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A PLANNING SCHEMA OF ON-SITE CONSTRUCTION ROBOT OPERATION

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SUMMARY*: The technology development for construction is leading to a variety of construction robots that have been, and continue to be, developed and implemented. When planning robot operation on a construction site, a wide variety of information is needed to support their safe and effective deployment. However, few researchers have summarized and structured the required information for planning construction robots' on-site operation. Therefore, this study developed a schema for planning and operating construction robots. The schema contains the planning information needed for construction robots to operate on-site, and the information is structured to enable planners to collect and query the needed information when assessing robot implementation. This study used a systematic literature review to identify the information needed for robots' construction work. The review focused on the information that users need in the case of operating the robot on site, and the description of that information. To validate the schema, the study interviewed industry experts experienced in deploying construction robots and testing the schema through a database to verify the scope of housed information and efficiency of information acquisition. The developed and validated construction robot schema has four categories, including physical properties, operational requirements, safety, and activity. There are 56 attributes housed in the schema with definitions, examples, and data types. The information in the schema can help construction teams and planners comprehend the configuration and function of the robot, which can facilitate planning operations or deploying robots to specific tasks. Future work will further improve the planning process by observing and recording the on-site operations of construction robots.*

KEYWORDS*: construction robots, data schema, construction work planning.*

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1. INTRODUCTION

Construction robots possess the ability to undertake diverse tasks within a construction site (Bock and Linner, 2016). With the participation of construction robots, the precision and productivity of construction operations can be improved (Melenbrink et al., 2020). In countries and regions with high labor and material costs, construction robots are gaining increasing attention to supplement manual labor and reduce material waste (Saidi et al., 2016 Pan et al., 2020). Some construction robots can perform hazardous tasks, such as working at heights or managing hazardous materials to reduce worker safety risks (Brosque and Fischer, 2022). Based on these advantages construction robots have been increasingly researched and applied in the construction domain in recent years.

While interest in construction robots is growing, one challenge in their implementation is that they require diverse information that differs from traditional craft needs, and many researchers have identified these information needs based on the purpose of their application (Li et al., 2024a). For example, Kim et al. (2021) developed a robot task planning system that integrates BIM and ROS to generate the robot's on-site behavior. In their case study, they selected a virtual mobile construction robot equipped with a manipulator and specific overall dimensions to simulate navigation and wall painting tasks based on the construction environment and task requirements. Zhou et al. (2022) proposed a protection system based on real-time human hand movement prediction and machine learning to avoid collisions in remote site operations using robots. To test the effectiveness of the system, they built and used a robot in a virtual construction environment that contained necessary information for collision testing, including movement speed, payload, torso, manipulator, and end effector movements. By comparing traditional on-site training methods, Adami et al. (2021) studied the impact of virtual reality (VR) based training on construction workers' knowledge acquisition, operating skills, and safety behaviors during remote robot operations. To provide subjects with a realistic training experience, they simulated a dynamic robot-involved construction site containing conditions including weather and uneven terrain. In addition, based on the requirements of physical simulation, the information used in building a virtual demolition robot includes a rigid body, a manipulator, four outriggers, and tracks. To evaluate the performance of a mobile construction robot, D. Kim et al. (2020) developed an automated framework that predicts the risk of imminent collision and proactively intervenes by predicting the proximity between workers and mobile ground robots. During the development of the collision prediction system, the robot information they used included size, movement speed, movement trajectory, and sensor detection range. Despite the efforts of these researchers to convey the information needs of construction robots, the information needs to be comprehensively summarized and organized when planning the use of each robot in construction, much less across multiple robots, and at a higher level of planning development.

When using construction robots, some information is necessary for construction planners to select the proper robot type, ensure safety, and plan for the successful integration of robots into a construction project (Li et al., 2024b). Before designing and deploying tasks, operators need information for reasonable planning (Ilyas et al., 2021). The different types of information, from logistical requirements to sequence of operations, affect robot applications in the construction domain, and some core planning needs have already been identified. Information to plan their use needs to inform the tasks performed by the construction robot, including site requirements, operator responsibilities, and levels of intervention (Czarnowski et al., 2018). Some task-oriented information of construction robots includes the required tools, materials, and participating activity processes to ensure consistent operations. In addition, task information can embody the robot's skills, representing its flexibility and adaptability in execution (Wu et al., 2022). Based on the current level of autonomy of some construction robots, they typically require human assistance in performing their tasks (Ma et al., 2022). Human safety around these new types of equipment needs to be considered when planning for the on-site operation of construction robots (Okpala et al., 2023). Construction robots can be a source of worker injuries, and information about the safe operation and protection of robots can help avoid these types of accidents (Bulgakov et al., 2020). In addition to information about the operation, physical information about the construction robot is required for planning. The physical information of the robot, such as the dimensions, degrees of freedom for manipulator movement, and end-effector posture associated with the construction robot arm, is needed to support planning for and communicating the robot's work and execution capabilities (Liang et al., 2022). Researchers' information needs are crucial in the planning process. However, these information needs about robot’s properties, operation, safety and tasks executed have not been comprehensively summarized and organized in previous studies. Based on the information needed for planning and operating on-site robots, a well-defined structure to summarize and organize this information to help planners understand and appropriately integrate robots into the construction process is needed.

Considering the need for organizing and structuring robot information for construction robot operations, this study proposes a schema to standardize the required information to support robot operation planning on construction sites. A schema outlines how data is organized, detailing and defining the structural components such as entities, attributes, relationships, and constraints (El-Sappagh et al., 2011). By organizing information, a schema helps users identify and access the information they need (Lee et al., 2014). Typically, schemas are visually depicted in graphical or tabular formats to guide the data structure design and administration processes.

In previous studies on structuring information of robots, many researchers developed or applied schemas for various purposes. Watanobe et al. (2019) proposed a framework for building data acquisition systems using integrated robot components and modern network technologies, enabling developers to build robot environments for data acquisition by defining scenarios with ontology languages. To quickly provide users with information related to robot status upon on-demand request, they provide a structured schema based on information field names, relationships, and data types. Their schema is good for robots to collect data but does not help robot users understand the robots for decision and deployment. Candell et al. (2020) proposed a graph database method that used the Neo4j database platform to capture and analyze factory work unit performance and built a testbed containing two robot arms as a case to evaluate the network physical performance of the work unit. They developed a schema for the two robots with the details of a specific task, including network elements, physical operating elements, and relationships between them to demonstrate work logic and intent. This schema helps the robot understand the logic of the task, but it is difficult for users to understand the information and use it to deploy the robot for construction tasks. Kumar et al. (2022) developed a method for generating and using a schema that contains visual and tactile information obtained from human behavior and is used to generate high-level actions of robotic agents through learning algorithms. This information can help robots understand human behavior and imitate it, but it cannot be easily understood by human users. These efforts shows how schemas can help robots understand and perform tasks, but when planning and deploying robots on a construction site, a schema is needed that contains information that is easy for human users to understand in the planning efforts.

For operating robots on construction sites, the schema needs to contain the required information about on-site operations, which needs to be readable and usable by the robot and understandable by human users when planning and deploying the robot to construction tasks. The readable schema helps construction planners understand the information used and generated by the robots so that they can efficiently plan and deploy construction robots to perform tasks specific to the characteristics of each robot and ensure safe operations (Wei et al. 2023). Especially for robots that perform tasks in dynamic environments, planners need to use the information in the schema to measure the performance of the robots (Chang et al., 2021).

Some researchers have identified that robot users need to understand the information in a schema and contribute to developing a schema that can be read by human operators. Kardos et al. (2018) introduced the workflow of context-dependent multimodal communication in a collaborative environment, focusing on providing work instructions and communication interfaces in an industrial assembly environment. To pass all process-related information to the worker and improve worker efficiency, they developed a schema containing the context defined by the process execution, the devices and robots available to the worker, and the worker's skills in using these devices and robots. The information about production in this schema can be used as a reference, showing that they have contributed to the development of information structures that can be understood by robot users. However, the schema contains limited information required for construction sites and does not cover the complexity of dynamic construction sites. Hwang et al. (2020) developed an open-source robot process automation middleware system for allocating tasks to multiple robots in multiple middleware environments based on user requests. The system includes a schema for providing users with information to update the robot's working status in real time. The information includes user requests, robot executable and root information, task descriptions, and job scheduling results. Their schema helps robot users understand and track the robot's work progress. However, in addition to task information, other operation-related information about the robot's operational requirements and safety has not been included for the on-site deployment of robots. Park et al. (2021) proposed a programmable motion fault detection based on collaborative robot motion residual analysis to establish standards for collaborative robot fault analysis, explain the meaning of detection values, and analyze the causes of faults. They used schemas to build data analysis models, which contain information such as sensing data, operating data, and corresponding relationships and explanations, to help users extract information and perform fault analysis. However, to apply the schema to construction planning, it is necessary to describe the robot's ability to perform the target task and the robot's physical information to analyze the feasibility. Although researchers have made efforts to make the schema contain various robot information, these schemas cannot directly be used to plan operating robots on construction sites.

By reviewing previous studies, we found that construction robots working on site require a variety of information to facilitate teams and planners to integrate robots into the construction process. Many researchers have developed schemas for robots for various purposes to structure this information based on targeted needs. These schemas can be understood by the robot and support specific tasks, but they do not provide information for the user to understand and plan the robot's tasks for the construction site. Although other researchers have created schema for human users to understand, the proposed schemas cannot be directly used to plan the operation of the construction robot. Due to the complexity of the construction site, the schema needs to include information showing the specific attributes or capabilities of the robot to meet the needs of the site operation. Therefore, this study develops a construction robot schema (CRS) based on the information needs of construction teams and planners in planning on-site operating robots. The resulting schema is designed to allow users to collect and query the required information to facilitate their analysis and selection of construction robots during the construction planning process.

2. RESEARCH PROCESS

The purpose of developing CRS in this study is to support construction teams and planners to collect and query the information they need for robot on-site operations based on a well-defined information structure to facilitate their comprehension and decision-making. As shown in Figure 1, this study conducted a systematic literature review to collect information on construction robots' operation on site to achieve this goal. This study filtered out information sources from the literature database and ROS wiki for review and information extraction. This study used Nvivo to encode and extract information based on the filtered information sources. The extracted information included attributes about the robot, corresponding definitions, data types, and examples. Subsequently, the information was categorized based on the commonalities across the information through axial coding to form an initial schema. To ensure that the schema's information meets the construction industry's needs for on-site operation robots, this study validated the schema through expert interviews. In addition, this study validated that the proposed schema can facilitate users' querying of information through database normalization. The details of the research process are as follows.

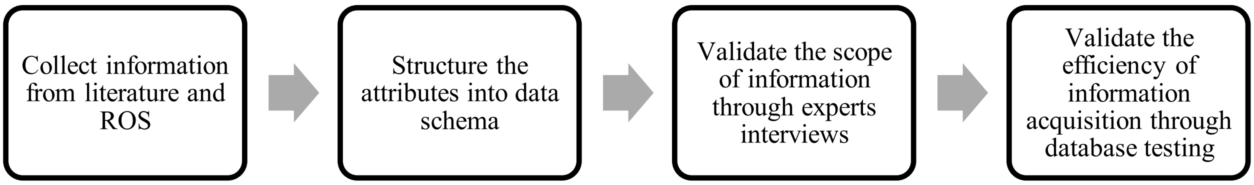

Figure 1: Research Process Flow of Systematic Literature Review and Validation.

2.1 Collect information of on-site operated construction robots

The study collected the required information based on a systematic literature review. To broadly cover papers about state-of-art construction robot studies, papers were searched through the Web of Science and Scopus using construction and robots as keywords and focused on the published year after 2018, which is the growth period of construction robots for importance, performance, and adoption (Aghimien et al., 2020). The papers search and collection work was completed in January 2023. To prevent missing papers, the original keywords were replaced with synonyms such as architecture and robotics, and some terms related to construction robots were added to the keywords, such as human-robot interaction, end effector, sensor, manipulator, and mobility. The search task was stopped when the keywords had been modified three times in a row, and the number of new papers identified was 0. The initial pool of papers was culled for domain match through a manual review of abstracts; for example, some papers using the terms construction and robots were about the assembly of robots and not related to the construction industry.

This study retrieved 6,225 papers by searching the keywords "construction" and "robot" in Web of Science and Scopus. The study first selected the publication time after 2018 to get state-of-art research and focused on the English publications to ensure readability, which retained 2,206 papers. Then, the research field was limited to construction to exclude irrelevant areas, which left 126 papers. To avoid omissions, multiple words were substituted for "construction" and "robot," and robot-related terms were added as keywords, which increased the number of papers to 293. The search query this study used is "(construction OR architecture OR building construction) AND (robot OR robotics) AND (human-robot cooperation OR human-robot collaboration OR human-robot interaction OR application OR analysis OR development OR end effector OR sensor OR robotic arm OR mobility)." Finally, the abstracts were manually reviewed to ensure the papers were relevant to the construction industry and demonstrated the development or use of construction robots. After these search procedures and domain filtering, 279 eligible papers remained and were used in the detailed review.

In addition to the information from the systematic literature review, this study cross-compared information for robot control, specifically based on data requirements and attributes from the open-source data contained in the Robot Operating System (ROS). ROS is an open-source framework for building, programming, and managing robot software systems, providing tools and libraries for hardware abstraction, device control, and message-passing between processes (Kharel et al., 2014). ROS provides more detailed information about the attributes of robots, because of its extensive community support and continuous development. This study reviewed the ROS Wiki to obtain information about various robots that can be used for construction tasks. These robots are divided into five categories: aerial, component, ground, manipulator and marine. After reviewing all robots included in these five categories, this study selected four robots including Husky, COEX Clover, BlueRov and Revel with the ability to perform construction tasks as representatives for information analysis.

2.2 Structure the information into data schema

This study used Nvivo to conduct open coding of these eligible papers and ROS information based on the grounded theory. In each paper, the study focused on the description of construction robots and their corresponding properties and attributes. For ROS Wiki, the study extracted attributes related to on-site planning of operational robots. Relevant information was coded and summarized into corresponding attributes. The target coding attributes of this study include all the information necessary for designing or using robots to perform specific construction tasks, such as the robot's body structure and configuration, mobility, characteristics of the target task, the roles of collaborating workers, the conditions required for operation, and mechanisms to protect humans. For each attribute, a concise definition of the attributes was captured along with corresponding data types and examples to facilitate user understanding.

Subsequently, this study used axial coding to conduct an initial classification of attributes by analyzing their commonalities. This resulted in four categories, summarized in Table 1: physical properties, operational requirements, activities, and safety. Physical properties include attributes of the robot body, manipulator, mechanical hardware, and performance attributes related to robot functions. The operational requirements capture environmental conditions, necessary infrastructure, or human assistance needs. The activities contain attributes, requirements, and responsibilities for robot participation specific to construction tasks or projects. Safety includes attributes that describe how construction robots requirements regarding keep humans away from danger and precautions for humans when working near or operating a robot. After the systematic literature review and coding, 35 attributes were initially identified across these four categories.

Table 1: Categories and Criteria for Collecting and Grouping CRS Attributes.

Categories	Criteria
Physical Properties	Attributes about the performance or physical characteristics of robots that can be observed or measured to ensure accessibility, maneuverability, and constructability during dynamic construction site planning and operation.
Operational Requirements	Attributes about the conditions of construction sites that are necessary for robots to perform tasks to ensure that the robot can perform its tasks functionally.
Activities	Attributes relevant to the construction process when robots participate in a specific project to ensure that the robot is adapted to the target construction task.
Safety	Attributes about preventing damage or injuries when robots perform tasks with humans to protect human workers who work with the robot or share the same work area.

2.3 Validate the scope of CRS through expert interviews

The study validated the scope of CRS through expert interviews to correct term use, refine appropriate categories, and identify missing information. These experts had to meet two primary criteria, they needed more than 10 years AEC experience and they personally needed experience developing or implementing two or more types of robots into construction projects. These strict criteria limited the number of potential experts (Melenbrink et al., 2020), however their specialized expertise was critical to understanding the link between robot attributes and needs for planning the implementation of robots on construction sites.

Four experts were invited to participate in semi-structured online interviews for this study. Each interview lasted 30 minutes, including 15 minutes of CRS introduction, 10 minutes of fixed questions, and 5 minutes of open dialogue. The interview consisted of asking the interviewees four questions to collect their suggestions and feedback on the content and structure of the information. The contents of these questions requested experts to:

1. Review and confirm attributes, terms, and structure of the CRS,
2. Give feedback and clarification of definitions for terms and attributes,
3. Check the scope, classification, and categorization of robot attributes, and,
4. Identify additional needs or missing information in the current schema.

Figure 2 illustrates how the categories and information in the CRS were introduced to experts during interviews in this study. Under each category, experts were introduced to the included attributes, corresponding definitions, and examples of information. Furthermore, this study enhanced experts' understanding of the CRS by introducing construction robot examples with this type of information, thereby better gathering their feedback.

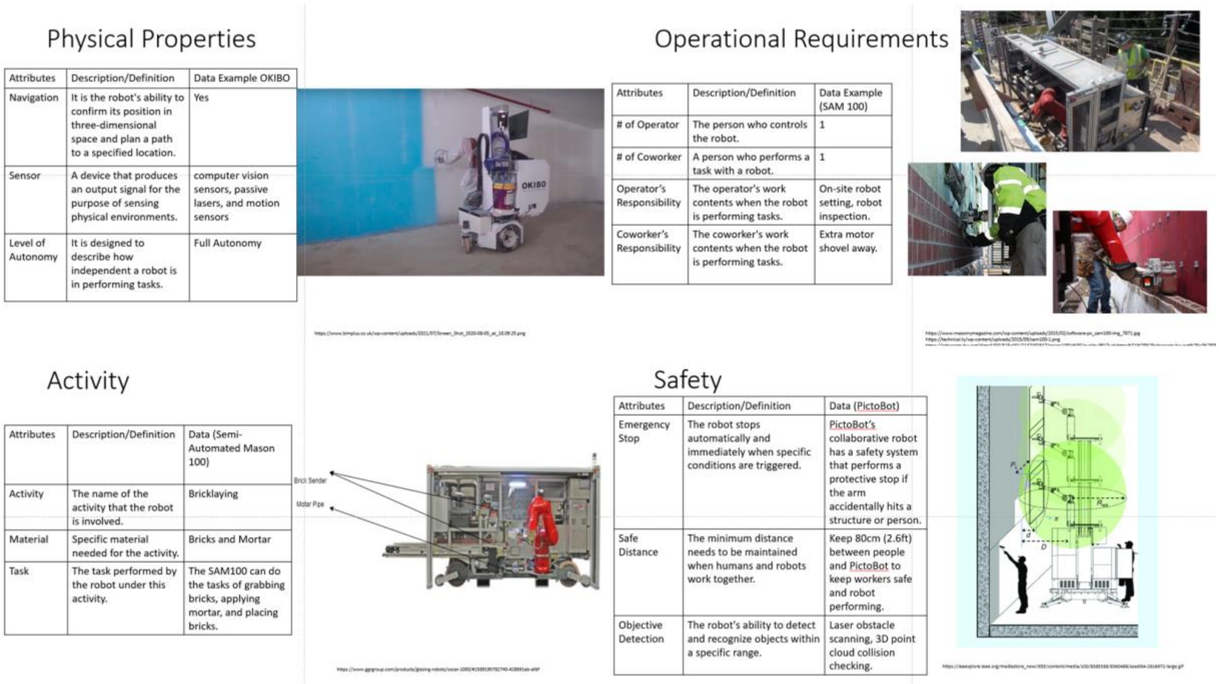

Figure 2: Examples of Slides Used for Introducing CRS in Interviews.

Following the review and questions, there was an open conversation for experts to share their experiences about developing or implementing robots to help the study check information that may not have emerged in the literature review.

2.4 Validate the information acquisition efficiency through database normalization

Following the development and validation of the schema scope, structure, and terms, a database normalization procedure was performed to explore information requirements in CRS and to validate the designed functions. Applying database normalization to the categories and relationships established in the CRS validates that these fields adequately capture relevant data about construction robots for construction planning. The resulting database serves as an example use case for the CRS, leveraging the data structure to provide relevant information based on user input. Database normalization is a prescribed process that, within each step, evaluates specific conditions between data points to work toward a resultant structure that is standardized to be read and modified using database query language.

The database extracted information and categorization from CRS to design and test the structure based on the data requirements of the five normal forms in the database normalization process (Kent, 1983). Most relational databases are managed using standard query language (SQL) to access and edit information. After normalization, the database process executed test queries to ensure that the database returned the expected results and effectively managed the queries for realistic applications. By referring to Solihin's (2016) method of validating data, the database established five functional categories of query types and developed two test queries for each category. As shown in Table 2, query categories, definitions, proposed queries, and target information are included.

Table 2 Five Categories of Query Types.

Query Category	Definition	Proposed Query	Target Information
General	General queries are designed to learn basic information about a specific robot. This is the simplest class of test queries used in this study.	How many sensors does robot x require to operate effectively?	Total number of sensors
		What is robot x's standard operating level of autonomy?	Level of autonomy
Physicality	Queries about robot physical properties. While queries in other robot properties may look for information about the robot's physical properties, this category contains basic queries that purely look for information about the robot's physical properties. This was developed as a separate category because these properties were found to be particularly useful in visualizing or simulating robots.	What are the dimensions of robot x?	Length, width, height
		What is robot x's power source?	Power source
Requirements	The query specifically attempts to find information about what is needed to implement robots on site. This information is particularly relevant when considering safe human-robot interaction, as it ensures that the necessary conditions are met for on-site operation. The job site must be appropriately equipped for an ideal robot implementation.	What jobsite conditions must be met to implement robot x?	Grade, temperature, max humidity, site preparation
		How close can work occur to robot x while in operation?	Safe operating distance
Comparison	Comparing two or more robots performing similar tasks is an important feature that helps decide which robot to use on a job site. Similar to large purchases, it is important for the management team to make informed decisions and have all the information needed to do so.	What robot can complete y task in the shortest amount of time?	Productivity
		Which robot completing y task has the longest duration?	Run duration
Planning	Deploying construction robots on a jobsite requires extensive planning to accomplish effectively. Planning queries are very specific and are seeking information about how the robot will operate on the job site to plan accordingly.	What is robot x's accuracy and precision?	Accuracy, precision
		How many workers does robot x need to work with to operate?	Total number of coworkers and operators

Table 3: Information in Construction Robot Schema.

Category	Attribute	Definition	Example	Type
Physical Property	Name	The official label or identifier of the robot given by the developer and second key of robot table (Fankhauser and Hutter, 2018).	A four-legged walking inspection robot named ANYmal.	String
	Manufacturer	The developer of the robot (Melenbrink et al., 2020).	Spot is the product of Boston Dynamics.	String
	Level of Autonomy	The independency of the robot in performing tasks (Melenbrink, et al., 2020).	SAM 100 is classified as semi automation.	Enum
	Network	The approach of robot to communicate and exchange data (Zou et al., 2020).	Cybe is required Wi-Fi to communicate and exchange data.	Enum
	Length	The measurement of the robot from one end to the other along its longest dimension (Kim et al., 2022a).	The length of ANYmal is 80 cm (31 inches).	Decimal
	Width	The measurement of the robot from side to side, perpendicular to its length, representing its breadth (Kim et al., 2022a).	The width of ANYmal is 60 cm (24 inches).	Decimal
	Height	The measurement of the robot from its base to its highest point, indicating its vertical extent (Kim et al., 2022a).	The hight of ANYmal is 70 cm (28 inches).	Decimal
	Weight	The physical mass of the robot (Gao et al., 2022).	The weight of ANYmal is 30kg (66 pounds).	Decimal
	Load Capacity	The maximum allowable weight that the robot can withstand for a long time when it is performing work (Ng et al., 2022).	ANYmal can carry a maximum weight of 15kg (33 pounds).	Decimal
	Mobility	The mechanism of the robot to move from one place to another and second key of mobility table (Rubio et al., 2019).	OKIBO is a painting robot based on wheel movement.	Enum
	Speed	The rate of the robot traversing a distance within a given timeframe (Kim et al., 2021).	ANYmal's walking speed is 1.2m/s (3.9ft/s).	Decimal
	Navigation	The robot's ability to confirm its position in three-dimensional space and plan a path to a specified location (Kim et al., 2019).	OKIBO can automatically plan path and move to the position.	Bool
	Power Source	The energy origin that supplies the robot to perform tasks (Asadi et al., 2018b).	ANYmal is powered by batteries.	Enum
	Run Duration	The period the robot can operating continuously on its available power source before requiring replenishment (Xu and de Soto, 2020).	ANYmal’s battery can supply normal work for 90 minutes.	Decimal
	Sensor Type	A device that produces an output signal for the purpose of sensing physical environment. (Quintana et al., 2021).	OKIBO painting robot has computer vision sensors, passive lasers, and motion sensors mounted on it.	String

Category	Attribute	Definition	Example	Type
	Sensor Location	The installation position of the sensor on the robot or outside (Komatsu et al., 2021) (Ercan et al., 2019).	The terrain sensing unit of Spot is mounted at (0, 21.7, 7.5) in.	String
	Sensor Requirements	The hardware or software that supports the operation of the sensor (Allwright et al., 2019).	Sensor installation on the robot requires a mounting base, sensor cable, and sensor adapter.	String
	Sensor Capability	The functions of the sensor (Lam et al., 2022).	LiDAR emits laser pulses and measures the time it takes for them to bounce back, providing distance and 3D maps.	String
	End Effector	The device attached to the robot to interact with the task environment and second key of end effector table (Pollák and Dobránsky, 2020).	DXR can perform different tasks by changing the end effector of the manipulator such as bucket, shears and cutters.	String
	Manipulator	A structure with a series of links and joints that perform tasks (Yoshinada et al., 2019).	Spot can be equipped with a semi-automatic electric manipulator to grab, lift and place.	String
	Coordinate Reach X	The maximum attach distance of the manipulator on the x-axis (Apriaskar and Fauzi, 2020).	The X reach of Oscar 1000 is 2m (6.6ft).	Decimal
	Coordinate Reach Y	The maximum attach distance of the manipulator on the y-axis (Apriaskar and Fauzi, 2020).	The Y reach of Oscar 1000 is 2m (6.6ft).	Decimal
	Coordinate Reach Z	The maximum attach distance of the manipulator on the z-axis (Apriaskar and Fauzi, 2020).	The Z reach of Oscar 1000 is 3.5m (11.5ft).	Decimal
	Yaw	The rotational movement range around the vertical axis (Iqbal et al., 2012).	The yaw of ED7220C is 172°.	Decimal
	Pitch	The rotational movement range around the lateral axis (Iqbal et al., 2012).	The pitch of ED7220C is 260°.	Decimal
	Roll	The rotational movement range around the longitudinal axis (Iqbal et al., 2012).	The roll of ED7220C is 360°.	Decimal
	Manipulator Position	The installation position of the manipulator on the robot (Colucci et al., 2021).	The installation position of the manipulator of the Paquitop mobile platform is (0, 0.2, 0.2) m.	String
	Degree of Freedom	Number of geometry axis that can be rotated or extended (Hong and Huang, 2020).	The manipulator of AR3120 welding robot has 6 degrees of freedom.	Int
	Lifting Capacity	The maximum weight that the robot can lift during operation (Kayhani et al., 2021).	The maximum lifting capacity of Oscar1000 glazing robot's manipulator is 1000kg (2204.6 lb).	Decimal

Category	Attribute	Definition	Example	Type
Operational Requirement	Grade	The acceptable flat level of the ground for the mobile robot (Baum et al., 2018).	ANYmal can walk on a slope less than 30° and can cross a gap of fewer than 11.81 inches.	String
	Temperature	The temperature range required for the robot to work properly (Pessoa et al., 2021).	The temperature required for the CyBe 3D printed robot is 5-50 °C (21-122 °F).	String
	Humidity	The humidity range required for the robot to work properly (Czarnowski et al., 2018).	The maximum humidity required for CyBe 3D printing robots is 95%.	Decimal
	Site Preparation	The preparations required for the robot to work properly on the site(Balzan, et al., 2020).	The Clapa Floor Master needs to be prepared with semi-dry sand/material on the floor before starting work.	String
	Req Number Operators	The quantity of person(s) who control the robot (Yu et al., 2018).	TyBot requires an operator to monitor the robot's operation.	Int
	Operator Responsibilities	The operator's work contents when the robot is performing tasks (Follini et al., 2020).	The operator of the SAM 100 needs to be on site to set up and inspect the robot.	String
Safety	Emergency Stop	The robot stops automatically and immediately when specific conditions are triggered (Salmi et al., 2018).	PictoBot has a safety system that performs a protective stop if the arm accidentally hits a structure or person.	String
	Safe Distance	The minimum distance needs to be maintained when humans and robots work together (E. Asadi et al., 2018).	Keep 80cm (2.6ft) between people and PictoBot to keep workers safe and robot performing.	Decimal
	Object Detection Range	The robot's ability to detect and recognize objects within a specific range (Akinosho et al., 2020).	ANYmal's depth camera can accurately detect obstacles within 2 m (6.6 ft).	Decimal
	Safety Barrier	The facility for the robot to avoid collisions between the robot and humans or objects (Landi et al., 2019).	SAM 100 has a metal door to separate the work areas for robot and human.	Bool
	Additional PPE Requirements	Extra personal protective equipment required when humans operate or work with robots (Davila Delgado et al., 2019).	DXR operators are required to wear soundproof earmuffs to block out the noise.	String
	Minimum Workspace	The minimum space required by the robot to avoid collisions while operating (Qin et al., 2022).	The DXR maintains a minimum of 81.9 inches with the demolished object.	Decimal
Activity	Task Type	The specific operations related to the construction activity performed by the robot (Huang et al., 2022).	The SAM100 can do the tasks of grabbing bricks, dipping in mortar, and placing bricks.	String
	Productivity	The amount of work or production of the robot per unit time (Yahya et al., 2019).	CyBe 3D printer has productivity of 50-500mm/s (2-20 in/s).	Decimal
	Precision	The degree of refinement of the robot when normally performs works (Zhang et al., 2018).	The precision of CyBe 3D printer is 1/1/1mm (about 0.04/0.04/0.04 inch).	Decimal

Category	Attribute	Definition	Example	Type
	Accuracy	The degree of correctness of the robot when normally performs works (Liang et al., 2019).	The placement accuracy of SAM100 is within 2-3mm (0.08-0.12 inches).	Decimal
	Productivity Units	The unit used to measure robot productivity (García de Soto et al., 2018).	SAM100 can lay 2000 to 3000 bricks per day.	String
	Precision Units	The unit used to measure robot precision (Ercan et al., 2019).	The precision of PictoBot is 0.017 in.	String
	Accuracy Units	The unit used to measure robot accuracy (Hu et al., 2023).	The recognition accuracy of the lidar on ANYmal is 3cm (1.2in).	String
	Activity Type	The construction activity that the robot is involved (Madsen, 2019).	SAM100 can participate in bricklaying activities.	String
	Material	The specific material needed by the robot to perform tasks (García de Soto et al., 2018).	The materials SAM100 needs when laying bricks are bricks and mortar.	String
	Data Output Type	The form of sensor data output (Kim et al., 2018).	Waco's laser sensors output in decimals in metric units to represent distance.	String
	Data Output File Type	The file format of sensor output data (Kim et al., 2018).	The data extension output by IES's Global Env. Modeler is .glo.	String
	Crew Information	Team composition working with robots (Kim et al., 2022b).	Liftbot requires 4 scaffolding installation workers.	String
	Crew Responsibilities	The crew's work contents when the robot is performing tasks (Brosque and Fischer, 2022).	Liftbot crew members need experience in scaffolding installation and operating robots.	String
	Worker Type	The categorization of workers who work with the robot (Adepoju, 2022).	The labor required by Liftbot is scaffolder.	Enum
	Worker Responsibilities	The worker's work contents when the robot is performing tasks (Amtsberg, et al. 2021).	Scaffolders working with Liftbot need to install and dismantle scaffolding, and Liftbot helps them move it vertically.	String

3. RESULTS

3.1 Construction robot schema

CRS has four categories, including Physical Property, Operational Requirements, Safety, and Activity, as shown in Table 3. Physical Property houses 29 attributes covering the information about physical descriptors and the performance of robots that can be observed or measured from on-site operation. Operational Requirement houses six attributes covering the information about necessary site conditions that allow robots to perform tasks. Safety houses six attributes covering the information about the robots' requirements or capabilities that prevent damage or injury to workers. Activity houses 15 attributes covering the information about the construction process that robots participate in. For each attribute, CRS has a definition, with references, to describe uses, an example to support understanding of the attribute, and a data type to point out the attribute's format in a database when using it. In total, CRS contains 56 attributes that are usable for planning the operation of on-site construction robots

3.2 Changes from validation

Through the validation by expert interviews and database normalization, this study made changes to the collected attributes from the literature and ROS review, as summarized in Table 4. During the validation, experts typically focused their attention on the attributes of the robot's operation on site. For example, they noted that some robots must be separated from the surrounding workers by barriers for safe operation. Database normalization, on the other hand, validated CRS from the perspective of user information query. For example, the word 'coworker,' while common in the human-robot interaction research domain, is rarely used in construction contexts, so it was replaced by 'crew' and 'worker' to facilitate users' vernacular fit to obtain information.

Table 4: Changes in CRS from Validation.

Changes of Attributes	Reason	Source
Add 'Safety Barrier'	When robots working with humans are deployed on site, facilities are needed to separate them.	Expert Interview
Add 'Data Output Type'	Get the type of sensor data output for further application or analysis. For example, the point cloud information output by the sensor.	Database Normalization
Add 'Data Output File Type'	Acquire the file type of the sensor data output to ensure it is readable and usable in the project's existing devices.	
Add 'Crew Information'	Aligning details of robot work to common construction practices. Defining a crew based on the composition and types of workers provides high-level information about requirements.	
Add 'Crew Responsibility'		
Add 'Worker Type'	Attempt to assign workers with common construction identifiers to align with industry practices.	
Delete 'Coworker'	To simply define what resources are necessary to work alongside a robot, encapsulating all required co-workers in a crew entity enables this summarization in a manner that is highly useful when assigning resources in planning for robot work. Additional details about each worker's responsibilities exist within the worker entity, but this level of detail is often not required for standard scheduling practices.	

3.3 Physical property

Physical Property includes the physical dimensions and performance of the robot. While reviewing and interviewing experts, this study found that this type of information is crucial in deploying robots on-site. For example, the length, width, height, and weight of the robot determine the robot's ability to pass through the opening of the construction site and the robot's constructability in a given space. The autonomy level and navigation determine the degree of human intervention in the robot working process. The degrees of freedom related to the manipulator and the specific six-axis motion information reflect the flexibility and manipulation accuracy of the robot's manipulator. The information related to sensors explains to users the capabilities of the equipped sensors and the equipment requirements, especially for integrated robots. In addition, the robot is considered to communicate with humans through a specific network. This information ensures that the construction robot can be effectively deployed on site from the perspective of robotics technology.

Figure 3 shows an inspection quadruped robot called ANYmal. The figure indicates the robot's dimensions, weight, walking speed, and the types of sensors it is equipped with. A robot as small and lightweight as this can navigate in relatively narrow and unstable environments. The robot's integrated sensors can take scene pictures and enable navigation and obstacle avoidance.

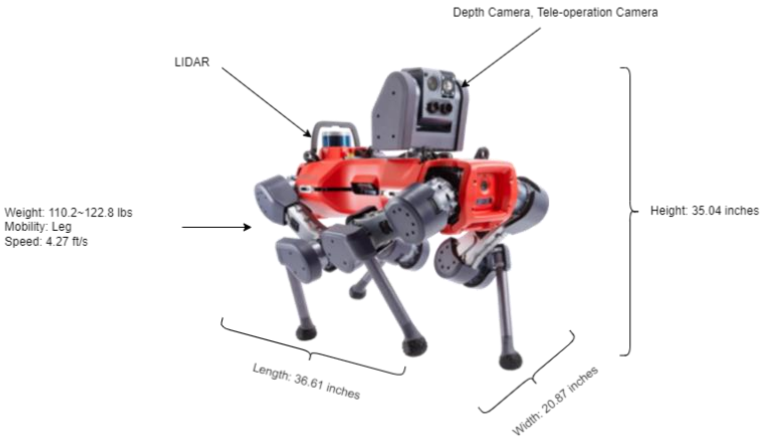

Figure 3: ANYmal Inspection Robot (ANYmal Research is a community to advance legged robotics., n.d.).

3.4 Operational requirement

The information in the Operational Requirements provides to the user on the conditions that ensure regular operation. The information includes the robot's requirements for terrain and slope, suitable temperature and humidity. The preparation for the robot requires humans to pre-treat the site area or materials to achieve the working conditions of the robot. Some robots require operators to control, monitor and evaluate their work.

Figure 4 shows a floor-screeding robot called FloorMaster. Before the robot starts working, it needs workers to help it roughly level the concrete on the ground, and then it can start to screed the surface in detail.

Figure 4: FloorMaster Screeding Robot (Smet, 2022).

3.5 Safety

Previous studies and experts point to the need to ensure the safety of humans working with robots. This study identified this need and included this information in Safety. This consists of the emergency stop function on the robot to ensure that the human worker can stop the robot at any time. The distance between the human and the robot required for safe operation, and the distance at which the robot recognizes objects, can provide a safe operating buffer for human workers. To clearly separate the robot and humans, some robots also provide work area separation facilities. Operating some robots requires humans to wear additional PPE, such as noise insulation. Minimum work area ensures that the robot will not collide with other existing facilities or equipment.

Figure 5 shows a demolition robot named DXR. The robot is equipped with an emergency stop system to ensure that workers can stop the robot at any time. In addition, workers who control the robot need to wear noise-isolating equipment to protect their hearing.

Figure 5: DXR Demolition Robot (Demolition robots to dismantle almost anything, anywhere, n.d.).

Figure 6: SAM100 Bricklaying Robot (Construction Made Simpler and Safer, n.d.).

3.6 Activity

Activity contains information directly related to the robot's on-site construction. It includes specific tasks the robot can perform during construction activities and the required materials. During the execution of the task, the operator needs to understand the productivity, precision and accuracy achieved by the robot, as well as the corresponding units. For some tasks such as robot inspection, humans need to obtain relevant data output from the robot, including the type of data and the file type. Some tasks on site, such as masonry, require robots and humans to complete them together. When deploying such robots, users need to obtain information about the responsibilities of the work crew, as well as the specific types of workers and the responsibilities of each worker working with the robot.

Figure 5 shows a bricklaying robot named SAM100. The materials required by the robot are bricks and mortar. In addition, SAM100 needs a work crew to complete the bricklaying work with it. The responsibilities of the workers in the crew include feeding bricks and mortar to SAM100, shoveling away excess mortar after SAM100 places bricks and placing bricks in certain locations that SAM 100 cannot reach efficiently.

4. DISCUSSION

In this study, the attributes information of CRS was derived from the literature and cross-compared with robot requirements published in ROS. The CRS was validated and modified through expert interviews and database normalization. This study addressed the challenge of insufficient information housed or proposed in previous studies by analyzing the information needed to operate robots on construction sites. By categorizing and defining the information contained in CRS, the limitation of human operators having difficulty understanding the information is addressed. From the results of this study, it was found that Physical Property contained the largest number of attributes, with a total of 29. This information reflects the robot's geometric information, hardware configuration regarding the platform and manipulator (arm), level of automation, and flexibility. When this information is applied on the construction site, it can be used to analyze the performance, space, and related logistical needs of a robot in a construction task. Subsequently, the Activity includes a total of 17 attributes. This category differentiates CRS from other schemas from other domains, such as manufacturing, to make robot operations relevant to the construction industry. Compared with other robot-related schemas, CRS was developed for the audience of construction planners. Especially in the Activity attributes, the information contains the role played by the robot in construction production, its specific performance for construction tasks, and the responsibilities of related human workers for operations or task augmentation. This information is necessary in deploying robots into specific construction processes. During the interviews, the experts were interested in and emphasized the needs related to Operational Requirement and Safety in CRS. This information includes the requirements for the on-site environment when the robot is operating, safety-related functions, and safe operation requirements, such as barriers. They believed that the construction process in which robots participate can be adjusted based on this information so that robots can be deployed appropriately and safely.

During the validation process, not all proposed information changes were accepted using the criteria proposed in this study. For example, more than one expert suggested that the information structure of the robot can cover some data related to business models, such as the price or price range of the robot. Their reason was that the construction planners could consider buying, leasing, or giving up the use of the robot according to its cost. Another suggestion was that in the safety section, 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 suggestions. The reason is that these two suggestions are not related to the operation of robots on the construction site. These suggestions are relevant to purchasing decisions or safety risk assessments during the planning phase when considering robot implementation. Suggestions also included adding an attribute about the ability of robots to report the position to construction teams. This ability has been included in the navigation attributes, so the study decided to reject this change.

Based on a review of previous research, we found that the construction industry needs information to understand robots and facilitate on-site deployment when planning and operating them. Many researchers have identified the need for information to enhance understanding of robot operation; however, they have overlooked the need for this information to encompass the complexities of dynamic construction sites. Our CRS independently includes information related to robot task execution in the "Activity" category to help plan robot operation in response to dynamic construction sites. We also utilize the "Safety" category to cover information on protecting human workers working alongside robots. Furthermore, information in the "Physical property" category helps planners deploy robots in confined construction spaces, improving robot accessibility and constructability. During validation, we ensured that human users of this information could access usable information for operating robots on-site, and that the terminology used was consistent with construction industry usage, through expert interviews and database normalization.

Based on the research process of this study, the use of CRS in actual construction planning may still pose some challenges. Since construction robots are not widely deployed and operated in the construction industry, this study did not have the opportunity to observe a variety of real robots and collect objective and detailed information to fully populate the outlined information requirements. In addition to this, the type of robot information obtained through manufacturers was limited due to the mechanisms that robot companies sometimes use to protect their products. This may cause the CRS to miss some potentially useful information for construction planning. In addition, the target users of CRS are construction planners, while the robots covered are used for on-site operations. While additional interviews and expertise were desired, there is a very limited pool of industry experts that fulfill the critera set for our initial and validation interview processes. However, for other users, such as researchers for experimentation and development, the depth of information in CRS may not fully provide some of their information needs.

5. CONCLUSIONS

This study developed a construction robot schema for construction planners. This study utilized a systematic literature review to collect information on robots operating on construction sites and reviewed relevant information on robots published in ROS to supplement CRS. To validate the information in the CRS, this study conducted expert interviews and database normalization to examine and validate the usability of information, the rationality of categorization, and identify missed information. After development and validation, this study made criteria-based changes to the CRS and finally obtained an information structure with four categories and 56 attributes with corresponding definitions, examples, and data types.

Through a review of previous relevant studies, this study found that construction robots operating on-site require various information, but there is not a well-defined structure to summarize this information to promote the integration of robots into the process during planning. The development of CRS filled this gap by referring to the perspective of on-site operating robots on construction sites. The information in the CRS can help planners identify the role of robots in on-site production processes, analyze their constructability and flexibility in the complex environment, and adjust the process so that robots can be appropriately integrated. The categories, definitions, examples, and data types in CRS help planners better comprehend robot information so that information can be collected, exchanged, and analyzed clearly as more robots emerge and are used on construction sites. For the industry, CRS offers help to planners to make decisions and analyze robots for corresponding on-site operations based on specific projects, thereby promoting the application of robots in on-site construction.

For future work, the database model of CRS could be further developed and populated with robot data sourced from manufacturers and industry professionals. By compiling data about various construction robots, this tool aims to further facilitate robot implementation by improving the ease of access to information for construction planners. The current CRS only covers operating robots on site. However, for the construction process, in addition to on-site operations, there are also opportunities for robots to participate in off-site fabrication and logistics.

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