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PERFORMANCE MONITORING OF MODULAR CONSTRUCTION THROUGH A VIRTUALLY CONNECTED PROJECT SITE AND OFF-SITE MANUFACTURING FACILITIES

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ABSTRACT

Cost escalations and schedule delays have rendered nuclear energy commercially unattractive. Much of the research and development has focused on developing new reactor designs with accident tolerant fuels and passive safety systems intended to reduce operating and lifecycle costs. In addition, small modular reactors (SMRs) are being developed with the premise that multiple smaller reactors will be less costly to construct and deploy than one large unit. To support the nuclear industry in lowering fabrication and construction costs, which will contribute to lowering the overnight construction costs, this paper presents the development of an innovative virtual environment to digitally manage QA/Quality Control (QC) inspections and construction progress and improve supply chain efficiency. This innovative concept builds upon recent advances in building information modeling (BIM) and reality capture that utilize the power of 3D laser scanners and camera-equipped drones for 3D image/video processing. We envision this construction performance modeling and simulation (CPMS) environment will facilitate automated inspections of components and subsystems before shipping. The presented solution will be embedded into the supply chain loop to ensure ongoing quality control, simulation of weekly progress and work schedules, and timely decision support throughout construction. CPMS will address these issues for new reactor designs that are expected to have either accident tolerant fuels or are inherently safe with passive safety features.

INTRODUCTION

Huge escalations in overnight construction costs and schedule delays have rendered nuclear energy commercially unattractive. Much of the research and development has focused on developing new reactor designs with accident tolerant fuels and passive safety systems intended to reduce operating and lifecycle costs. In addition, small modular reactors (SMRs) are being developed with the premise that multiple smaller reactors will be less costly to construct and deploy than one large unit. However, Hopf (Hopf 2013) argues that the primary reasons for construction cost escalation and schedule delays are related to: (i) extremely stringent nuclear safety and quality assurance standards, (ii) inexperience in managing and staffing to nuclear QA standards, (iii) excessive paperwork, and (iv) supply chain delays due to rework. Despite the smaller size of SMRs, their construction is not likely in the U.S. unless overnight construction cost and schedule improvements are achieved via appropriate research, incorporation of technological innovation in construction, lower operating costs with reduced staff, and a feasibility study to assess potential risks (Hopf 2013; Plumer 2016; Smith 2017).

To support the nuclear industry in lowering fabrication and construction costs, which will contribute to lowering the overnight construction costs, this paper presents monitoring framework for modular construction of nuclear energy facilities that uses a virtual environment to digitally manage QA/Quality Control (QC) inspections and construction progress and improve supply chain efficiency. This innovative concept builds upon recent advances in building information modeling (BIM) and reality capture that utilize the power of 3D laser scanners and camera-equipped drones for 3D image/video processing.

The presented framework will model and simulate construction performance in a virtual environment, hence denoted hereafter as Construction Performance Modeling and Simulation (CPMS). CPMS will facilitate decision making through virtually connected construction site and off-site facilities. The presented solution will be embedded into the supply chain loop to ensure ongoing quality control, simulation of weekly progress and work schedules, and timely decision support throughout construction. CPMS will address these issues for new reactor designs that are expected to have either accident tolerant fuels or are inherently safe with passive safety features. Figure 1 illustrates this concept. Figure 1. Schematic diagram of CPMS in the supply chain loop. This paper presents the preliminary studies that are the pieces of CPMS and gaps-in-knowledge to be investigated to complete the development of CPMS.

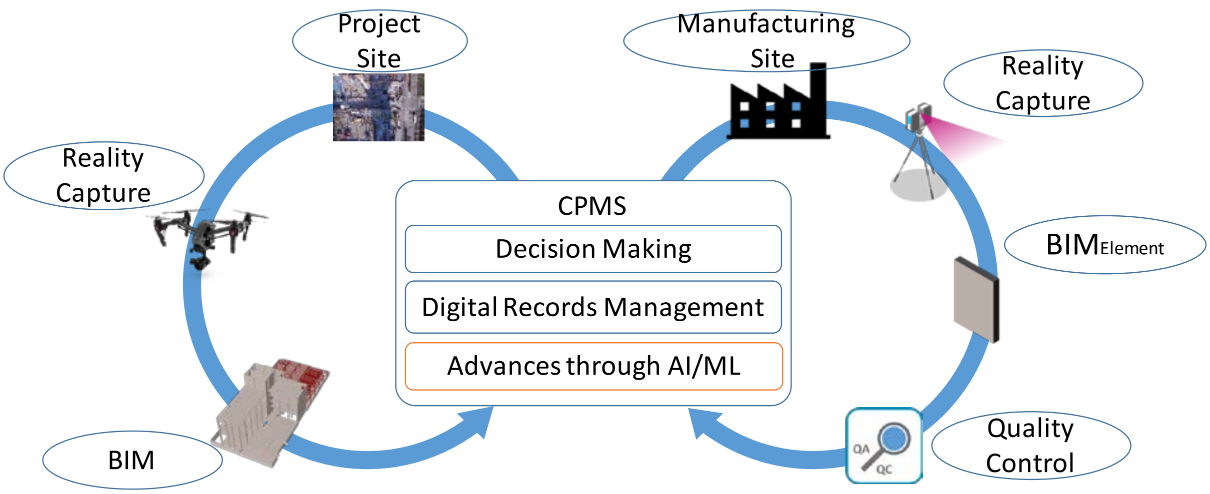

Figure 1. Schematic diagram of the proposed CPMS in the supply chain loop.

BACKGROUND

State-of-the-Art Technologies to Overcome Construction Cost and Time Escalation

To reduce construction overnight cost and time, the construction industry has been actively advancing the following state-of-the-art technologies. These technologies also serve as enabling factors for the presented method in this paper. BIM serves as a database of structures, equipment, and components in a construction project and allows visualization of interdependence among them. It can capture 4D (i.e., time) to simulate construction progress over time and assist with future planning (Kifokeris and Xenidis 2017; Park et al. 2017). BIM has been proven to be an enabling factor to apply lean manufacturing theory in construction (Sacks et al. 2010).

Rapid growth of reality capture technologies allows creation of as-built models that can be aligned with BIM for project management purposes. For example, fly a drone over a construction site, capture videos/images, and create a 3D point cloud (Ham et al. 2016; Han et al. 2018; Han and Golparvar-Fard 2017). Advances in high precision reality capture technologies using 3D laser scanners (i.e., mobile and stationed) for documentation and inspection in the construction and manufacturing industry (Tang et al. 2011).

Despite of these state-of-the-art technologies, there is no existing technology that brings them together into a single pipeline of decision making from trades, subcontractors, vendor manufacturers, general contractors, and all the way to owners. For instance, 3D laser scanners have been used at various construction projects, including VC Summer. However, VC Summer still had the escalation in cost and time. What the existing QA/QC using these laser scanners did not offer was conformation against construction drawings (BIM) and compatibility check with other components.

Quality Assurance and Controls for Modular Construction

As illustrated by Figure 2a, on-site assembly of a component can increase the project duration when there is an incompatibility and/or quality issue on site. The significant delay caused by the lead time to re-manufacture and ship the component can affect the construction activities on the critical path, propagating quickly into other delays and further escalating the overnight construction cost and schedule. Moreover, a halt in nuclear construction can significantly increase indirect costs (i.e., overhead and interest). For instance, The DOE has provided more than $8 billion in loan guarantees to Plant Vogtle (Bustillo 2018). Therefore, accumulated interests due to delays can be significant for nuclear power plants – also reported to be 17% of the total capital cost according to the MEITNER webinar by Lucid Strategy (Ingersoll et al. 2018).

On the other hand, the proposed CPMS allows virtual assemblies of different components and high precision inspection prior to being shipped, as illustrated by Figure 2b. By starting to fabricate Component 1 early, Manufacturer 2 (M2 in the figure) can access the digital representation of Component 1 during the fabrication of Component 2. M2 can ensure that Component 2 is compatible with Component 1 during the manufacturing process and prior to shipping. This process will eliminate the uncertainties associated with compatibility and QA/QC of Component 1 and 2. In addition to preventing the delay, the estimation of time and cost by the general contractor, M1, and M2 will be lower due to the eliminated uncertainties (therefore reduced buffers in schedule and cost) associated with incompatibility.

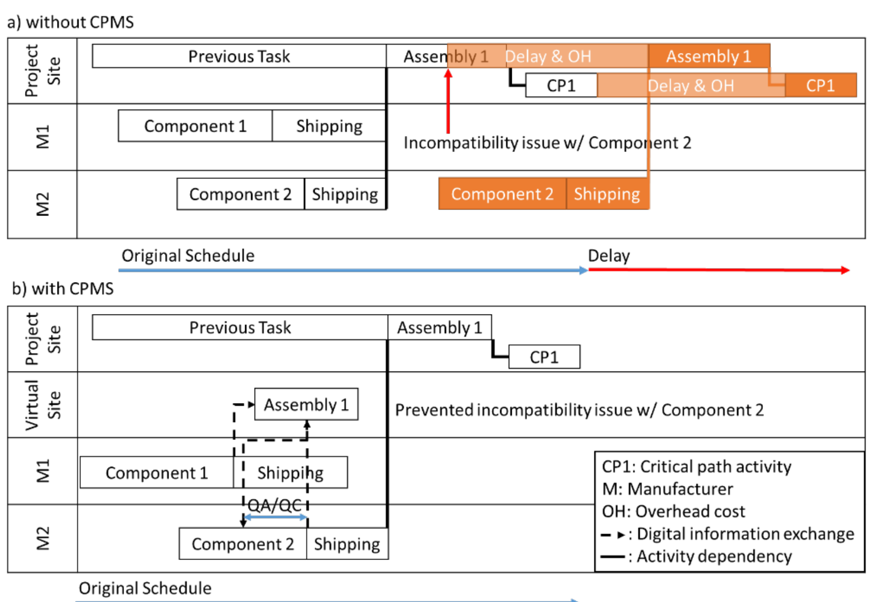

Figure 2. Illustration of a modular nuclear construction schedule a) with an unforeseen delay due to an incompatibility issue and b) without the delay and reduced schedule using proposed CPMS.

CPMS FOR PRODUCTION CONTROLS AND VIRTUAL QA/QC

The presented CPMS builds upon recent innovations in 4D construction simulation technologies that combine 3D BIMs and construction schedules (Reconstruction Inc 2017). Reconstruct (Reconstruction Inc 2017) visualizes 3D models of both as-built and as-planned statuses at multiple time instances (denoted as 4D models for combining 3D models with time). The project management can use this web-based software to assess construction progress during short-term planning sessions and daily and weekly coordination meetings. Recent studies on automated construction performance monitoring emphasize the use of visual production models to capture what has happened at a construction site, what should have happened, and what will happen (Han et al. 2015, 2018; Han and Golparvar-Fard 2015, 2017). These tools and studies can help in identifying delays and root causes of the delays. Figure 3 shows a snapshot of a virtual environment that visualizes a BIM and as-built model of a building under construction at NC State University.

Figure 3. Virtual Environment with as-built point cloud and as-planned BIM.

However, their benefits in modular construction is limited because many components are manufactured and shipped from vendor manufacturing plants. Benefits of such automation in construction would require digital capture of progress, virtual environment for virtual assemblies based on as-built data, stringent QA/QC at manufacturing sites, and digital record generation and management to improve decision making in the supply chain loop.

CPMS overcomes these constraints by developing a data-driven approach to assist with visualization and simulation of BIM and 4D point clouds for modular construction of nuclear plants. As shown in Figure 4, the proposed solution consists of: 1) virtual assembly of individual components through a virtual project site; 2) individual component modeling at vendor manufacturing plants using laser scanners and virtual QA/QC; and 3) 4D as-built modeling of the project site through periodic use of drones and 3D laser scanners and alignment with BIM.

Virtual assemblies involve geometry alignment of as-built and as-planned models. To increase the level of immersion, user-interaction with models and with other project participant, virtual and augmented reality via a hand-motion sensor and a head-mounted display (HMD) are used. The concept of macro-level alignment of 3D objects and virtual manipulation is used (see Figure 5) (Noghabaei et al. 2019). This method uses triangular surfaces (referred as meshes in computer graphics) that make up the 3D models (both as-built and as-planned models). The three parameters of the macro-level alignment are 1) the sum of the areas of all meshes, 2) object dimension, and 3) aggregated normals of the meshes (See equation 1).

$$\sum_{mesh_i} \vec{N}_{mesh_i} \times Area_{\,mesh_i} \;/\; \sum_{mesh_i} Area_{\,mesh_i} \qquad (1)$$

Where $mesh_i$ is each mesh of the object and $\vec{N}_{mesh_i}$ is the absolute value of the normalized vector of $mesh_i$ in direction that is normal to the mesh surface.

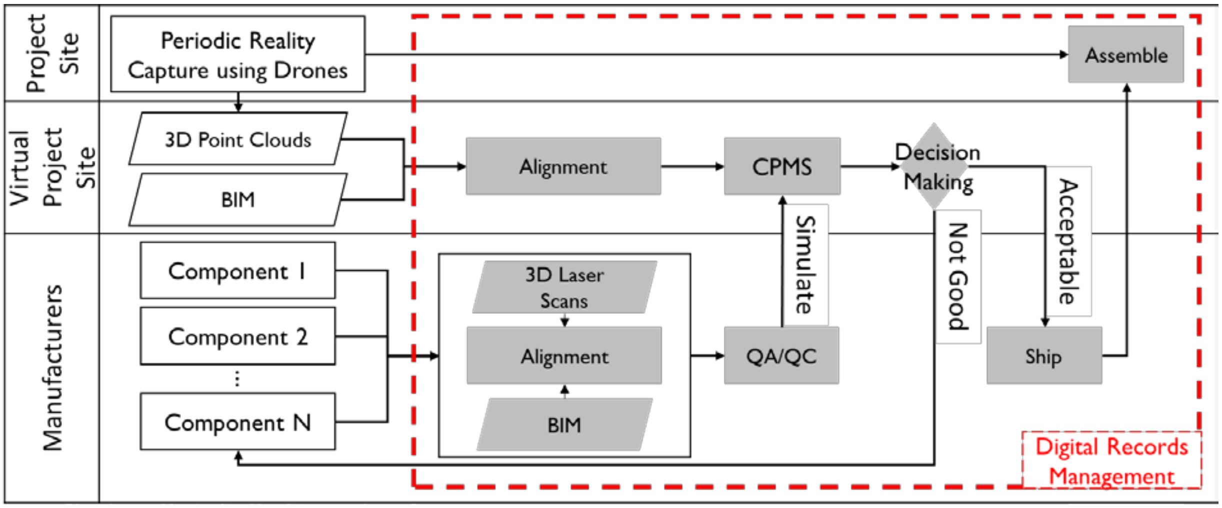

Figure 4. Process diagram of the proposed CPMS.

AS-BUILT MODELING AT OFF-SITE FACILITIES FOR QA/QC

There are various types of 3D scanning technologies and studies for inspecting equipment (i.e., terrestrial and mobile laser scanning and industrial CT) and building components (i.e., terrestrial and mobile laser scanning) (Cho and Gai 2013; Hamamatsu 2018; Tang et al. 2011; Tristan 2011). The proposed technology can utilize existing scanning technologies through mobile and/or stationed laser scanners to capture various nuclear reactor components and equipment, such as reactor internals, reactor vessel, piping, valves, tanks, spent fuel pool, reactor building concrete and rebar, aux building, turbine and turbine building etc.

After manual scanning, multiple point clouds will be registered as one point cloud. The point cloud will be aligned with a 3D construction document (i.e., BIM). A QA/QC engineer will define a set of inspecting activities, such as flatness/plumpness and honeycomb for concrete and steel components and sophisticated measurements for equipment and hook-ups). The aligned point cloud will be loaded to CPMS. An additional area that needs further investigation is the development of quality inspection that cannot be captured using the existing software. In addition to QA/QC, frequent data capture can be used to document every step in the fabrication process and will help vendors and subcontractors who are not accustomed to the required documentation and QA/QC process.

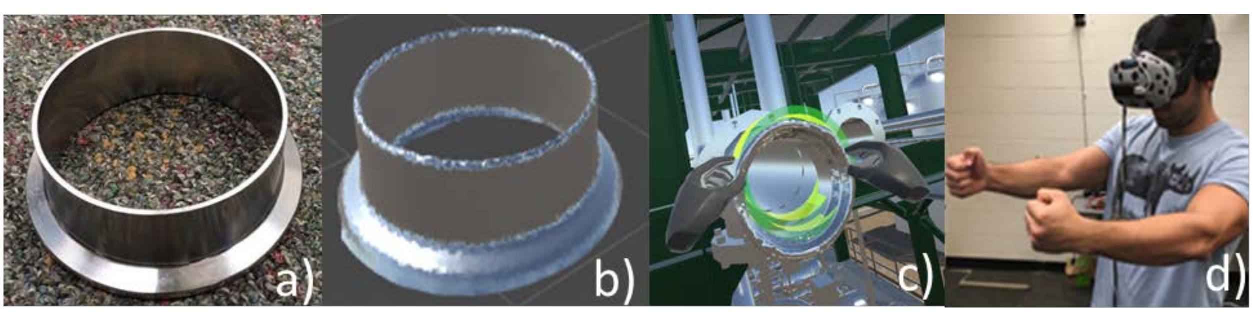

Figure 5. A component, b) its laser scan, and c-d) assembled with other components performed by a user in an immersive virtual environment.

This process of data capture, analysis, and digital information exchange consists of manual and automated steps using robotics solutions (Asadi et al. 2018a, 2019a). Asadi et al. (2018) developed an unmanned ground vehicle (UGV in Figure 6a) that can autonomously navigation on a construction. This UGV serves as a robotic platform that can interact with an unmanned aerial vehicle (UAV or a blimp in Figure 6b) and a robotic arm attached to UGV (Figure 6c).

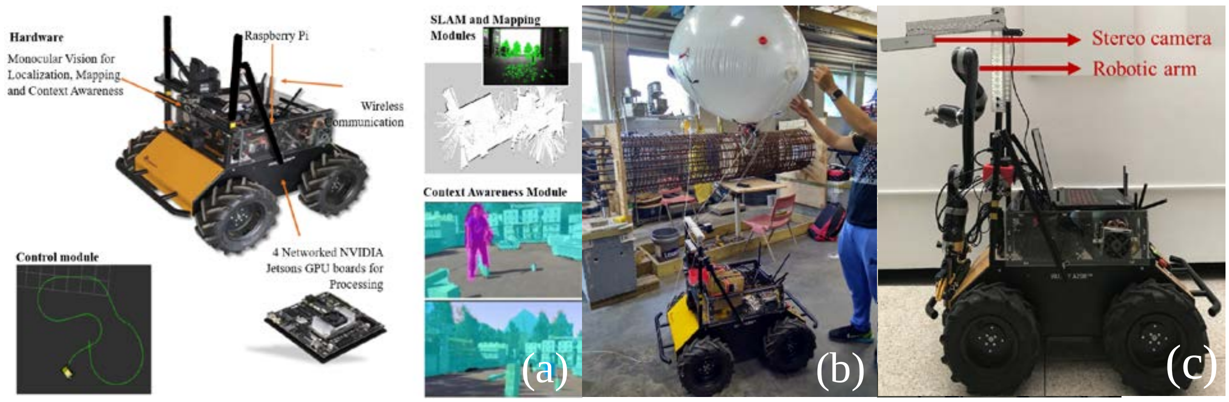

Figure 6. Automated data capture using a) UGV (Asadi et al. 2018), b) a blimp for indoor, and 3) robotic arm on UGV.

AS-BUILT MODELING AT THE PROJECT SITE FOR PROGRESS CAPTURE

There are various type of 3D scanning technologies and studies for capturing construction site for documenting construction process (i.e., time-lapse photographs, camera-equipment drone, and terrestrial laser scanning) (Bosché 2010; Han and Golparvar-Fard 2017). Figure 4 illustrates the process of capturing visual data, 3D reconstruction, and alignment with BIM. Through this process, 4D point clouds and 4D BIM are used to update construction progress and plan. Although not shown in the figure, terrestrial laser scanners can be also used for as-built modeling of the site (Asadi et al. 2018b; El-Omari and Moselhi 2008; Zhang and Arditi 2013).

Similar to the previous section, as-built models of the project site need to be aligned with BIM. A common practice to automate the process is to use pre-surveyed ground control points (Han and Golparvar-Fard 2017; Lin et al. 2015). These ground control points can be also used to manually register the point clouds with BIM. CPMS leverages the existing work of the authors to perform as-built modeling and registration with BIM (Han et al. 2018; Han and Golparvar-Fard 2015, 2017). Camera-equipped drones for outdoor and terrestrial laser scanners for both outdoor and indoor can be used to capture as-built conditions throughout construction.

To autonomously navigate on a large project site, localizing robotic agents is important. Building on the authors' ongoing work on geometry-informed localization that utilize BIM as *a priori* knowledge (Asadi et al. 2019b; Asadi and Han 2017), real-time localization of visual data in the site coordinate system (NOT camera coordinate system so we can turn these virtual as-built model into intelligent "BIM" objects) will be investigated (see Figure 7). These as-built and planned modeling approaches can be used with the aforementioned software (e.g., Navisworks, Synchro, and Reconstruct) that can visualize point clouds and BIM for construction managerial tasks, such as short-term planning and daily management of jobsites. For the proposed project, CPMS will serve as a software platform that brings as-built and as-planned modeling, virtual QA/QC and assembly, and progress management. Serving as a base modeling and simulation tool, CPMS can also be used for digital record documentation and management for supply chain approvals as illustrated by Figure 1.

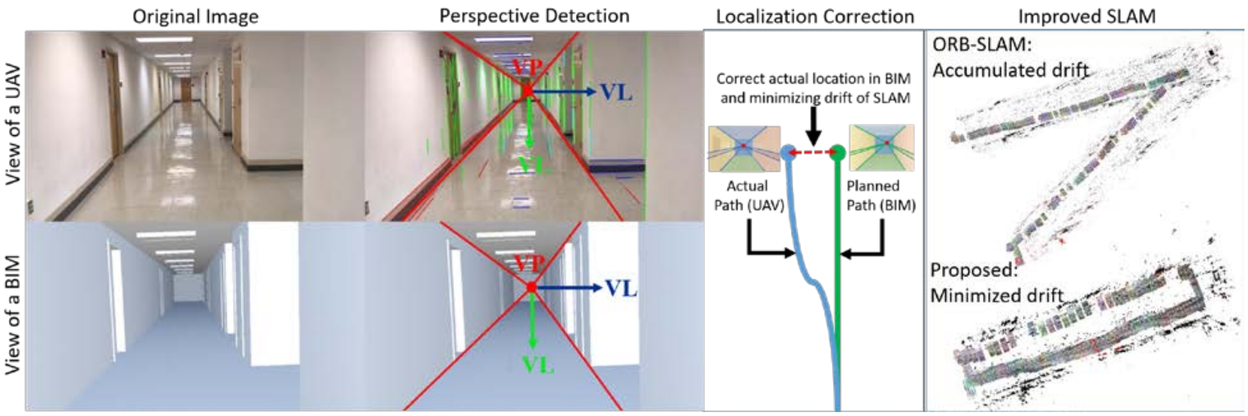

Figure 7. Improved real-time localization through perspective alignment between BIM and visual data (Asadi et al. 2019b)

CONCLUSIONS

This paper presents a monitoring framework for modular construction of nuclear energy facilities. It presents major components of the presented CPMS, including as-built modeling at the main project site and off-site facilities, data captures through advances in robotics and computer vision, and virtual environment that visualizes as-built models and as-planned BIM. The presented CPMS will allow visualization of actual construction progress compared against plans (4D BIM). As 4D BIM has embedded construction schedule, reasoning about the dependencies of construction activities along with the compared progress will allow traveling back in time to identify root-causes and forward in time to identify potential issues. CPMS has the potential to serve as a monitoring and digital data management solution that can serve all stakeholders of construction of nuclear energy facilities, including owners, construction managers, general contractors, subcontractors, and venders.

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