

Validation of A Construction Robotics Schema for Site Operation Planning

Fangxiao Li¹; Ziyi Wang²;
Yuqing Hu, Ph.D., A.M.ASCE³; Robert M. Leicht, Ph.D., A.M.ASCE⁴

¹Ph.D. Student, Dept. of Architectural Engineering, Pennsylvania State Univ., University Park, PA 16802 (corresponding author). Email: fjl5160@psu.edu

²Ph.D. Student, Dept. of Architectural Engineering, Pennsylvania State Univ., University Park, PA 16802 (corresponding author). Email: zbw5207@psu.edu

³Assistant Professor, Dept. of Architectural Engineering, Pennsylvania State Univ., University Park, PA 16802 (corresponding author). Email: yfh5204@psu.edu

⁴Associate Professor, Dept. of Architectural Engineering, Pennsylvania State Univ., University Park, PA 16802 (corresponding author). Email: rml167@psu.edu

ABSTRACT

This paper presents a construction robot schema (CRS) for construction planners to facilitate decision-making and project planning in operating robotics. CRS is a database schema structure that was developed in our previous study, which can facilitate collecting and exchanging data of various construction robots based on the data requirements of the construction domain. We validated the applicability of the schema by the simulation of robotic construction operations. In addition, we conducted interviews with experts from the construction industry to validate the information in CRS. As a result, the schema was validated with minor revisions to some parameters. The characteristic of CRS compared to other types of robot schema are that its development and application are based on the perspective of the construction domain and are designed to cover different construction robots broadly. The conclusions highlight the contributions of the data schema use and applicability for the construction industry.

INTRODUCTION

A construction robot schema (CRS) is a database schema used to collect and exchange construction robots' data, which is developed for construction planners' decision-making and project planning to operate construction robots. In the previous study, we developed a CRS to help construction planners increase their awareness of various types of robots. The preliminary CRS has four categories to classify construction robots' relevant data parameters, including Ontological Properties, Operational Requirements, Activity, and Safety. Ontological Properties refer to the parameters that can be observed and measured about the performance or tangible things of robots. Operational Requirements refer to the parameters of the conditions of construction sites that are necessary for robots to perform tasks. Activity refers to the parameters relevant to construction activities when robots participate in a specific project. Safety refers to the parameters of preventing damage or injuries when robots perform tasks with human colleagues. Based on the systematic literature review, our previous study summarized and classified parameters with corresponding definitions, data types, examples and references.

Many researchers proposed data requirements for construction robots in their study. For example, when they conducted simulations to create models for construction robots, they needed

data on robot bodies such as length, height, and width. When they studied the efficiency of operating construction robots on sites, they needed the performance data of robots. However, few researchers considered summarizing the data requirements of the construction domain to facilitate data collection and exchange for better operating construction robots. In practice, construction robotics manufacturers may provide users with a lot of robotics information. However, for the construction planners who make decisions and plan projects in operating robots, the variety and complexity of information provided by manufacturers make it difficult for construction planners to use this information to comprehend robots. Based on these limitations, our previous study developed CRS as a consistent data structure to summarize the data requirements of the construction domain and designed it for construction planners to help them better understand construction robots to facilitate making decisions and planning projects in operating robots.

For the preliminary CRS, our previous study summarized, classified, and defined parameters based on a systematic literature review method without observing the working status of construction robots. This limitation may impact the quality of CRS. The study validated the information inside the database schema to ensure the usability, comprehensiveness, and completion of CRS. The purpose of the validation process in the study is to correct the term used, determine reasonable relationships, and identify missed information. In this study, we conducted two types of validations including simulation validation and interview validation. After the validation, the study made decisions for changing CRS based on the analysis during the validation process.

LITERATURE REVIEW

In the construction domain, when researchers need construction robots to conduct simulations or experiments, they need to obtain data about robots for support. Melenbrink et al. (2020) mentioned in the study that the use of simulation to evaluate the production performance of construction robots needed to consider the robot's relevant data including mass, power, efficiency, reliability and overall mission cost. The study by Feng et al. (2015) included collision checking of construction robots in unstructured construction sites. They pointed out that the experiment required acquiring positioning data for the robot and then using grasshoppers in Rhino to generate a checking system. In addition, in their 3D printing experiments of mobile robots, Zhang et al. (2018) mentioned that based on the data of the working range of their robotic arms and the repeatability, they defined a feasible solution as the ability of the robot to accurately place the material on the desired print path without collisions. These researchers have demonstrated the need for robotics data for robotics-related research and operations in construction. To summarize the data needs from the construction domain, we developed CRS for construction planners to cover various construction robots to facilitate awareness for implementation and operation planning.

A database schema refers to the structure and organization of data stored in a database (Batini, Lenzerini, and Navathe 1986). Database schema validation is the process to ensure that the database schema defining the database structure is correct and consistent with the expected design (Coronel and Morris 2016). In terms of validating the database schema, Farré et al. (2008) performed a series of experiments to verify the correctness of the database schema using the prototype tool they developed. The tool they developed can automatically check the contents and relationships of a database schema in a short time. Bonifati et al. (2019) used mathematical models to validate the schema of graph databases. Their validation method can consider both prescriptive and descriptive database schemas. Hu & Qu (2007) used a mapping method to verify the

consistency among the attributes, relationships, and properties in the database schema. They then demonstrated the performance of the method in practical applications through case studies and experiments. According to their previous validation studies, the common in their studies was that they used experimentation and application to validate the correctness of relationships and attributes in database schemas.

For the validation of CRS, based on the review of these researchers' previous validation studies, we decided to conduct a simulation experiment to validate the correctness of CRS. By simulating a construction robot in an unstructured construction site, this study identified the correctness and completeness of the information in the CRS (Kim et al. 2019). In addition, the study conducted expert interviews. Use peer review to help further scrutinize the information in the CRS in case there was any missed information during the simulation (Huber et al. 2011). Through these two methods, this study ensures that the CRS can be more comprehensively validated.

METHODOLOGY

To improve the quality of CRS, this study determines the rationality of the information in the CRS through validation. The validation of the study is divided into two parts including simulation and interviews. The simulation checked the constructability and accessibility of construction robot in the site. The interview invited experts who have knowledge and experience of developing and implementing various types of robots. The study validated 5 aspects (Di Zio et al. 2016) of CRS including term use of parameters, correct categorization, definition, usability of parameters, and comprehensiveness.

Through simulation experiments on construction robots, the definition of CRS, usability of parameters, and comprehensiveness were validated. During the simulation experiment, CRS must ensure that the definition can fully describe the parameters, the parameters selected and used by the simulation fully meet the experimental requirements, and the experiment can extract any required information from the CRS.

To complement the simulation experiments, expert interviews were conducted in the study. In addition to validating the definition of CRS, usability of parameters, and comprehensiveness, expert interviews can also validate the term used of parameters and correctness of categorization. Through interviews, the CRS must ensure that the terminology used for the parameters is correct and not misleading, and that each parameter is classified under the correct category.

After the simulation and interview, the changes of CRS include the modification of the terms, definitions, and categories of parameters in the data structure, adding new parameters or categories, or deleting existing parameters or categories. For any changes in CRS, there are two criteria to accept the suggestions and conduct changes. The first criteria are that modification opinions must come from knowledge and experience in the development, analysis, and application of robots in the construction site or research and should follow the perspective of construction planners for planning to operate construction robots. The second criteria are that when making modifications, it is necessary to be able to find corresponding literature or cases of applications and experiments to support changes. If any of these criteria is not met, the study should reject the suggestions for changes.

SIMULATION RESULTS

Figure 1 shows the outline of the simulation experiment. For simulation validation, the CRS was validated through the modeling of construction robotic for analysis of the constructability and accessibility. Through this part, the study validated that the CRS should meet the data requirements of the simulation experiment for the robot. For the modeling, the selected construction robot, the Canvas robot, was studied and the selected experimental method is the simulation experiment. The accessibility was analyzed by simulating the robot moving through the opening, and the robot traveling on the temporary structure. The study analyzed constructability by simulating the robot's work in confined spaces on a construction site. When the simulation experiments obtained information from CRS, this study found that some data can be provided by CRS, while some data required for simulation were not readily available from the initial CRS.

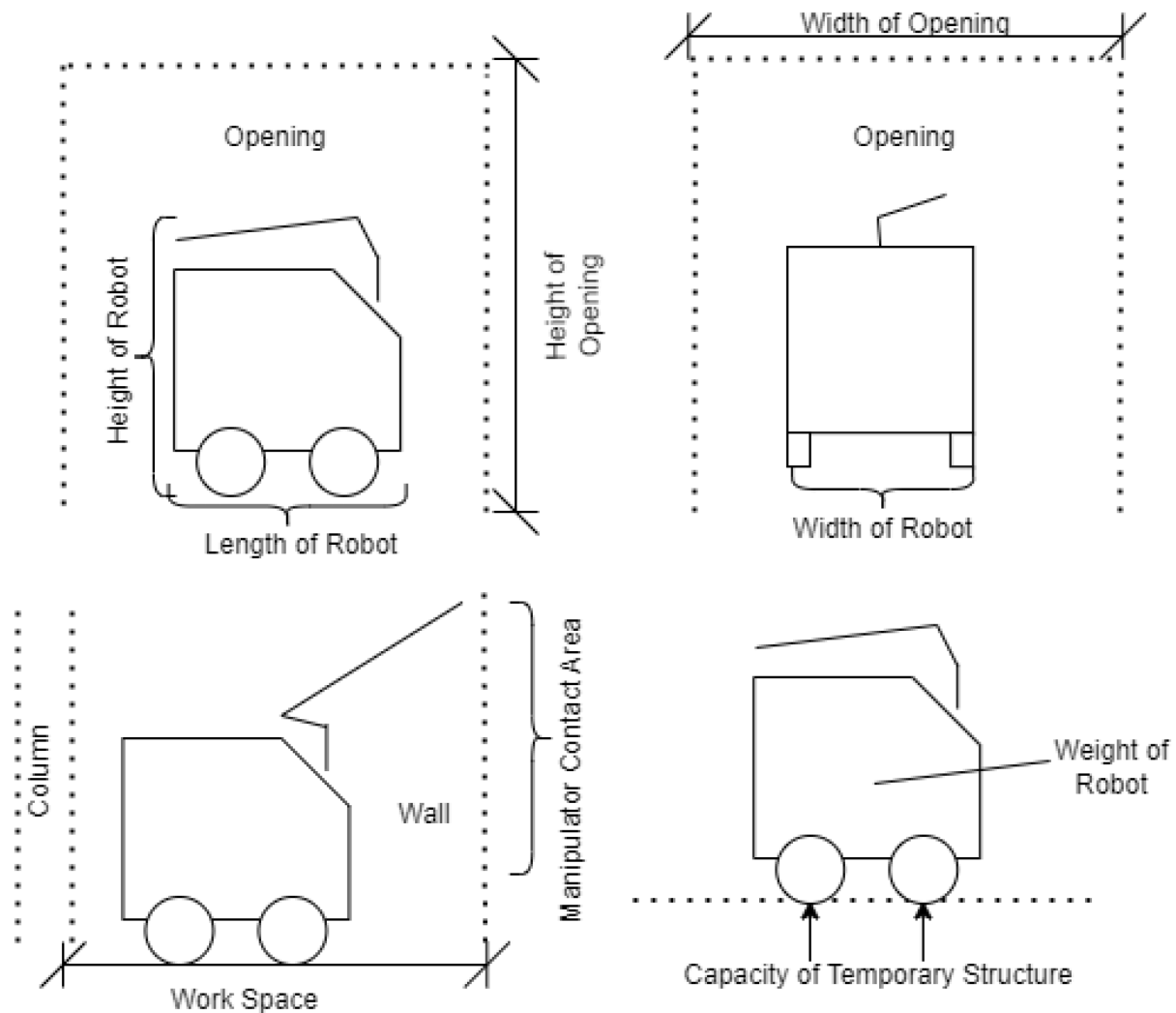


Figure 1 The Outline of the Simulation Experiment

The information in the CRS was validated through the simulation experiment of the construction robot. The information in the CRS contains descriptions of the construction robot's body, manipulator, performance, operational requirements, and safety, which can be used to support the establishment of a construction robot model in a simulated environment. During the

modeling process, this study examined the degree of completeness and refinement of information in the CRS by reviewing the process by which simulated experiments extract information from the CRS.

Figure 2 shows the model of the robot and the construction site in the simulated environment. To validate the CRS, the accessibility and constructability of construction robotics was analyzed through the application of a case study of Canvas. Canvas is a drywall finishing robot which can scan the environment, coat, and sand drywall. The robot can be evaluated in a simulated building environment by connecting BIM data with the ROS platform and Gazebo simulator. Obtaining pertinent geometric and functional data allows for more precise simulation experiments in the virtual environment, which is used to construct virtual buildings and construction robot models. The accessibility and constructability assessment of the robot is determined through comparing the geometric and configurational information of the robot and its arm with the information of the robot-related building model (e.g., doors, walls, columns, and other building components).

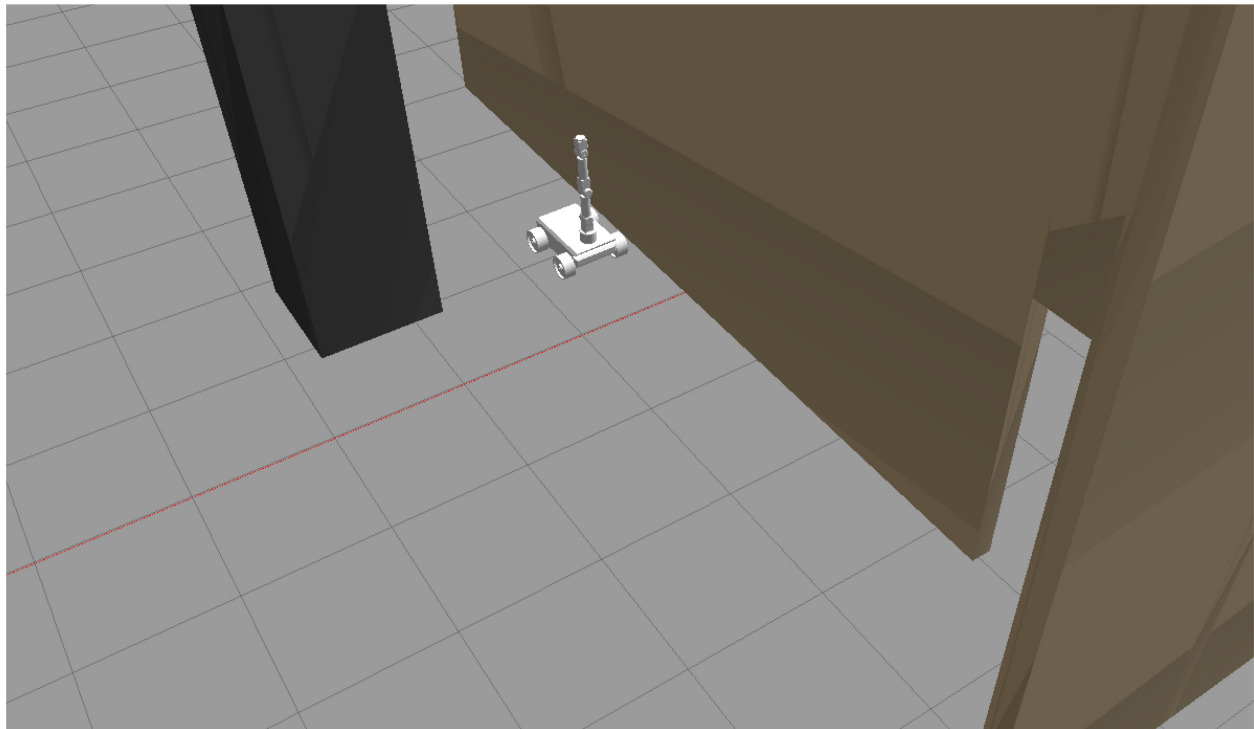


Figure 2 Robot and Construction Site in Simulated Environment

The simulation experiment checked the accessibility of the robot. When the simulated robot passed through the passage or the entrance, the length, width, and height data of the robot were required to support it. Such data has already been included in the 'Dimensions' parameter of the CRS. In CRS, the 'Dimension' parameter is used to collect the length, width, and height of the construction robot. In addition, in the accessible simulation, the robot was also simulated to pass through temporary floors in the construction environment. In an unstructured construction environment, temporary facilities such as temporary structure can't allow heavy objects to pass through, so the weight of the robot is required for simulation. The 'Weight' parameter has also been covered by the CRS.

When the simulation experiment checked the area of the wall that the Canvas robot can touch, the required data was not been provided by the CRS. Since the distance between the mobile robot Canvas and the wall can be artificially determined, the contact area between its manipulator and the wall can be calculated. The data of contact area was not initially provided by CRS. To conform to the needs of the simulation experiment for this type of data, the study decided that CRS can indirectly provide several parameters to help the simulation experiment calculate the contact area during the simulation process. These newly added parameters included coordinate reach, range of motion and manipulator installation position.

The coordinate reach defines the maximum attach distance of the manipulator on the x-axis, y-axis and z-axis (Apriaskar and Fauzi 2020). The range of motion is defined as the maximum rotation angle of the manipulator in the directions of yaw, pitch, and roll (Iqbal, Ul Islam, and Khan 2012). The manipulator installation position is defined as a relative position in a coordinate system which is established by the center of the projected surface where the base of the mobile robot being in contact with the ground as the origin, the forward direction of the robot being the positive direction of the x-axis, the right side of the forward direction being the positive direction of the y-axis, and the upward direction being the positive direction of the z-axis (Colucci et al. 2021). The combination of these three parameters can be used to describe the maximum reach area of the manipulator and the relative position of the manipulator on the mobile robot base in three-dimensional space.

INTERVIEW RESULTS

CRS was further validated through expert interviews. During the interview process, the study invited experts from the construction domain, including experts from the construction industry who have experience developing and implementing various types of construction robots. Table 1 shows the experience for each type of expert. The interviews used slides to present the CRS structure and parameters. The introduction and overview of the CRS took approximately 10-15 minutes. After the introduction of CRS, the content was revisited, one category at a time. To all the experts to provide suggestions and feedback about the data content and structure. Then in the open conversation section, experts shared their experiences about developing or implementing robots to help the study check information that may not have been included from the literature review. In total, for each interviewee, the study took typically 30 minutes to introduce the experts to the current structure, review and collect feedback on the current content, and gather additional information from them.

Table 1 Criteria of Experts Selection

Experts Type	Experience Requirements
Robot Developers	Participated in the development of construction robots for more than five years.
Robot Users	- Five or more years of construction industry experience - Direct experience of two or more robots.

One of their modification suggestions was in the safety section. Using a bricklaying construction robot as an example, one interviewee pointed out that the two wide sides of the robot have metal doors. When the robot was performing tasks, the two doors were locked by the operator to separate the robot from the worker. In this way, after the robot places the brick, the workers can

stand at a safe distance and clean up the excess (spilled) mortar. This external physical security measure is also applied to other robots. For example, some 3D concrete printing robots need to have an installed ‘fence’ after arriving to a specific work position, to separate the robot and the workers when they are required to work in the same area simultaneously. Based on this, the study identified and classified this new parameter to Safety categorization named *safety barrier*. It is defined as a temporary facility built around the robot to avoid collisions between the robot and human or objects (Landi et al. 2019). The new parameters met the criteria for modification proposed in this study, so the CRS accepted the new parameters.

Other interviewees have extensive experience in the application of various construction robots. Some of them suggested that the data structure of the construction robot can include some business models, such as the price or price range of the construction robot. Their reason was that the construction planners can consider buying, leasing, or giving up the use of the construction robot according to the price. Another suggestion was that in terms of safety, the data structure can contain some statistical instances, such as the type of accident and the probability of occurrence of the construction robot. Based on the modification acceptance criteria, the study rejected both recommendations. The reason is that these two suggestions neither come from the application of robots on the construction site, nor from the application of robots to construction research. Some of them also suggested adding a parameter about the ability of robots for reporting the position to construction teams. This ability has been included in the navigation parameters, so the study decided to reject this change.

However, for another part of their suggestions, one interviewee said that the parameter named sensor in CRS cannot clearly cover the configuration of the construction robot in terms of sensing. His reasoning was that some robots can accomplish tasks using sensors mounted on their bodies, while others need external sensors to complete tasks. Therefore, he proposed to divide the sensors into internal sensors and external sensors. Internal sensors are sensors mounted on the body of the construction robot (Komatsu et al. 2021). External sensors are sensors that are required for construction robots to be installed on the construction site (Gawel et al. 2019). Because the three new parameters were from the application of robot on the construction site and had literature supports, which conformed to the criteria of modification acceptance, the study decided to accept the three new parameters.

CRS CHANGES

After validation, the study summarized the changes in the CRS. Table 2 shows the results of simulation experiments and experts’ interviews. The table includes the added or deleted parameters with corresponding categories, reasons, and validation methods. Based on simulation, CRS was added 3 new parameters and deleted 1 parameter. Based on interviews, CRS added 3 new parameters and deleted 1 parameter. In total, the study added 6 new parameters and deleted 2 parameters in CRS.

Table 2 Changes of CRS Based on Validation

Parameters (Category)		Reason	Validation Method
New Parameters	Coordinate Reach (Ontological Property)	From construction robot application research and with literature support.	Simulation
	Range Of Motion (Ontological Property)	From construction robot application research and with literature support.	Simulation
	Manipulator Installation Position (Ontological Property)	From construction robot application research and with literature support.	Simulation
	Safety Barrier (Safety)	From construction site robot application and with literature support.	Interview
	Internal Sensor (Ontological Property)	From construction site robot application and with literature support.	Interview
	External Sensor (Ontological Property)	From construction site robot application and with literature support.	Interview
Deleted Parameters	Reach (Ontological Property)	The movement space and position of the manipulator cannot be fully described.	Simulation
	Sensor (Ontological Property)	It cannot distinguish between internal and external sensors indicate to miss information.	Interview

CONCLUSIONS AND FUTURE WORK

The study conducted a simulation experiment and experts' interview to validate construction robot schema. The purpose of the validation is to ensure the quality of the data structure through correct term used, determine reasonable relationships, and identify missed information. After the validation, the study added 6 new parameters and deleted 2 parameters with corresponding reasons and validation methods. In addition, based on the simulation and interview, the study demonstrated the feasibility of CRS for construction planners to facilitate better comprehension for operating construction robots. The limitation of the study is that the development and validation process of CRS is for construction planners. However, there are also other construction robot users such as researchers that may need more detailed information from construction robots. CRS is required to conduct more specific and detailed development and validation to provide information to different users and satisfy their data requirements. In addition, the study only focused on the correctness of data structure of CRS. However, the query efficiency of database schema is also important to be validated.

For the next step and future work, the study needs to establish a construction robot database based on CRS to facilitate data collection and exchange. Currently in the construction domain, there is a lack of databases to collect and manage data from various types of construction robots. The parameters and categories in CRS can support the establishment of the database in order to

summarize the fragmented information of construction robots. Through this process, the relationships, parameters, and query efficiency can be further validated and modified.

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