Towards a new BIM 'Dimension' -Translating BIM Data into Actual Construction using Robotics

Shrinath Tandur

B.Arch. (Bangalore U.), M.Phil. (CUHK, Hong Kong), FIIA. Partner, FBA Architects, Bengaluru, India.
E-mail: shrinath.tandur@fbaconsulting.in

ABSTRACT

There is a heavy reliance on the skill set of human workers on a building construction site. Most building structures are compromised by human error due to the following partial list of factors such as inadequate training, non-availability of the proper toolset, inaccurate measurement systems, incomplete data, incorrect interpretation of input based on 2D data and/or written documentation, improper construction scheduling, the vagaries of climate, and worker fatigue. The manufacturing industry has overcome many of the limitations due to the above factors by increasingly investing in some form of automated processing of information, including the employment of robotics, to directly output a part, or a sum of parts. This concept paper investigates some of the directions that the construction industry can take in emulating the manufacturing industry [1][2]. Some real world examples of attempts at automating construction tasks are examined. One promising vision of the future is to translate BIM (Building Information Modelling) data into actual construction by the further use of technology, i.e., by programming construction robots to interpret metadata associated with a BIM file (with or without human assistance or oversight) and carry out the necessary construction tasks at acceptable precisions and adherence to specifications as recorded in the BIM file.

Keywords -

Construction, Manufacturing, Automation, BIM, Metadata, Robotics

1 Background

The first time that the author pondered the accuracy of the constructed dimension was when he held a Leica Disto® at a fit out job site in Chicago in 1998 and fired off a series of laser measurements (accurate to one millimetre in a hundred metres). Later, the Disto was connected to a PC and the measurements transferred into it.

As far as the author was concerned that was the first time that a digitally measured dimension from the real world was transferred into a virtual world. More importantly, transferring the laser assured dimensions to the PC without manual data entry *eliminated one level of human error*. Less than a decade later this sort of event is routine in both directions, i.e., from virtual to real and from real to virtual.

In the late nineties, in its early stages of implementation, computer aided design was more or less adopted as a drafting tool in the design and construction field. Few had heard about BIM, let alone venture into the virtual world of BIM, even though BIM software did exist around this time, notably the 'Virtual Building' concepts developed in Graphisoft's Archicad. Over the past two decades as BIM has evolved with various software developers putting out more and more sophisticated BIM software such as Autodesk Revit, and Bentley's AECOsim, various BIM 'Dimensions' – a play on the common expressions 2D (drawings) and 3D (models) – have made their way into our vocabulary. At present four extra 'dimensions' describe the present modelling standards in the virtual world: BIM-4D for Project Phasing/Timelines; BIM-5D for Costing; BIM-6D for Facilities Management; and BIM-7D for Energy Performance Monitoring. More 'dimensions' may be added on yet.

The author suggests that this will over time evolve into a complex dimension where *buildings of the future will not just be BIM designed but BIM executed*. We will refer to this complex dimension as ‘BIM-XD’ for now.

2 Convergence of Key Technologies

BIM-XD is to construction what CAD/CAM is to manufacturing. In order to develop this complex BIM-XD dimension, the author proposes that the following four key technologies must evolve together to successfully construct a building with minimal (or even without) on-site human activity.

1. **BIM (and the IFC standard)**
2. **Robots for Construction**
3. **Reference Base Stations**
4. **Wireless Charging**

The first two are core technologies; the latter two are supplemental, but essential, to the core technologies.

2.1 BIM (and the IFC Standard)

The present-day BIM lies totally in the virtual world and bears no responsibility in getting the building constructed.

It is visualized that BIM-XD must ensure that the virtual model is ‘actualized’ while adhering to the information supplied by the existing dimensions of BIM.

Another take on BIM implementation looks at what are referred to as ‘BIM Maturity Levels’. As discussed in a March 2011 Strategy Paper for the Government Construction Client Group, from the BIM Industry Working Group, there are at present 4 recognized maturity levels [3]:

BIM Maturity Level 0: representing unmanaged 2D CAD with paper or epaper output as the most likely data exchange mechanism.

BIM Maturity Level 1: representing managed 2D or 3D CAD format in a common data environment.

BIM Maturity Level 2: representing managed 3D environment held in separate BIM tools that could be proprietary. This approach may use 4D and 5D elements as well.

BIM Maturity Level 3: representing fully IFC compliant BIM, perhaps web services enabled, and managed by a collaborative server.

Now, just as metadata is to a file, a BIM file must incorporate metadata corresponding to an ‘instruction set’ that a robot can interface with to build from the BIM data within that file. This approach does not tinker with the inner workings of the file. It just reads the information contained within and makes decisions on how to build it. This is to be done in much the same way that a building contractor does not tinker with the contents of a drawing but reads the drawing along with the associated specifications and decides how he will build it.

BIM as we work with at present is an evolving field. It has taken over thirty years of diverse and distributed thought processes by thousands of experts in the mechanical and AEC professions. A BIM file (or set of files) contains objects that are defined by both first-principles as well as data driven engineering models. For example, a wall’s geometry is arrived at by first-principles whereas its thermal properties are attributed to it based on data driven engineering models (or observed data). Apart from this, the construction of a building based on BIM can be logistically simulated, including the insertion and removal of temporary material (such as formwork).

Announcements at the Bentley Year in Infrastructure 2014 and Trimble Dimensions 2014 Conferences had this to say [4]:

“Today, architects and engineers perform design modeling with BIM toolsets that support optioneering and analytical modeling, and enable owners to make better decisions for better-performing assets, including in respects that would be pertinent and valuable during operations and maintenance. However, some of the most advanced BIM deliverables have simply not been useful for constructors’ requirements. Accordingly, the constructors have been left to create their own discrete 3D models for the limited purposes of construction visualization. As a result, owners have been unable to expect their designers’ BIM work to even survive the construction process let alone provide visibility into the engineering and analytics, which otherwise could have been useful during operations. In practice, therefore, this discontinuity has negated the potential benefits of BIM for either better-performing projects or assets. Construction modeling is the response by Bentley and Trimble to fill this gap and to enable all the potential benefits. In construction modeling the architects’ and engineers’ work is preserved and referenced, with construction modeling overlaid and as-built changes included.”

There are many approaches to the software design in BIM. Therefore, to facilitate data interchange between the many BIM software vendors, as well as various manufacturers’ products, a vendor neutral standard termed IFC (Industry Foundation Classes) [5] has been adopted by the BIM industry. It is defined under ISO standard 16739:2013 [6] for data sharing in the construction and facility management industries and the current specifications are published under IFC4. Figure 1 shows IFC data as created with Revit 2014 but viewed in the open source Data Design Systems (DDS) CAD Viewer [7].

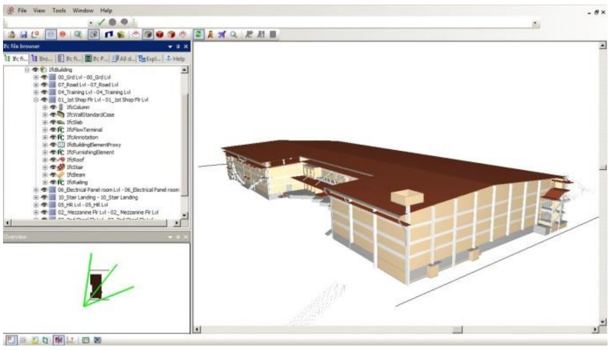

Figure 1. IFC data exported from one BIM software and displayed in another

However, the construction sequence modelled in a BIM environment is quite different from the construction sequence that is followed in the real world. Simply reading and parsing the contents of an IFC file will not be enough for automated construction.

Take this real world example: a BIM object such as a masonry wall may be defined with a complex cross section, which can include internal plastering and painting and external cladding. In actual construction the raw wall is built first, other activities take place prior to applying plaster, yet other activities take place prior to applying paint. Cladding on the exterior of a wall for a tall building poses other serious challenges for a building contractor. Such issues are not yet addressed in the present day BIM. BIM-XD however, will have to address this. Another key parameter missing from the virtual world of BIM is gravity. While this parameter is addressed in a limited way, such as for the placement of objects at various levels, it could be an option that you can turn on when simulating the construction process.

Metadata about these partial activities have to be added to the IFC file such that these when read sequentially will allow a robot to realize the intent of the design.

Experienced building contractors who have invested in BIM as a design checking and clash detection tool prior to commencement of on-site work will be most likely to have the necessary expertise to participate in the analyses required. We cannot skip this process.

There may be more than one way to interpret the IFC file. This is where BIM-XD, the new BIM ‘dimension’, is required.

2.2 Robots for construction

The root of the word ‘robot’ comes from the Slavic *robota* which translates to labour [8]. It was first used in the 1921 Czech dystopian play ‘R.U.R. (Rossum’s Universal Robots)’ authored by Karel Capek. The word ‘robotics’ was first coined by author Isaac Asimov in his 1941 short stories ‘Liar!’ and ‘Runaround’.

In Capek’s play, the robots closely resembled humans, (much like the Replicants depicted in Ridley Scott’s movie ‘Blade Runner’ from 1982). However, as has been demonstrated by industrial robots over the decades, a robot can be any shape or size as long as it gets the specific job done to the specifications and tolerances demanded by the manufacturer. We are not necessarily obligated to have the complexities associated with androids, cyborgs or other such humanoid robots in order to effectively perform a construction task. We need to look at task specific robots [9].

The construction industry is very different from the manufacturing sector. The working conditions vary tremendously by location, and building type [10]. Pre-fabrication of building components is arguably one of the valid shortcuts to automating the construction process [11] [12]. Another valid approach is to re-think the construction process itself [13].

In order for a construction site to be ‘robotized’ a variety of robot types will have to be considered, both from the point of view of locomotion, tasking, communicating and reporting, i.e., robots that can walk, roll, crawl, climb up or down steps or ramps, or fly and hover; robots that can be controlled manually, be supervised or be fully autonomous; robots that can see and hear (in various spectrums), touch, sense, smell and talk (communicate), robots that can grasp, lift, drop, measure, weld, cut, etc. Importantly, robots can be instructed to record every activity they perform and report these activities. These results can be ‘superimposed’ upon the corresponding BIM. This, when combined with an augmented reality environment, will allow the designer, builder or owner to get a clear picture of events.

The building contractor of the future will be able to work from a location remote with respect to the actual construction site. As systems become more sophisticated over time, the distinction between designers and builders will begin to blur, the distinction between large and small design practices will blur [14], and architects may even take on the roles of builders.

2.3 Reference Base Stations

Geo location services for civilian use have matured to sub 6-metre levels over the past decade. While this is considered adequate for general purpose navigation, this resolution is simply not good enough for construction.

To achieve sub metre level accuracies, one or more reference base stations, such as those offered by Trimble®, have to be first set up at a construction site. Thousands of such reference stations have been set up around the world, (including one, as stated on their website, at "the world's northernmost Department of Geography", at the University of Oulu).

Such accuracies may be sufficient for large area surveys, however. But, in order to achieve the sub-centimetre level of accuracy that's required on a construction site, these reference base stations have to be augmented with traditional electro-optical technologies where accuracy can be enhanced by a couple of orders of magnitude.

In reverse, laser scanning systems from companies such as Leica Geosystems® can recreate existing structures or internal envelopes (such as that required for interior fit out projects, for example) and integrate it back to total station measurements.

2.4 Wireless Charging

In 2007, researchers at MIT, Cambridge, MA, USA, invented a completely new method of safely transmitting electricity wirelessly using the principle of coupled resonators. They demonstrated the lighting up of a 60W bulb that drew power wirelessly from a power source placed over 2.4 metres away. They coined the word 'Witricity' to describe wireless electricity. The patent and intellectual property rights are now owned by Witricity Corporation. Witricity has matured enough that you can today, for example, set up a home theatre system such that your speakers receive both music radio wave signals and electricity wirelessly.

Witricity allows devices to continuously stay charged while on the go. As far as robots go, their battery packs can be made much smaller, therefore lighter, and their horsepower can be put to more useful work, continuously, as well as for longer time periods.

The actual specifications for the wireless charging of a device is evolving under the "Alliance For Wireless Power" (or A4WP), which was established in 2012. A non-profit organization, it includes most major computer and electronics corporations across the globe, including Witricity Corp. itself. A4WP is dedicated to building a global wireless charging ecosystem based on what it terms as "Rezence™ technology" , a second generation wireless charging system that also sets standards for the simultaneous charging of multiple power receiving units (PRU) from one power transmitting unit (PTU), as well as communications between the PRU and PTU using Bluetooth. The outline specifications are as follows (*From A4WP Wireless Power Transfer System Baseline System Specification (BSS)* Version 1.2, © A4WP. Reprinted with permission.):

"System Description

The Alliance for Wireless Power (A4WP) WPT system transfers power from a single Power Transmitter Unit (PTU) to one or more Power Receiver Units (PRU's.) The power transmission frequency is 6.78 4 MHz, and up to eight devices can be powered from a single PTU depending on transmitter and receiver geometry and power levels. The Bluetooth Low Energy (BLE) link in the A4WP system is intended for control of power levels, identification of valid loads and protection of non-compliant devices.

Figure 2 illustrates the basic WPT system configuration between a PTU and a PRU. The PTU can be expanded to serve multiple independent PRUs. The PTU comprises three main functional units which are a resonator and matching unit, a power conversion unit, and a signalling and control unit. The PRU also comprises three main functional units like the PTU.

The control and communication protocol for the WPT network is designed as the bidirectional and half duplex architecture and is used to signal PRU characteristics to the PTU as well as to provide feedback to enable efficiency optimization, over-voltage protection, under-voltage avoidance, and rogue object detection.

The WPT network is a star topology with the PTU as the master and PRUs as slaves. The PTU and the PRU perform the bidirectional communication to each other to identify the device compliance and to exchange the power negotiation information.

In this specification, section 2 provides high level requirements and section 3 identifies device classifications. Section 4 provides power transfer requirements (including a fixed 6.78 MHz operating frequency, resonator requirements and load parameters) while section 5 provides PTU and PRU power control requirements. Section 6 provides signaling requirements, section 7 identifies approved PTU resonator designs and Annex A includes reference PRUs for PTU acceptance testing. Annex B is an informative annex for PTU lost power."

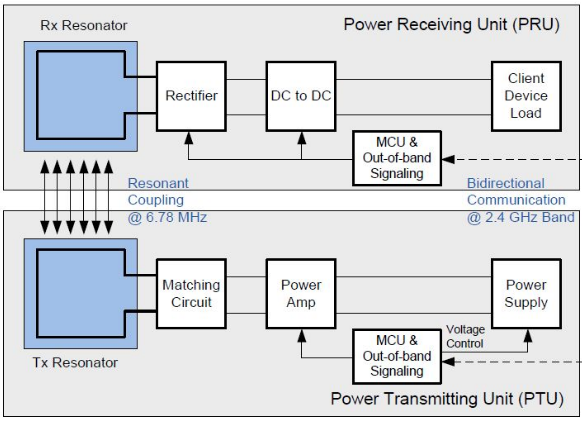

Figure 2. Wireless Power Transfer System

We have to also recognize that there are competing standards to A4WP. 'Energous', a company based out of San Jose, CA, has demonstrated its RF-based 'WattUp' standard at CES 2015. With this technology you would be able to charge a device with 90% efficiency at distances up to 6m. The actual specifications for the wireless charging of a device are evolving under the "Power Matters Alliance" (or PMA).

Happily for the industry, and therefore in the larger interests of the consumer, these competing organizations have signed a Letter of Intent on 4th of January 2015 to merge the two, with a timeline to do so by the 30th of June 2015. With a unified standard, there will be considerably less confusion for both manufacturer and consumer.

2.5 Bringing these technologies together

For the first time in the history of construction a host of technological solutions are simultaneously available to address the complexities of modern building construction.

- We are in the unique position of being able to comprehensively design and describe a building within a virtual environment and simulate the entire construction process. A universally acceptable data exchange mechanism in the form of IFC files can be fed into a 'robot' server.
- We are able to create microprocessor controlled machines - robots - that can be programmed to perform exacting, laborious and repetitive tasks. These robots can be programmed to obtain all the required construction data from centralized servers, perform the necessary actions required, record their actions, and report the results back to the servers.
- We are able to pinpoint a location in three dimensions accurately, within the tolerance levels of a building construction project.
- We are able to create robots that can be untethered, yet stay powered for as long as required, if enough wireless charging points are distributed around a construction site.

We are not looking at a remote or futuristic scenario. Japan has been at the forefront of research and practice into this genre since the 1980s. During the author's research on these topics it was discovered that a majority of technical papers on the subject were written by Japanese researchers.

3 On the frontlines

BIM-XD will be to construction what CAD/CAM is to manufacturing. Three examples of automating construction related as well as actual construction activities using some form of robotics are presented here for discussion:

1. **Theometrics**
2. **Construction-Robotics**
3. **Vanku**

3.1 Theometrics

'Theometrics, LLC' is a company based in New York, USA. It specializes in the accurate transfer of CAD dimensional data onto a work site. As described by the company:

"Theometrics navigates users from any point on any CAD drawing or BIM model to the exact field location, with laser-sharp accuracy.

Theometrics is the art and science of precision measurement and navigation in and on construction sites. We have created "The New Standard & Best Practice" by which architectural and construction measurements are performed worldwide. We have transformed the antiquated, inaccurate and inefficient practice of using strings and tape measures to perform construction as-built or layout, while developing "a new legal standard of care."

Theometrics provides a bridge between a virtual model and real world construction.

Examples of their work:

• Accurate marking of a complicated reflected ceiling plan was required for Xanadu Mall, NJ. The contractors estimated that 64 man hours would be required to complete the marking. Theometrics completed the job in just 4 hours.

• For their work on the Lincoln Center David Koch Theater, Theometrics won the FIATECH CETI Award in 2009 [15]. They not only made renovation of this theatre possible without disturbing the performance schedule but demonstrated that, empowered with a single digital measurement, comparison and layout tool set, it was possible to achieve a new workflow and really enhance performance of a construction cycle. On this work they were well beyond a survey scope or a modelling scope or even coordination. Figure 3 shows the extensive three dimension modelling undertaken. Theometrics established a new workflow or trade.

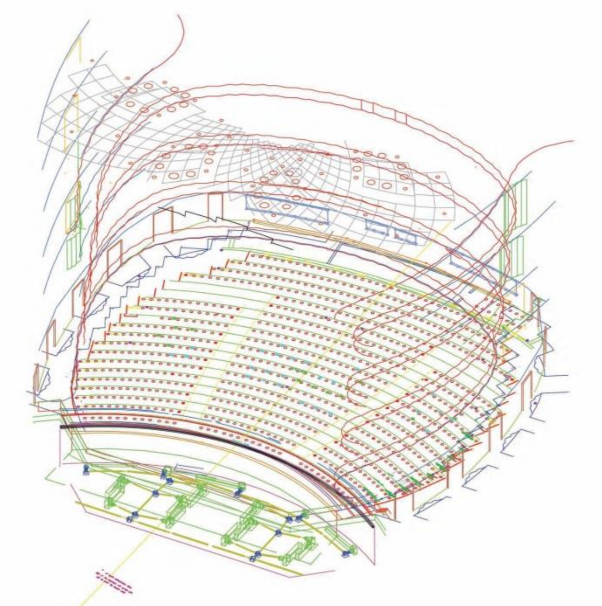

Figure 3. 3D-digital measurements for the Lincoln Center David Koch Theater

3.2 Construction-Robotics

'Construction-Robotics' is a company that is at the frontline of actually using a robot to construct one aspect of a building - their Semi Automated Masonry robotic system, or SAM. Figure 4 shows the entire system from the external side while Figure 5 shows a close-up view of the same robot holding a brick after applying mortar and ready to place it in its course.

Figure 4. External view of SAM at work

SAM can be loaded with full, half, or even odd sized bricks. A construction sequence program is fed into it. SAM then picks up the bricks with an arm, applies mortar, and precisely builds a wall course by course.

Construction Robotics lists the following benefits arising out of their system:

- Job savings of greater than 30%
- Reduced physical strain on the mason and crew; mason focuses on tooling joints and wall quality
- Lower health and safety impact on the workforce
- Consistent production rate and performance

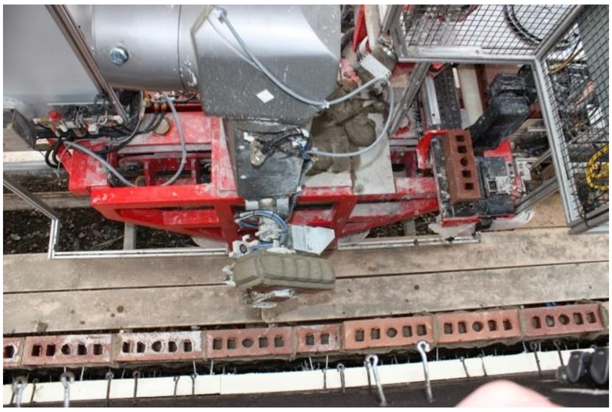

Figure 5. A close-up of SAM laying a brick course

Recently, SAM has been nominated for the '2015 Most Innovative Product' award at World of Concrete, Las Vegas.

3.3 Vanku

'Vanku', a construction company in the Netherlands, has patented a semi-automated brick paver machine known as Tiger Stone. The paver lays a 4, 5 or 6m wide high quality road including kerb finishing. Figure 6 shows a Tiger Stone paver with its hopper loaded and laying a herringbone pattern paving. An operator is needed for fine tuning the adjustments; otherwise the bulk of the work is performed by Tiger Stone. For example, the machine has sensor plates that read and pave as per the camber desired while other sensors ensure that the kerb stones are laid in the right direction.

Figure 6. Tiger Stone paver at work

4 Conclusions

The existing technologies, resources and expertise required for achieving the goals stated in this paper are scattered far and wide around the globe. Architects are not trained computer programmers. Programmers do not understand building construction. Building contractors are not robot builders. *The expertise is there, but not all in one place.* This concept paper is written with a view to bring together a collective of thinking minds backed by adequate funding to bring these disparate technologies together. Traditional, labour-oriented construction methods may not lend themselves easily to mechanized construction and we may have to rethink construction materials or methods used. The starting point is the BIM file itself. The metadata associated with the BIM file must form the bridge between design intent and constructability by a system of robots. This is what will lead us towards a new BIM dimension.

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