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SYSTEM ARCHITECTURE FOR SUPPORTING BIM TO ROBOTIC CONSTRUCTION INTEGRATION

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Abstract: The adoption of robotics into the construction industry has been progressing slower than in the manufacturing and industrial sectors. Current shortfalls in skilled labor, productivity trends, and ongoing safety challenges point to the need for a drastic shift toward adopting robotics. Addressing these shortfalls would be a necessary component of the shift toward industrializing the construction industry. Despite this lag in technology adoption, the interest and development of robotic technology targeting the construction industry has grown in recent years and is ranging from the use of drones for tracking to advances in offsite fabrication. However, the integration into fundamental site construction necessitates reconsidering the information technology infrastructure needed to support detailed task execution information needs in the change from craft labor to robotic operations. This research presents the identification and mapping of the Information Technology (IT) system architecture required to support building information modeling (BIM) to robotic construction. Combining elements of BIM architecture and information exchanges with the needed construction task decomposition is required. These elements are mapped to the robotic system elements vital for mobile robotic operations. In addition to defining the functions and integration required to support the BIM to robotic Construction Workflow, shortcomings in existing infrastructure, notably regarding the ability to decompose construction fabrication and assembly means and methods, are defined.

1 INTRODUCTION

The construction industry has progressed at a slower rate than other industries such as manufacturing and industrial sections in terms of technology adoption, more specifically, robotics. However, robotics are becoming more commonplace in the construction industry, with multiple companies developing targeted robots for construction tasks. Some of these robots are made for a single task, such as the Semi-Autonomous Mason (SAM100) made by Construction Robotics or Tybot made by Advanced Construction Robotics. Other robots complete more general tasks, such as Spot by Boston Dynamics. These robots can carry out tasks that can help the construction industry's current labor shortfalls or address human-worker safety challenges. Despite this potentially valuable contribution, the transition from craft labor to robots' use requires a change in the required information provided. One of the fundamental issues is how the robot receives, interprets, and uses the information from a facility design to execute construction tasks to the same degree or scope as craft laborers, showcasing a need for technology infrastructure to support this information transfer.

To create the appropriate technology infrastructure for delivering information for robots to use the building information model (BIM), it is essential to understand the elements that make up a system architecture. A system architecture is a conceptual model that defines the system's views, behavior, and structure. System architecture can be defined as the conceptual model of a system and then models derived from it. This aspect of the system architecture will represent the different views on top of the conceptual model, facets or concerns of the system independent of the scope and abstraction level of various stakeholders, restrictions for the deployment of the system, description of the quality warranties of the system, and embeddings into other (software) systems (Jaakkola, H., & Thalheim, B., 2010). The system architecture is a critical underlying element of the BIM to robot construction information transfer because this is how the robot will receive specific information to carry out its tasks on the job site.

2 METHODOLOGY

This paper will present the system architecture and mapping required to support BIM to robotic construction information transfer for in situ construction. This will be done by analyzing examples in the literature to identify both necessary components for the system architecture, as well as define the interactions needed for the information flow; a new system architecture is defined based upon these analyses, which will consider the information needs of the construction industry embued within it. The method will be validated through a simulated test case to verify the system architecture's links, components, and structure.

The literature review research for this paper consisted of two primary literature searches. The first search was for the construction system architecture, and the keywords for the included construction system architecture, BIM, construction, system, and architecture. This phase utilized google scholar as the primary location to receive papers. Papers first were filtered by date in the range from the year 2000 and onward. After that, the reviewed papers would contain the keywords and wherein this timeframe. The next step was to determine if the study had relevance. The abstracts were the starting point for this and were reviewed for verification of focus on information architecture and relevant information exchange support. If the abstract was deemed relevant to the paper, a full review of the paper followed. The second literature search was to identify examples of the robotic system architecture. This literature review involved the same criteria showcased for the construction system architecture; however, the keywords differed focused upon robotic, computer, system, and architecture to search.

3 LITERATURE REVIEW

The system architecture is an essential step in having robots contribute to on-site construction activities. This section will focus on the pre-existing system architectures for BIM within the construction industry and comparable systems to determine the need for robotic system architecture. The new BIM to robotic system architecture presented in this paper used both robotic and BIM system architectures to develop it.

3.1 CONSTRUCTION SYSTEM ARCHITECTURE

Kim and Russell (2003) focused on the system architecture for an intelligent earthwork system. This study explored the phases of earthwork for construction, including site preparation through finish work. Following the phases, the authors defined the factors that impact earthwork tasks, such as site conditions, work type, and managed work. The data flow is organized into the system architecture module for the task identification and planning and used to determine resource allocation and then the task execution once all the data has been input. This study found that the system architecture will contain three main sections: the task-planning subsystem, task-execution subsystem, and the human control subsystem.

Similarly, Dakhli, Z. et al. (2019) developed an intelligent construction site's information system architecture. This study determined that the construction resources will have intangible qualities, such as cost, time, weather, material resources, and human resources. Sanguinetti et al. (2012). proposed a system architecture to analyze and give feedback in architectural design. The system architecture structure adapted to various analytical models, such as an energy analysis. While this study is not directly related to robotics in construction, a few constants identified for extracting information from BIM are: 1) It is dependent on the level of detail in the model, 2) External factors can influence the analysis, and 3) Data extraction of the geometry of the structure is of the utmost importance to better refine the process to perform an accurate analysis. A study by Ibrahim et al. (2017) developed a conceptual framework for BIM system architecture.

Their model defined four phases that the data will progress through 1) Extracting data, 2) Integrating data, 3) Analyzing data, and 4) Interpreting the data. The fundamentals from this study are that the data collected from the model is of high importance, then the information is processed, analyzed, and finally, humans interpret the information from the computer. The main point that this paper is trying to make is that once the data is collected, it must be post-processed to be adequately utilized. Aleksandrov M. et al. (2019) addressed a similar point which where they determined the four main steps for the system architecture are inputting the data, structuring the data with databases, updating the structured data, and finally, data visualization. Another study looked at system architecture for building information modeling and geographic information systems. This study looked at various architecture data integration such as schema, service, ontology, process, and system. This study has a similar method to the rest for the architecture but limited the steps to three: extract, transform and load the data (Kang, T.W. and Hong, C. H. (2015)). Bilal, M. et al. (2016) looked at significant data architecture for construction waste analytics. The focus of this study was incorporating the modeling information with the big data architecture, and the was analytics to produce results. For this research, the big data architecture had three layers: the storage layer, the analytics layers, and the applications layer. These layers allowed the information from each to be shared while receiving data from various sources.

Based on the studied construction system architectures, a few elements were identified that will be necessary for the BIM to robotic system architecture: the data extraction and structure of the data output is of extreme importance, external data sources utilized, such as site conditions, and the need for post-processing the data. A system architecture for construction applications can be developed from here while addressing the limitations of the previous studies. For example, most of the studies reviewed here focused on BIM or big data system architecture, with the result to visualize the data not having a robot carry out the applications(Bilal, M. et al. (2016), Ibrahim et al. (2017), Sanguinetti et al. (2012)). Therefore, it is imperative to identify robotics system architecture.

3.2 ROBOTIC SYSTEM ARCHITECTURE

In addition to system architecture from related construction technology, robotic system requirements will play a critical role in developing a BIM to robot system architecture. Ahmad and Babar (2016) studied a basic system architecture for robotics applications. This study evaluated the different sides of the robotic system first by examining a software platform where the application is determined and moves into the control system where the robotic operates. Their research determined three parts to their system architecture: robotic operations, robotic evaluation, and robotic development. Operations focused on the coordination of the robot, evaluation was for the robotic adaptations and reengineering of the task, and finally, development was for programing/ data inputting (Ahmad, A., & Babar, M. A. (2016)). One study focused on sensor fusion-based robotics system architecture with human interaction. In this study, the robot's system architecture depends on retrieving the information from sensors and then having the system data infused into it through the robot operating software (ROS). After that, the robot would check to see if the inputted commands were feasible to be carried out; if so, the command would then be executed (Ruiz and Chandrasekaranxs, 2020). Another study in the robotic system architecture field focused more on the system architecture for a swarm of robots. In the model presented by this study, the system architecture had a task demand and decision layer heavily reliant on the human-computer interaction; after that, it would go into the planning and execution layers. Each layer inputs sensor data as needed to aid with future decisions and carry out work (Leng et al., 2017). Another study focused on robotic system architecture was completed by Jahn et al. (2019), which focused on system architecture for modular robotic usage. Their proposed architecture had three layers: the controller, the reflective operator, and the cognitive operator. The control is responsible for the sensors and actuators on the robot, i.e., the data collection. The reflective operator is in charge of processing the data from the controllers. Finally, the cognitive operator is responsible for optimizing the behavior of the system. Integrated into either operator layer is a human-computer interface.

Examples of robotics system architecture can also be identified outside of the construction industry and can play a significant role in creating a system architecture for robotics in the construction industry. One paper looked at modular system architecture. The architecture identified three primary levels: the application level, fusion level, and sensor level. The application-level gets carried out when the data gets delivered for the application. The fusion level is when the data is verified and incorporating the data. The last level and the first carried out is the sensor level. This level picks up the raw data for the application and filters it during the fusion level (Darms and Winner, 2005). This architecture is similar to the other robotics systems in its levels, where the sensor level lines up with extracting data, the fusion level lines up with the integrating data, and the application lines up with analyzing and interpreting data in Ibrahim et al. (2017). Another modular system architecture with a similar design is in a study by Klose et al. (2010). This study examined the modular system architecture for an autonomous robot for plant evaluation. While this study did focus on plants, the basis is applicable for construction application. The main aspects discussed are sensing the data, storing the data, and analyzing the data. Building upon these functions, the robot control system becomes paramount. In summary, the overall process is proposed by sensing the data and collecting it, then using that information to control the robot (Klose et al., 2010). Another type of robotic system architecture is cloud-based robotics—a study by Wan et al. (2016) looked at defining the system architecture and identifying issues associated with it. For the system architecture of cloud robotics, they have data collection, data storage, database integration, and carrying out the robotic task while all steps provide feedback. A few of the critical issues this study identified are resource allocations, data interaction between robot and cloud, and security concerns (Wan et al., 2016).

These studies can lead to a few general consensuses about robotic system architecture. One is that there is a constant influx of data into the system. This can be from a variety of different sensors and actuators on the robot as well as external sources. Another is an output responsible for executing tasks and other data collection that a human can interpret. A critical aspect is the control of the robot. The control gets carried out by different simulation software, such as ROS. Therefore, the robot will be in an eventual loop of planning, sensing, and executing tasks as a simple model. The loop identified creates a system architecture that will allow for BIM to robotic interaction. Based on the robotic system architecture shown, elements have been identified necessary for the BIM to robotic system architecture. These elements are extracting data, integrating the data, and analyzing and interpreting the data (Darms and Winner, 2005; Klose et al., 2010; Jahn et al., 2019). However, these studies are limited in nature as they do not directly relate to integrating a BIM model for the robots data collection. Most of these studies had large amounts of their data come from sensors, which will be needed but will also need information about the task from the model

4 SYSTEM ARCHITECTURE

Based on previous studies, a system architecture for BIM to robot construction is developed and a similar in design as proposed by Kim and Russell (2003). This model will have three different and equally essential phases, including task planning, task decomposition, and task execution, to send the information from a BIM model to be executed by a robot. Figure 1 shows the overall system architecture for supporting BIM to robotic construction integration developed in this study. This method is dependent on a BIM model of sufficient detail for construction purposes.

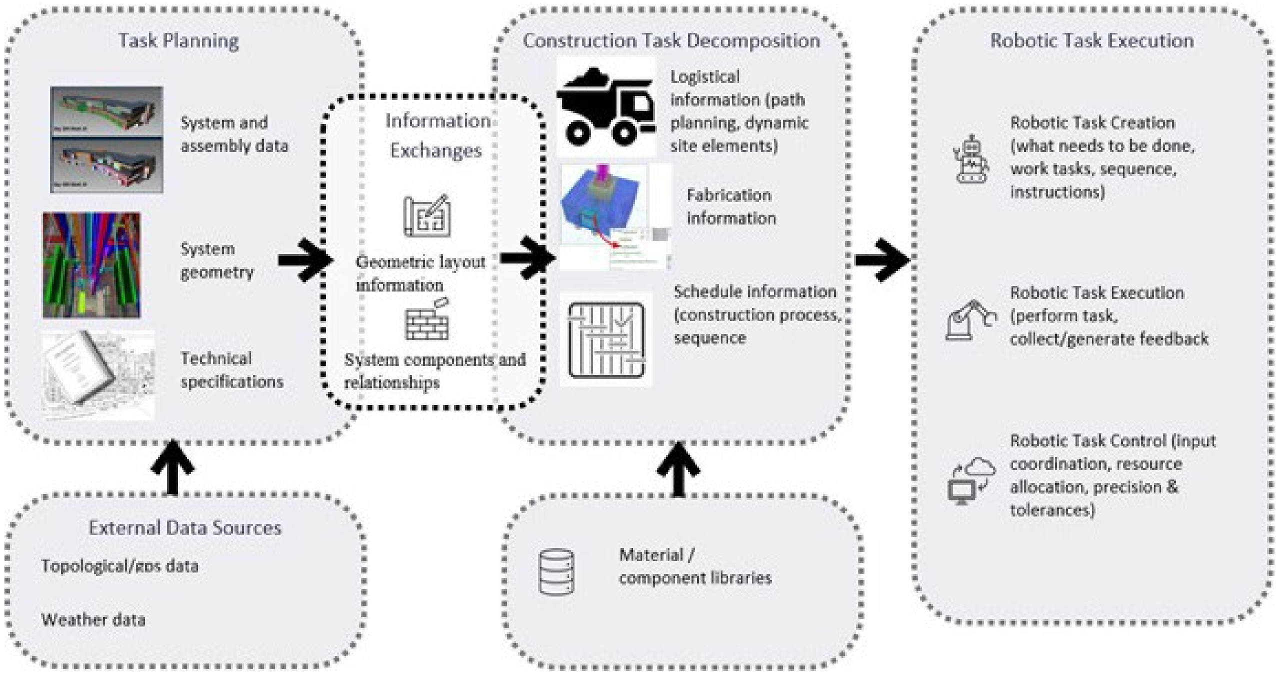

Figure 1 BIM to Robot System Architecture

4.1 TASK PLANNING

4.2 TASK DECOMPOSITION

The second phase of the system architecture is task decomposition. This phase is also shown in Figure 1, occurs once the task planning phase is complete. The purpose of the task decomposition phase is to determine and formalize the logistical steps associated with the task or system assembly chosen in the previous phase. There are three main subtasks associated with this phase which are 1) logistical information, 2) fabrication information, and 3) scheduling information. The logistical information primarily incorporates the data extracted or generated in the previous phase, such as storage locations, site hazards, and facility geometry. It will also incorporate dynamic aspects of the site, such as moving construction equipment. The tasks in this phase allow for the robot's path planning in a later phase of the proposed system architecture. The second task in this phase is for fabrication information. This task refers to systems that require additional fabrication before being installed. In current processes, the specifics for fabrication are often left to the contractor. Building upon the ductwork, the flange or other connection interface between two sections of ductwork would be defined and incorporated at this stage. The final task in this phase is to determine the scheduling information for the chosen task and corresponding system components. The schedule for the task will be determined by analyzing the construction process and sequence. The analysis will consider the overall facility systems and how the subsystems relate to the task chosen, including duration, resources, and imposed site constraints.

Ductwork is a prime example of the task decomposition phase because of the proximity to numerous other building systems. First, the general process for installing one piece of ductwork can be clearly defined. From there, the method expands to allow the installation of subsequent pieces of ductwork. Some pieces will have to be installed into the structure earlier or later based on the building's location and the building systems. Therefore sequencing of the work must be taken into consideration. If not done correctly, it could potentially cause delays for other trades on the construction site. This phase must consider the dynamic nature of the construction site.

4.3 TASK EXECUTION

The task execution phase is the last phase in the system architecture. This phase is shown in Figure 1 as robotic task execution. Task execution is based heavily on the work done by Ibrahim et al. (2017) and Sanguinetti et al. (2012) to provide the information and data collected from the previous phase to the robot to carry out its task. This phase contains three main tasks: robotic task creation, robotic task execution, and robotic task control. These tasks work in conjunction to allow the robot to carry out its task and provide feedback to the operator to improve future construction work. The robotic task creation relies heavily on the scheduling and logistical information determined in the task decomposition phase. The schedule determined in the previous phase will give the robot the order of operations to carry out its task and the logistical information to define the locations for that task on the job site. The next task is the robotic task execution. During this part of the phase, the robot will carry out its task. It will interpret the control's commands and receive the information from the task creation task. With this information, the robot will carry out its task and then identify which subsequent task to complete. Task creation will further allow the robot to generate a construction report that provides feedback on the construction site or reports errors in the process. The final task to be discussed in this section is robotic task control. Task control takes the information from the task creation and inputs it to the robot allowing the task execution to result in the performance of work on the project. It will receive information from the task execution, letting the robot know if the previous task was completed and completed correctly. If completed correctly, it can then send the command for the next task to the robot. This task will also take into consideration aspects such as tolerance to ensure the quality of the job. These tasks will continue to work together until the last task gets completed. Revisiting the ductwork example for this phase is critical. The robot must receive the information from the previous steps and install the ductwork into its final location. It must be able to identify the correct piece at the correct time and ensure proper installation. The robot must also identify if this work is correct to ensure quality. If the panel was missing or not correctly installed, the robot should identify this and adjust to this.

4.4 INFORMATION EXCHANGES

The information exchange is a critical aspect of the system architecture. One of the information exchanges is highlighted in greater detail than the other in figure 1, but it takes place between each phase of the system architecture. The information exchange between the task planning phase and the task decomposition phase is highly dependent on the task or system was chosen for the system architecture. The information exchange depends on the task and is also subject to constraints based on the BIM model's level of development for a specific component or assembly. The information exchange allows for the information that was initially included in the BIM model to be extracted and augmented to support the task decomposition phase. Continuing with ductwork as a prime example, while sufficient sheet metal information may be present in the model for the system, items such as hangers may not be represented in the model. This information is an example of supplemental information that may just be expressed as a note or in the project's specification. Information on how different systems interact with the ductwork may need to be added as well.

The other central information exchange takes place between the task decomposition phase and the task execution phase. This information exchange aims to take the schedule, logistical, and fabrication information and convert it into a form easily interpretable by the robot. The robot will need this information to carry out its task and use all the information collected by the system architecture's previous two phases. As noted, the task execution needs the scheduling information, site information, and an understanding of the construction process. Some of this information will have to be continuously updated based on the site's dynamic nature. Looking at the site information as an example, material, equipment, progress on other systems, and site conditions is constantly changing. This information gets relayed to the robot. Also, depending on the robotic system-specific file types may have to be used to allow the robot to interpret the assembly instructions. To briefly revisit the ductwork example, the information needed for location and interaction with other systems is sent to the robot. However, the ductwork may be threaded through a truss or an opening in a wall. This information must be detailed and structured to allow the robot to install the components correctly.

5 CASE STUDY

This case study considers the simulated use of a robotic method for setting masonry blocks, specifically for concrete masonry units (CMUs). This section will use the case study to validate how the BIM content gets translated into robotic tasks with the system architecture laid out in the previous section. To begin, after the specific task is chosen, it is essential to understand how it gets accomplished traditionally. This case would consist of gathering the material and tools, laying out the wall, determining the start location, placing mortar to the CMU's bottom, placing the CMU, and finally repeating for each brick after. At this time, gathered data determines weather and topological data of the construction site. Technical Data from the specifications will get gathered. This data will include information such as tolerances associated with the construction (e.g., the spacing between bricks), types of allowable materials for construction, and other design or quality performance details. The system's general layout will also be extracted from the BIM model to determine component layout and orientation.

The information exchange exports the model content, geometry, and supporting data. The first activity is to determine what information must be supplemented to the BIM model, and in this case, it would be for a CMU wall. In most BIM software platforms, such as Revit, sub-assembly components, such as individual CMU blocks, are not typically individually modeled, and therefore are not split into separate components. This lack of detail raises an issue because the robot will need to know the count, spacing, and orientation of the blocks and their exact location on the construction site to place the block precisely. Therefore, external data must be utilized to determine this, or each block can become a model. There are numerous ways of accomplishing the additional information. One method of accomplishing this would be to manually add the information to the model or take an automated approach by having an interim step to decompose the model and surface hatching to define sub-components. Once the model has the supplemental information, it will be converted into a format that the robot will be able to read. In the pilot, the data was translated into a .csv file, similarly an.IFC file could be considered. A map of the site should be created and available during this phase. This map can act as an occupancy grid to work in tandem with sensors on the robot to prevent a collision with fixed or stationary objects within the construction zone.

From here, the system can move into task decomposition. Since this task needs very little fabrication information, this case study will skip that aspect of the proposed system architecture. The crucial part of this phase would be determining the task scheduling information for the robot. The schedule needs to contain the order in which each block gets placed so that the wall will be correct and structurally stable upon completion. For example, the robot would start work at an initial corner, go to a doorway or a place toothing may occur, and then return to the initial corner to lay the next course. From there, it would continue along the wall to a set stopping point. The robot repeats for each course until there are no more blocks to place. To simplify, a schedule for the bricks gets developed utilizing typical industry standards to describe laying a course of brick. This schedule seems logical for a human worker, but it will need to be programmed for the robot to carry out this task. Once this is determined, the robot's route to transfer can be determined based on different construction site obstacles.

The last phase of the system architecture for the BIM to robot integration is the task's execution. During this phase, the data collected or added from external sources for the model is transmitted to the robot. Through coordination with other craft or on-site workforce, the robot will navigate its path to carry out the task of gathering blocks and moving them to their install location. The bulk of the information will come from the schedule, including each of the blocks' orders and locations. The occupancy map would then allow the robot to understand the site based on a coordinate grid. However, an issue can arise with the occupancy grid because the construction site is dynamic. The construction site's dynamic nature results in the occupancy grid's need to evolve and adapt to the construction's progression. This occupancy grid allows the robot the ability to carry out its assigned task. While the robot is carrying out its task, it is essential to determine if the job is being done to the design specifications, ensuring that the blocks are correct and not missing. Therefore, the robot will need to provide feedback on the wall's progression to the site workers.

6 DISCUSSION AND CONCLUSIONS

This study set out to create a system architecture for BIM to Robotic Construction Integration and accomplished this by reviewing literature into construction system architecture and robotic system architecture, then piloting it for a case study. From there, aspects of typical system architecture were determined and used to create the proposed system architecture. For the construction system architecture, the parallels between the studies presented found that the data collections are of extreme importance, external sources taken into account, and a human aspect involved. For the robotic system architecture, the parallels are as follows: there is constant data flow within the system, humans oversee executing tasks and data collections, and there is a control module for the robot. These system architectures influenced the system architecture presented in this paper by 1) providing insight into how the robot interprets information providing the final phase of the system architecture presented, 2) providing a basis to how BIM system architecture gets typically accomplished, and 3) where and when information gets supplemented. The method developed integrates both of these types of system architectures. The method is broken into three major phases: task planning, task decomposition, and task execution. These phases' descriptions are in detail above and state what would take place in each phase. After which, a case study got presented utilizing the various aspects of this system architecture.

However, a few areas that need to be further developed were identified from the case study. One was with the initial stages of the information exchange because of the lack of information in some BIM model systems; however, the system architecture utilized the areas that require the supplemental information will be determined. This information can then be added to the model in a format accessible by the robot. Some systems, such as MEP, may contain extensive detail, while others, such as blocks wall, may not. Another point for further consideration is the recognition of the dynamic nature of the construction site. Since the site changes daily, and in some cases constantly, there will be a need to navigate obstacles for the robot.

Some areas for future work include investigating the information exchange and methods to supplement design model data, leaving room for a more standardized process. Also, work on how site utilization plans can be developed as smart rather than passive elements may offer solutions to site navigation for robots.

The proposed system is not without its limitations. It is constrained by limitations associated with this software. Another limitation is that the proposed method focuses mainly on all systems in general. As shown by the case study, different systems will have different requirements, data sources, standards, and practices resulting in aspects of the architecture that must be flexible. The final limitation is what robot gets chosen for the last section of the proposed system architecture. Each robot will have different capabilities and its own set of limitations. These limitations need taking into consideration for the proposed method to be successful.

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