A Schema for Robotics Operations in Construction

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ABSTRACT

This study gathered data into a construction robot schema (CRS) with an initial data structure that can be used to collect and exchange various construction robots' information based on the data requirements of construction planners for robotics operations. To develop the CRS, the study conducted a systematic literature review using the Web of Science database to filter and identify relevant papers which were published from 2018 to 2022. Based on 279 eligible papers, the study identified significant information which involved data requirements of the construction domain on robotics using Nvivo software. To structure the information, the study summarized the information into parameters then categorized, defined, matched data types, and exemplified for these parameters. All the parameters were grouped into four categories, including ontological properties, operational requirements, activity, and safety. As a result, CRS supports data structure including 4 categories and 35 parameters with corresponding definitions, data types, examples, and references.

INTRODUCTION

A construction robot is a robot capable of performing various tasks on a construction site. They are usually controlled by computers and use devices such as sensors and cameras to sense their surroundings and mission requirements. Construction robots can perform work based on digital models of building designs to improve the accuracy and efficiency of construction. They can also perform tasks in place of workers in hazardous environments, such as working at heights, and handling hazardous materials. However, there are still many challenges in the construction industry that robots may be able to help address.

The construction industry is a labor-intensive industry with high labor costs, and it is also prone to worker fatigue and mistake. Most of the work in the construction industry is performed manually, such as building walls and concrete placement, so the construction duration is often relatively long (Ibrahim, Esa, and Rahman 2021). As construction relies on manual operation, construction accuracy is often difficult to guarantee, resulting in low project quality (Nguyen, Nguyen, and Do 2020). There are safety risks in the construction industry, such as high-altitude operations and handling of hazardous materials, which can easily lead to injury or even death of workers. There is a lot of waste in the construction industry, such as material waste, which has a negative impact on the environment. The lack of a unified standardized management system in the construction industry makes it difficult to guarantee construction quality (You and Wu 2019).

These challenges not only affect the development and competitiveness of the construction industry, but also have adverse effects on the environment and society. The application of robotics in the construction industry is a potential solution to these challenges.

Construction robots can perform tasks based on digital models, complete work much faster and improve construction production efficiency (Ding et al. 2020). Han et al. (2006) mentioned that construction robots can replace labor-intensive jobs and reduce labor costs. Goh and Goh [illegible]9) pointed out that construction robots can perform tasks accurately and reduce errors, thus improving the overall quality of construction work. Davila Delgado et al. (2019) proposed that construction robots can replace humans in dangerous environments to ensure construction safety and avoid worker injury. Construction robots equipped with sensors can record the construction process, realize the visualization of the construction process, and facilitate later management and maintenance (Feng et al. 2015). Bock and Linner (2016) argued that construction robots could accurately control the consumption and waste of building materials, which would help reduce environmental pollution. In fact, using construction robots in the construction industry has multiple merits, from increased efficiency and safety to reduced labor cost and environmental impact.

To help the construction planners better understand and operate construction robots on jobsites, we conducted a systematic literature review to identify the information for the industry's data needs. Based on the needs, we extracted the information as parameters and organized them into a consistent data structure. The study developed an initial Construction Robot Schema (CRS) with parameters used to collect and exchange robotics data based on the data needs of the construction domain to facilitate analyzing, and operating construction robots on a construction site.

LITERATURE REVIEW

Database schemas include the description and definition of the data structure in the database, including the specifications and regulations of elements such as entities, attributes, relationships, and constraints. It stipulates the attributes of each entity in the database and the relationship between different entities. Database schemas are usually displayed in graphical or tabular form to guide the design and management of the database (Uschold 2015). Database schemas can help different systems and applications share and exchange data to better support data integration and use. By studying the theory and method of database schema, data sharing and exchange can be facilitated to promote the cooperation and integration between different applications (Vanlande, Nicolle, and Cruz 2008). Overall, a schema can achieve consistency of data, guide the establishment of database, and support data exchange. Therefore, when construction planners need to consider robot use, they also need a database schema to collect and exchange robot data to better analyze and operate construction robots.

When robots are applied in the construction industry, relevant data support of robots is needed. Descriptive data about the body, function, and performance of construction robots can be incorporated into a detailed digital model, to better promote the digitization and automation of buildings and construction (Zhang et al. 2022). On the construction site, interaction and cooperation between robots or between robots and human workers are required, and robot's sensing and trajectory data can provide support for interaction and collaboration (Ajoudani et al. 2018). Meanwhile, the robot data corresponding to different tasks and environments can provide support for the intelligent control of robots (Varlamov 2021). By integrating the robot's data into the robot's intelligent control system, the robot's autonomous decision-making and actions can be established or the operator can be helped to make decisions (Oliff et al. 2020). According to their studies, the construction domain needs the support of robot data for research and operations. Based on their demonstrations, robot data contributes to different applications in construction and is important for operating robots on jobsites.

Many researchers have demonstrated through their research that the analysis and application of construction robots in different aspects require different data support. Xu & de Soto (2020) mentioned in the paper that the advances in data-driven technologies have greatly improved the efficiency and accuracy of robotic systems, and such technologies have become an effective approach to address this challenge. When S. Kim et al. (2021) developed a BIM-integrated robotics simulation system, they acquired a virtual construction robot with the data of robot's size and mobility to conduct a navigation and wall painting task simulation. To promote the development of a collision avoidance system for a construction robot manipulator, Zhou et al. (2022) conducted an experiment with the data about the manipulator, end effector, and payload of the robot to apply the trajectory of the human arm on a robot manipulator to avoid collision. In these studies, researchers have demonstrated that their required robot data was useful in their research or operations. However, they have not structured these data for the construction domain. In addition, their studies focused on a specific type of robot or specific task performed by the robot. A robot database schema offered for construction should integrate the robots' data needs of construction domain and broadly cover various types of construction robots.

METHODOLOGY

The purpose of this study is to develop an initial Construction Robot Schema (CRS) based on the data needs of construction planners. In order to facilitate project planning and decisions making of construction planners for robotics operations at a project site, the study needs to summarize the information of construction robots. Table 1 summarizes the three steps and their corresponding objectives and tasks. This study used the method of systematic literature review to capture the data requirements for construction robots in the domain of construction and robotic data to extract parameters, classify, define and exemplify the extracted parameters to structure them into a formal CRS.

Table 1 Research Development Steps, Objectives, and Tasks

Development Steps	Objectives	Tasks
Literature Filter	Select the literature on the application or research of robots relevant to the construction domain.	Identify keywords
		Search Web of Science database.
		Filter by year and domain.
		Manually filter by reviewing abstracts.
Systematic Literature Review	Identify the data requirements of construction for the robot.	Define categories.
		Review literature in Nvivo.
		Code the literature to identify parameters.
Organize and Define Parameter	Organize parameters into a structure and relationships.	Classify parameters into categories.
		Define the parameter.
		Identify the data type.
		Exemplify the parameter using construction robots.

LITERATURE FILTER

Before filtering the papers, it is necessary to determine the scope of the selected papers. The study selected papers published from 2018 to 2022. The study also considered the state-of-art achievements of construction robots. The domain chosen for the study before filtering the papers is construction robotics.

The study used Web of Science (WoS) because it houses one of the largest literature databases. To capture the proper scope of papers for the analysis, development and application of construction robots, we used robotics and construction as keywords for the initial search. When searched, WoS showed 6,225 papers related to the keywords. The publication time period of selected papers in WoS for this study was from 2018 to 2022 and reduced the result to 2,206 papers. Using the WoS filtering function by research areas, unrelated domains were removed further narrowing the research area to 126 papers.

To ensure the search parameters were not overly narrow, additional keywords were searched in the focused domain to check for missing papers. The original keywords were supplemented with synonyms, such as replacing robotics with robot and automation. Similarly, construction was supplemented with architecture and building. Additional keywords related to construction robots, such as human-robot cooperation, human-robot collaboration, human-robot interaction, application, analysis, development, end effector, sensor, robotic arm, mobility were added. The criterion for the end of this step is that three consecutive new keywords resulted in zero new publications. After this step, WoS identified 293 papers.

Manual filtering was to exclude papers that do not meet the requirements from the selected papers by reviewing the abstracts. Some papers only mention robotics and construction but were not the subject of the paper. In some instances, the meaning of "construction" used in the paper did not match the required meaning of construction industry, resulting in the filtered focused on the assembly of robots or something similar. Ultimately, 279 eligible papers were considered.

SYSTEMATIC LITERATURE REVIEW

Through a systematic literature review, this study extracted the parameters for the schema from the selected articles. A systematic literature review gathers available evidence from the literature and then evaluates the evidence against predetermined criteria (Linnenluecke, Marrone, and Singh 2019). Before reading and parameter extraction, the study identified four categories to facilitate the identification and classification of data from these papers including: Ontological properties, Operational Requirements, Activities and safety. Ontological Properties include the parameters of the robot body, manipulator, and various mechanical hardware as well as related performance parameters needed for a functioning robot. Operational Requirements in the study address required environmental conditions, necessary construction site infrastructure or necessary human assistanc. Activities contain relevant parameters, requirements, and responsibilities of robots to participate in construction projects. Safety includes parameters that describe construction robots helping humans stay away from danger and the precautions when human works near or operates robots. These four categories provide an initial, high-level grouping for the corresponding parameters.

After determining the categories, the study reviewed these eligible papers using Nvivo. Nvivo is a qualitative data analysis software that helps researchers analyze unstructured or qualitative data such as interviews and journal article. Before reviewing papers, the study added these four categories into Nvivo as coding categories. When reading one of the identified papers housed in the Nvivo database, the study coded paragraphs in the article corresponding to the named categories. When reviewing each paper, the study focused on the paragraphs of the paper that describes construction robots and corresponding attributes. These paragraphs often appear in the chapters on methodology, case studies, or validation. Based on the passages about construction robots, the information was captured and summarized into corresponding parameters.

ORGANIZE AND DEFINE PARAMETERS

The initial grouping of data within CRS contains four categories: Ontology Properties, Operational Requirements, Activities and Safety. The study used each category to group relevant parameters. The study coded text that described the parameter and extracted this parameter and related description into a specific defined category based on the criteria in Table 2. Each criteria explains the data requirements for a specific category.

Table 2 Criteria of Each Category for Grouping Parameters

Categories	Criteria
Ontological Properties	Require parameters about the performance or physical things of robots that can be observed or measured.
Operational Requirements	Require parameters about the conditions of construction sites that are necessary for robots to perform tasks.
Activities	Require parameters relevant to construction planning when robots participate in a specific project.
Safety	Require parameters about preventing damage or injuries when robots perform tasks with humans.

After categorizing the parameters, this study defined each parameter from the captured literature. According to the paragraph of the parameter in the selected paper, the information was summarized into the definition of the parameter in Table 3. In addition, the study identified the data type for each parameter. To correctly identify the data type for each parameter, the study referred to the structured query language (SQL) which is a standard language for managing relational databases. It allows users to query, update and manage data in the databas. Currently in CRS, there are 5 types of data matched including: text string (text) – a string of letters or numbers, decimal number (decimal), integer number (integer), enumeration (enum) – a pre-defined list of values or categories of data, and Boolean (bool) - binary value of “true” or “false.” To illustrate the understanding of the parameters and their definitions, this study found corresponding examples specific to construction robots. The examples used in this study come from two sources, one is from the construction robot case in the paper to which the parameters belong, and the other is from the data published by the construction robot manufacturer. Finally, the study identified the source paper of the parameter as a reference to support transparency regarding the source of the parameter. Considering the page limitations of this paper, references were not included in the table. The full table with all the information can be seen in the author’s thesis (Li 2023).

RESULTS

The results show the contents and categorization in the CRS in the form of a table. As shown in Table 3, CRS contains 4 categories and 35 parameters. Among them, Ontology Properties contain 19 parameters, Operational Requirements contain 8 parameters, Activities contain 3 parameters, and Safety contains 5 parameters. The definition of each parameter comes from literature. Among the examples, the 35 parameters exemplify 10 robots that are in use and 4 robots that are described in the research applications related to construction.

Table 3 Construction Robot Schema

Categories	Parameters	Definitions	Data Types	Examples
Ontological Properties	Name	The official name given to the robot.	Text	A four-legged walking inspection robot named ANYmal.
	Weight	The physical weight.	Decimal	The weight of ANYmal is 30kg (about 66 pounds).
	Dimensions	The length, width, and height of the robot.	Decimal	The dimensions of ANYmal are 80x60x70cm (about 31x24x28 inches).
	Power Source	The energy type that supplies the robot.	Enum	ANYmal is powered by batteries.
	Run Duration	The working period of the robot under typical power supply.	Decimal	ANYmal battery can supply normal work for 90 minutes.
	Productivity	The amount of work the robot performs per unit time.	Decimal	The CyBe 3D printing robot has productivity of 50-500mm/s (about 2-20 in/s).
	Precision	The degree of refinement of the robot is output.	Decimal	The precision of CyBe 3D printing robot is 1/1/1mm (about 0.04/0.04/0.04 inch).
	Accuracy	The consistency of how the robot performs tasks.	Decimal	For bricklaying robots, the placement accuracy is usually required to be within 2-3mm (about 0.08-0.12 inches).
	Load Capacity	The maximum allowable weight that the robot can withstand when it is performing work.	Decimal	ANYmal can carry a maximum weight of 15kg (about 33 pounds).
	Manipulator	An electronically controlled structure consisting of a series of links and joints that perform tasks by interacting with the environment.	Bool	Yoshinada et al. introduced a dual-arm construction robot that can perform different tasks simultaneously.
	Degree of Freedom	Number of geometric axes that can be rotated or extended.	Enum	The manipulator of AR3120 welding robot has 6 degrees of freedom.
	Reach	The maximum distance the manipulator can contact.	Decimal	The manipulator of the AR3120 welding robot can reach 3,124mm (about 123 inches) in the horizontal direction.
	Lifting Capacity	The maximum weight that the robot can lift during operation.	Decimal	The maximum lifting capacity of Oscar1000 glazing robot’s manipulator is 1000kg.
	End Effector	A device attached to the end of a manipulator to allow the robot to interact with the task environment.	Text	The DXR demolition robot can perform different tasks by changing the end effector of the manipulator.
	Sensor	A device that produces an output signal for the purpose of sensing physical environment.	Text	ComfBot introduced by Quintana et al. has camera, ultrasonic sensor, odometry sensor, microphone array and many other sensors.
	Mobility	It is the method employed by a robot to move from one place to another.	Enum	OKIBO is a painting robot based on wheel movement.
	Speed	The transport distance per unit of time.	Decimal	ANYmal's walking speed is 1.2m/s (about 3.9ft/s).
	Autonomy Level	The level of independence of a robot performing tasks.	Enum	Melenbrink et al. classified the SAM 100 bricklaying robot as partial automation according to the level of autonomy.
	Navigation	The robot's ability to confirm its position in three-dimensional space and plan a path to a specified location.	Bool	Kim et al. developed a system that utilizes drones to assist ground construction robots in navigating cluttered environments.
Operational Requirements	Operators	The persons who controls the robot.	Integer	The TyBot rebar tying robot requires an operator to monitor the robot's operation.
	Coworkers	The persons who performs a task with a robot.	Integer	SAM100 requires a worker to work alongside to smooth over the mortar before placing more bricks.
	Operator’s Responsibility	The operator's work requirements when the robot is performing tasks.	Text	The operator of the SAM 100 needs to be on site to set up and inspect the robot.
	Coworker’s Responsibility	The coworker's tasks when the robot is performing tasks.	Text	The coworker of SAM 100 needs to shovel excess mortar after the robot has placed the bricks.
	Site Preparation	The preparations required for the robot to work properly on the site.	Text	The Clapa Floor Master needs to be prepared with semi-dry sand/material on the floor before starting work.
	Grade	The acceptable flat level of the ground for the mobile robot.	Text	ANYmal can walk on a slope less than 30° and can cross a gap of fewer than 11.81 inches.
	Temperature	The temperature range required for the robot to work properly.	Decimal	The temperature required for the CyBe 3D printed robot is 5-50 °C (about 21-122 °F).
	Humidity	The humidity range required for the robot to work properly.	Integer	The maximum humidity required for CyBe 3D printing robots is 95%.
Activities	Activity Type	The category of activity that the robot can support.	Enum	SAM100 can participate in bricklaying activities.
	Material	Specific material needed for the robot to perform a given activity.	Enum	The materials SAM100 needs when laying bricks are bricks and mortar.
	Task	The task performed by the robot under this activity.	Enum	The SAM100 can do the tasks of grabbing bricks, dipping in mortar, and placing bricks.
Safety	Emergency Stop	The robot stops automatically and immediately when specific conditions are triggered.	Bool	PictoBot’s collaborative robot has a safety system that performs a protective stop if the arm accidentally hits a structure or person.
	Safe Distance	The minimum distance needs to be maintained when humans and robots work together.	Decimal	Keep 80cm (2.6ft) between people and PictoBot to keep workers safe and robot performing.
	Objective Detection	The robot's ability to detect and recognize objects within a specific range.	Decimal	PictoBot has laser obstacle scanning, 3D point cloud collision checking.
	Additional PPE Requirement	Extra personal protective equipment required when humans operate or work with robots.	Enum	DXR operators are required to wear earmuffs to block out the noise.
	Minimum Workspace	The minimum space required by the robot to avoid collisions while operating.	Decimal	The DXR maintains a minimum of 81.9 inches with the demolished object.

CONCLUSIONS AND FUTURE WORK

Based on the literature review method, the study developed initial parameters with categories for a construction robot schema to support construction planners. The intended data structure will facilitate data collection and exchange, and further contribute to the analysis and operation of construction robots. The value of CRS is that it is a consistent data structure developed for construction planners to collect and exchange various types of robots' data to facilitate the analysis and operation on construction sites.

This study established the CRS data parameters through literature review, but this method has some limitations. The sources of information about construction robots in this study did not use real observation of the working status of construction robots when performing construction tasks. Also in the current construction industry, there are only a small number of robots. These may impact the comprehensiveness of CRS.

For the future work, the study will validate the CRS to ensure the information quality. The information quality includes the correct terms used, concise definitions, reasonable categories, usability of parameters, and comprehensive information. The validation will include the simulation experiments of robots and interviewing the experts who have knowledge and experience with developing and implementing several types of robots from the construction industry. In addition, to help the construction robots users get the data, the study needs to improve the database which contains a variety of construction robots and has corresponding data. The contribution of this work is to standardize data acquisition and facilitate the analysis and application of construction robots.

ACKNOWLEDGEMENTS

This material is based upon work supported by the National Science Foundation under Grant Number 1928626. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation.

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