIM model. This need is arising from the fact that a 3D BIM model of the facility is available prior to construction and operation of that facility. As a result, various construction activities related to dimensional data could be conducted far more effectively by leveraging the prior information contained in the asset’s 3D BIM model. Such activities include: construction dimensional control [18, 19] progress control [20], structural health monitoring, and even as-built 3D modelling that is currently supported by Scan-to-BIM processes. The previous research mentioned does show the recent yet rapidly growing interest of the research community around this topic. There is little doubt that as the AEC/FM adopts BIM it will rapidly come to the realisation of the value of Scan-vs-BIM processes for improving performance of various activities such as those mentioned above.

Fig. 3: Scan-vs-BIM for dimensional compliance control in a process plant facility during installation.
new worlds allows an IFC compliant GeoBIM extension to facilitate the embedding semantic IFC data into a GIS context. [23] and [11] also demonstrate the importance of an IFC compliant open source web-based model server that allows AEC/FM stakeholders to collaborate remotely via a central repository. In fact, companies such as Autodesk and IBM have started to follow the open source route. For instance, Autodesk have made their IFC import/exporter for Revit open source to increase and enhance usage, quality, and productivity of development [25]. IBM believes that open source and open standards is key to making our planet smarter by improving the way humans work and live their lives.

However, with respect to applications integrating Virtual and Real data/information (Virtual-and-Real applications hereafter), it is clear from the literature above that the AEC/FM industry has not yet considered the benefits of integrating open reality capture and BIM models in a single open source environment, especially one that is built on top of an open infrastructure.

The authors are thus proposing an open Virtual-and-Real cyber-physical software platform that affords these needs. Our approach (presented in Section 4) is similar to [22] in the sense that it aims to provide an open solution to a context where two new worlds, Real and Virtual, are beginning to converge. The authors argue that such a system is in fact almost necessary. Indeed, the deployment of Level 2 BIM requirement in the UK and now elsewhere, and soon Level 3 BIM requirements (Digital Built Britain for 2025 [24]), increase the pressure on solving integrated project delivery in general, and interoperability in particular. The availability of an open Virtual-and-Real software platform would afford the following benefits. First, it would enable the development of solutions that pass the test of time by complying with the BIM Level 3 proposals that clearly promote the use of open formats and processes, e.g. IFC format. By being open, such a system would benefit from academic and industry institutions that will have the ability to add their own contributions to it. In turn, everyone globally would have access to utilise and add to the current, i.e. most recent, developments upon release by all individual third party developers. This is further detailed in the following section.

IV PROPOSED SYSTEM

The authors envisaged from prior and current research that the integration of RFID, GPS, semantically-rich IFC BIM models, and reality capture can be converged into a single cyber-physical system that would deliver bi-directional interoperability between virtual and real worlds. Our
aim is to leverage prior knowledge and solutions delivered in the various sub-domains above and embed these into an open system where users and developers can benefit globally via a web-based open source solution where reality capture data (e.g. point clouds) and BIM models live hand-and-hand.

Earlier in this paper, we have shown that there is a clear need for a cyber-physical system that converges virtual and real worlds. When it comes to manage geometric data and information, whether within Scan-to-BIM or Scan-vs-BIM contexts, it is surprising that, despite all comments about interoperability issues within the industry, no open source framework and software platform exists that co-locates Real and counter-part Virtual data.

The authors are thus proposing the development of an open source framework and software platform for the convergence of BIM and 3D imaging. No such system exists and our main goal is the development of the software platform that will be utilised as a catalyst for industry and academia to build upon. The authors promote the use of open source systems for this very reason. The initial contribution of the authors will be the software platform and its framework to be utilised by other developers in both industry and academia aiming to develop various Scan-to-BIM or Scan-vs-BIM solutions.

The system and approach increases the efficiency of on-site methods, in-house design processes, reduces computational and physical waste, and supports a leaner methodology in general. A cyber-physical system process is foreseen that utilises less human interaction. This framework could for example be used for the development of a Scan-vs-BIM solution for dimensional quality control. Such a solution would utilise algorithms to automatically recognise real world objects in TLS data and correlate them with virtual BIM objects, i.e. a recipe for a cyber-physical system [26]. The matching of real to virtual objects would enable the automated application of various types of dimensional control procedures. The data acquired from the real object as well as the dimensional control results can then be recorded in a structured manner as semantic information attached to the virtual BIM objects of interest.

The proposed system is to be built on an open source centralised repository where the users can upload and download the open standard files, i.e. IFC BIM models and e57 reality capture data. In conjunction with the server, we aim to demonstrate an open source web-based virtual environment accessible from the Graphical User Interface (GUI), similar to the 6D BIM framework prototype from [11]. In this virtual environment the user will utilise algorithmic functions via the GUI to compute, using the power of cloud computing, results based on the IFC BIM model and the TLS e57 point cloud existing in the same environment. The authors’ vision can actually be achieved in many different ways due to various open source technologies being already available free to the public, e.g. Torque 3D Game Engine (T3D), BimServer.org, xBIM, CloudCompare, etc. At this current stage no final decision has been made on the virtual environment method that will be utilised to facilitate the IFC BIM model and e57 reality capture data via the web-based open source server. Yet, the authors have already gathered knowledge through the development of two prototypes. The first is local and support e57 and IFC BIM models (and has been used to report the results in [28] for example). However, this system has not yet been embedded into the open source server. The second prototype utilises the T3D game engine as the virtual environment for BIM models [27], but does not support reality capture data in its current state. The authors are in the process of integrating the two prototypes. IfcOpenShell, CloudCompare, and other open source tools are under consideration to be utilised as ingredients to the software system framework.

V CONCLUSION

Incentives such as the UK BIM mandate for 2016 aims to enforce accurate As-Built and As-Is BIM model as handover deliverables for FM and Operations and Maintenance (O&M). In reality the industry has much to learn to truly achieve this vision. The authors of this paper have a vision to increase the development of technologies to make ideas such as the UK mandate become a reality. Realistically speaking it is very time-consuming and difficult to track development during construction and assure what was designed is actually being built on site. Many researchers are trying to solve these problems through various different methodologies, e.g. [1, 2]. The authors believe that an open source solution is an essential key component for speeding up the process of truly accurate as-built/as-is BIM handover deliverables to owners in the AEC/FM. The proposed methodology is centred around a free web-based open source software platform that will act as base infrastructure on top of which solutions supporting future growth of such technologies can be added. The industry (academics and professionals) shall “drive” this proposed system, instead of using traditional proprietary methods that keep the consumers out of the development driver seat and high risk purchasing technologies that do not provide adequate solutions to their problems. Proprietary systems are very expensive and do not always facilitate the needs required. Open source systems allow the user to omit functions not needed in their business model and add at free will new functions that directly benefit their business model.
to help ensure success at a lower cost. One of our goals is to reduce human interaction during the bi-directional flow of information exchanged through integrated systems while also providing a platform for the direct implementation of novel technologies in the future.

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