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Game Simulation to Support Construction Automation in Modular Construction Using BIM and Robotics Technology – Stage I

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ABSTRACT

Modular construction has been proven to be more time-efficient comparing to stick-built construction. However, the lack of automation technologies adoption shows a missed opportunity in modular construction, where the time efficiency of the modular process can be further improved, along with quality and safety. To address this problem, the authors proposed a new simulation method for modular construction using BIM, game simulation, and robotics technology, to help analyze and promote automation in modular construction of wood structures in a controlled indoor environment. As a first stage, the authors presented their simulation methodology, definition of the parameters and constraints for the construction simulation, and creation of the interactive simulation model. This first stage will be the foundation for further development that will enable the assessment of construction productivity when integrating robotic systems into the modular construction workflow.

INTRODUCTION

The productivity of the construction industry in the U.S. and many other countries had been stagnant for decades comparing to a faster productivity improvement in other industries such as the manufacturing industry (McKinsey Global Institute, 2017). Recent construction workforce shortage in the U.S. led to the resurgence of modular construction due to its advantages compared to stick-built construction in time efficiency. However, the lack of a wide adoption of automation technologies shows a missed opportunity in modular construction, where the time efficiency of the modular process can be further improved, as well as quality and safety. For example, fabrication and assembly operations of modular construction in residential units are still mainly manually performed, which can be prone to human errors, safety issues, and labor constraints. Therefore, a methodology to determine the performance of automating the modular construction process with robotics technology is needed, to quantify the potential productivity improvement in comparison to solely manual operations.

To address this gap, the authors proposed a simulation of modular construction using building information modeling (BIM), game simulation, and robotics technology, to help analyze automation in modular construction. The proposed game simulation consists of using robotic systems to automate the modular construction of wood residential units in a controlled indoor environment. The simulation game will be created in a modular fashion that will enable easy reconfiguration and customization of the simulation components. Modular construction workflows of a single-story wood housing unit with and without the use of robotic systems will be simulated and analyzed to determine the performance difference between them. As a first stage, the authors: (1) presented a simulation methodology, (2) defined the parameters and constraints of automation technologies used, and (3) created an interactive simulation model. This first stage will serve as the foundation for further development of the methodology that will enable the assessment of productivity performance by integrating robots in modular construction operations.

BACKGROUND

Modular construction. Modular construction is a construction method where building components and/or systems called "modules" are built in a factory setting and then transported to its final locations where the modules will be installed (Modular Building Institute 2010). Modular construction can be designed and constructed using different types of materials such as concrete, steel, and/or other types of composite materials (Lawson et al. 1999, Lawson et al. 2014). This study focuses on wood because it is one of the most utilized material for residential buildings in the U.S. (Foliente 2000).

In North America, the concept of off-site construction has been around for more than a century with the introduction of prefabricated houses shipped in pieces and then assembled on site by local builders (Sears 2012). The use of prefabrication in mass production began after the world war II, when stick-built construction could not keep up with the high demand of houses in that time (Musa et al. 2016). After the industrial revolution, the advancement of technologies and development of automation techniques such as robotics technology has opened new possibilities for modular construction.

The selection of modular construction is subject to many factors and constraints such as suitability for the project, need for expediting the schedule, site accessibility, restriction of site layout, flexibility in changes, and owners' perceptions (Azhar et al. 2013). However, modular construction has many advantages over conventional stick-built construction such as working in a controlled environment, the ability to do parallel activities to compress schedule, and the reduction in construction-site wastes (Lawson and Ogden 2010, KPMG 2016, McGraw Hill Construction 2011).

Automation in modular construction. The adoption of robotic systems in modular construction is suitable because modular construction is performed in an indoor environment similar to a factory setting, which reduces complexity caused by the unstructured environment of a construction site and benefits from productivity gain through repetitive prefabrication and assembly tasks (Balaguer and Abderrahim 2012). A recent increase in automation research of modular construction has been observed (Neelamkavil 2009; Taghaddos et al. 2018), especially with the integration of robotics into the construction and fabrication processes. For example, Willmann et al. (2016) integrated a manipulator robot into the construction of non-standard timber structures from a series of simple wood members. Eversmann et al. (2017) combined CNC machines and two industrial robots to enable a large-scale spatial fabrication of timber construction.

Game Engines. Game engines are traditionally used for game development, but they can also be used for simulation and modeling purposes because of their flexibility and capability in creating virtual scenarios with realistic interactions. Game simulation has been widely used in the architecture, engineering, and construction (AEC) domain (Nikolic et al. 2009; Natephra et al. 2016; Bille et al. 2014) to serve different purposes such as building virtual walk-through based on architectural design (Yan et al. 2011), airflow simulation and visualization based on MEP design (Shen et al. 2012), interior design decision support through intuitive comparison of alternatives (Heydarian et al. 2015), construction equipment training (Mastali and Zhang 2017), construction safety investigation (Yu et al. 2017), facility management (Shi et al. 2016), and lighting fixture design evaluations (Bucarelli et al. 2018), among others. The implementation of these simulation systems would be technically difficult and/or time consuming without the use of a game engine (Bille et al. 2014).

In this study, a game engine is used to simulate the construction process of modular buildings because of its ability to (1) incorporate BIM and robotic model, (2) add physic properties to objects, and (3) make changes to the simulation through programming environment. Although simulation tools that use BIM are available, they are not as capable to incorporate robotic systems into their simulation comparing to game engine. Similarly, many robotic simulators are available, however, they lack the support of BIM. The authors' literature review showed a lack of simulation work that incorporate modular construction, BIM, and robotic system all together.

PROPOSED GAME SIMULATION METHOD AND EXPERIMENT

The authors proposed to use game simulation to analyze the productivity difference between conventional modular construction and modular construction with robotics technology. The game simulation will be built upon BIM, and will integrate robotics components (e.g., mobile robot), according to their real world data such as capabilities and movement speed, to help analyze their use in construction. The proposed game simulation method is divided into three phases and each phase is consisted of two steps, resulting in six steps in total (Figure 1).

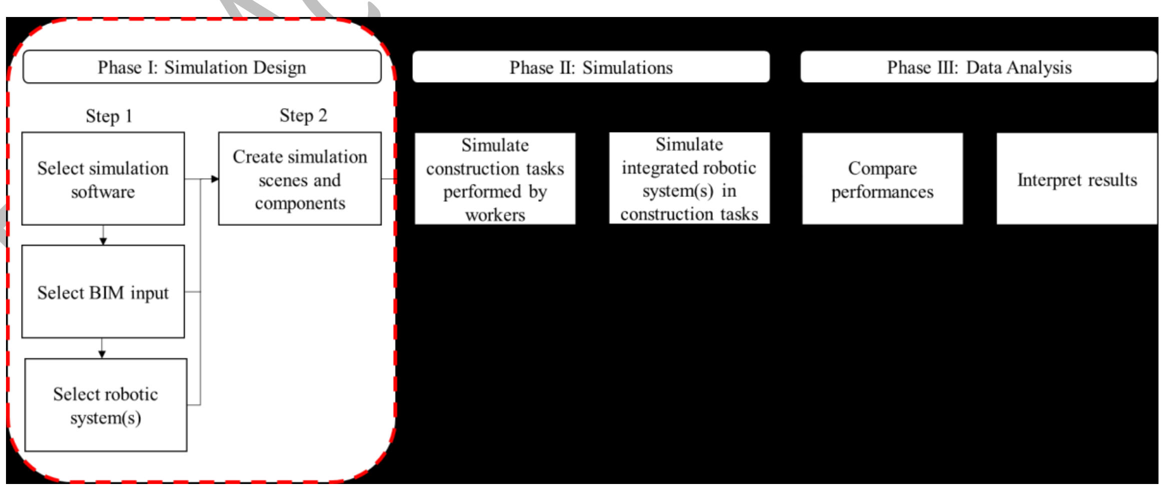

Figure 1. Proposed simulation method for modular construction.

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Phase I is consisted of: Step 1 – Select simulation software, BIM input, and robotic system(s); and Step 2 – Create simulation scenes and components. For Phase II, two main scenarios will be simulated. In Step 3 – Simulate construction tasks performed by workers, a construction operation solely based on manual labor will be simulated. In Step 4 – Simulate integrated robotic system(s) in construction tasks, selected robotic systems will be integrated into the workflow of modular construction using their real world performance data. Lastly, in Phase III, the two steps will focus on analysis and interpretation of results based on experiments from Phase 2: Step 5 – Compare performances in terms of productivity between different scenarios, and Step 6 – Interpret results. The implementation of Phase I is presented in the following section.

PRELIMINARY EXPERIENTIAL RESULTS AND ANALYSIS

By implementing the Phase I (Steps 1 and 2) of the proposed method, the following preliminary results were obtained.

Step 1 - Select simulation software, BIM input, and robotic system(s). In this study, a single-story residential wood building was modeled using 3ds max and Revit according to design drawings. Similar to Aldafaay et al. (2017), who presented a knowledge extraction, game simulation and visualization development of a steel erection operation, the authors integrated BIM into the game engine to examine the modular construction of a wood structure. To incorporate real world data into the simulation of the construction process, the actual construction operations in the Purdue University construction lab were observed and recorded.

Among game engines available, the authors selected Unity in this study based on its functional fidelity (physics modules), availability and composability (ability to import/export various resources), according to the criteria for game engine selection described by Petridis et al. (2010). The game engine is compatible with many data formats such as .fbx, .dae, .3ds, .dxf, .obj, and .skp, and supports proprietary files such as those from Maya, Blender, and 3D Studio Max (Unity Technologies 2018). One major limitation was the lack of a direct and seamless integration with BIM (e.g., IFC). To overcome this limitation, a partial solution was to use third-party pipeline approaches such as those summarized by Bille et al. (2014). Recently Unity disclosed full integration with Autodesk Revit, making the integration of BIM into game simulation more straightforward (Unity Technologies, 2018a).

The robotic system selected is the Fetch research robot, which is a wheeled robot with 2D mobility and flexibility in Omni direction motion. Later, a workflow will be developed that integrates the use of this mobile robot to mobilize small resources on the jobsite, and to aid in the assembly of the wood structure.

Step 2 – Create simulation scenes and components. In this step, the background, static and dynamic components, and movement/interaction rules were developed and added to the simulation scenes. The Purdue University construction lab was used as the background, where the building structure and its enclosed space were modeled. Static components mainly refer to the wood structure under construction, and dynamic components include a heavy-duty crane, construction workers, and the robotic system. All resources were modeled based on their real world geometries. For example, the building structure was created in BIM based on the drawings, and then imported into the game simulation (Figure 2).

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In addition to modeling the components, movement/interaction rules were also developed. An experimental test to determine the speeds of the 3 DOF heavy-duty crane in the construction lab was conducted. The speeds (rotational, horizontal and vertical translations) of the crane movements were determined by measuring the time the hook took to travel specified distances. The orientation and directional movements of the hook were chosen as shown in Figure 3.

The time and distance measured for the rotational, horizontal (forward – backward) and vertical (up – down) directional movements are presented in Table 1. A total of three measurements were taken for each directional and rotational movements. The rotational speed was calculated by dividing the circumference of the crane rotation (i.e., 360 degrees) by the time the crane arm finished a complete circle. For the horizontal and vertical directional speed measurements, predefined horizontal and vertical distances were used together with the travel times of the crane to determine the horizontal and vertical speeds. The average speeds were computed based on the collected data.

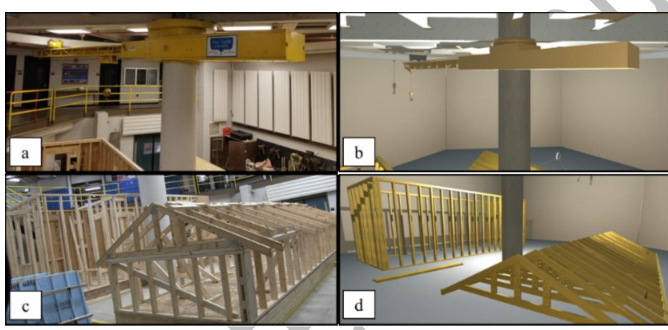

Figure 2. (a) Crane; (b) crane simulation; (c) wood structure; (d) wood structure simulation.

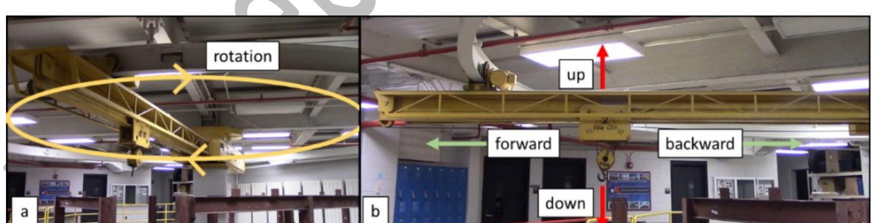

Figure 3. Measurements data: (a) rotation; (b) horizontal and vertical directional movements.

Table 1. Experimental data and speeds calculation.

#	Rotational Speed			Horizontal Speed			Vertical Speed		
	Rotation (degree)	Time (s)	Angular Speed (degree/s)	Distance (ft)	Time (s)	Speed (ft/s)	Distance (ft)	Time (s)	Speed (ft/s)
1	360	103.65	3.473	12.46	21.86	0.570	4.00	9.18	0.436
2	360	103.30	3.485	12.46	21.88	0.569	4.00	9.15	0.437
3	360	103.62	3.474	12.46	21.11	0.590	4.00	9.17	0.436

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Avg.	3.477	0.577	0.436

The average speeds were used as input for the modeled crane. To evaluate the feasibility of such simulation, a comparison between the simulation results and an actual crane operation was executed. The simulation of the crane operation in carrying a bucket from a predefined point (a) to another predefined point (b) was conducted, a total of 100 seconds was predicted in performing this operation (Figure 4). A physical test in the construction lab gave us a total of 109 seconds used to perform this operation (Figure 5). The time difference between simulation prediction and actual operation is under 10%, which showed the proposed simulation method is promising.

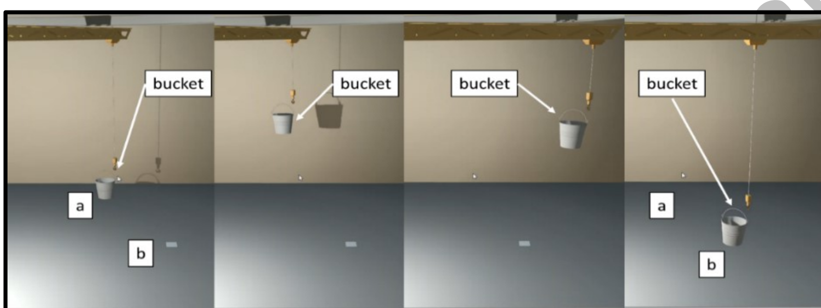

Figure 4. Simulation of crane operation by transporting a bucket from point *a* to point *b*.

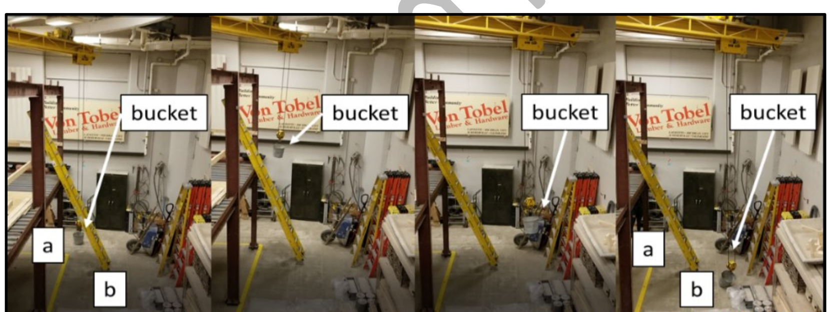

Figure 5. Testing of crane operation by transporting a bucket from point *a* to point *b*.

CONCLUSION

In this study the authors proposed a game simulation method that integrates BIM, game engine, and robotic systems, in a modularized way, to investigate the modular construction of a wood structure in different scenarios regarding the use of robotic systems. The authors implemented the first phase of the method to build the fundamental assets of components from a wood structure, a construction lab environment, and a 3 DOF heavy-duty crane. All assets were modeled following their real-world geometries and functions. At the completion of all phases in the proposed method, the simulations will help analyze productivity of building the wood structure in different ways. The authors' preliminary results in predicting the operation time of the heavy-duty crane in picking up and transporting an object (bucket) gave a time difference under 10% and showed such promise.

LIMITATIONS AND FUTURE WORK

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A main limitation of this study is acknowledged: despite the promise of incorporating real-world data as showed in the preliminary results, the level of difficulty in simulating real operations may increase when more interactions are introduced into the simulation between workers, robots, and equipment/environments. In future work, the simulations for constructing the wood structure with and without robotic systems, and their comparison will be carried out. The study will be extended to further assess productivity implications when introducing different types of robotic systems into the construction workflow. Lessons learned from this simulation method can be used to support its use in a wide range of scenarios such as interactive safety training and construction education by integrating with virtual reality interfaces.

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