A SCHEMA FOR PLANNING ROBOTICS OPERATIONS IN CONSTRUCTION

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by
Fangxiao Li

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The thesis of Fangxiao Li was reviewed and approved by the following:

Robert Leicht  
Associate Professor of Architectural Engineering  
Thesis Advisor

Yuqing Hu  
Assistant Professor of Architectural Engineering

John Messner  
Charles and Elinor Matts Professor of Architectural Engineering

Julian Wang  
Associate Professor and Graduate Programs Officer
Abstract

Construction robots are increasingly developed and used in the construction domain. To understand and optimize the capabilities, applications of construction robots, and better organize the construction activities performed by construction robots, construction planners need access to various information about robots. A schema is used for data collection and organization to identify required data items for performing construction robot tasks. Previous studies on schema development have not considered the integration of construction planning to facilitate the collection of various robots’ data. This study gathered and validated data for 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 for robotics implementation in construction and associated factors of human-robot cooperation. The CRS was designed to be used by construction planners to conduct the project planning and decisions making for operating construction robots at a project site. The advantage and characteristics of the CRS compared to other types of robot schema are its development and application based on the perspective of the construction domain and are designed to cover different categories of construction robots broadly and comprehensively. 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 organized the information into parameters and categorized, defined, and exemplified these parameters. All the parameters were grouped into four categories, including ontological properties, operational requirements, activity, and safety. The study further identified the detailed data items under each category. After the CRS development, the study conducted database validation using current robots, simulation validation for constructability planning, and experts interview validation to correct terms used, determine the reasonable relationships, and identify information missed. As a result, the study resulted in a data structure including 4 categories and 39 parameters with corresponding definitions, data types, examples, and references.
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Chapter 1 Introduction

The degree of automation in the construction industry lags other industries, such as manufacturing. One of the technologies facilitating the advancement of automation in the construction industry is robotics (McClymonds et al., 2023). Robot users in the construction industry need to properly understand and apply robots in different ways to meet a given project needs and constrains. Over the past few decades, different robotics companies have introduced their products to the construction industry. As their technology continues to mature and the robots they produce are put into use, robot researchers or users can obtain relevant information about robots from official channels. This technical data of the robot introduces the robot to the user for different purpose. For example, the content may include the robot's body structure, function description, operating conditions, or safety precautions. The information is generally provided to the user from the perspective of the developer. However, when the construction industry is the user, the information provided by the robot developers is often either too detailed or not available. This means that some of the information needed for construction is not readily available for planning the application of robots in the construction industry, or the information that the construction industry needs have not included. To make up for this information gap of the construction industry in obtaining robot information, this study explores and organizes the content of the construction industry's need for robot information from the perspective of the construction planning needs of construction companies using robots.

1.1 Robotics

In the Oxford dictionary (2016), a robot is defined as a machine that can be programmed by a computer and is capable of automatically performing a complex series of actions. A robot is a smart device that can perform tasks independently, which can complete various tasks, often in the place of humans. These tasks range from common industrial assembly to complex space exploration tasks (Haddadin et al., 2018). Robotics more broadly refers to a series of technologies involving the design, manufacture, control, and application of robots. Robotics usually requires the incorporation of mechanical design, sensor technology, control system(s), and artificial intelligence or similar levels of automation (Polygerinos et al., 2017). Robotics aims to improve the autonomy and flexibility of robots by studying aspects of robot perception,
control, planning and decision-making. Robotics uses different sensors and algorithms to enable robots to perceive the surrounding environment, obtain information, make decisions, perform actions, and interact with humans (Nahavandi, 2017). Therefore, robotics is the combination of multiple domains and disciplines typically implemented to serve human society.

With the development of robotics, people realize that robots can bring benefits to human society. The advantages of applying robots include:

1) High precision: Robots can perform tasks with precision and are not as prone to errors as humans. This makes robots useful in tasks that require a high degree of precision (Zhu et al., 2022).

2) Efficiency: Robots can often perform tasks at a faster speed, which can increase productivity and efficiency. Robots can also continue to perform tasks without interruption, without the need for rest and downtime like humans (Sherwani et al., 2020).

3) Safety: Robots can perform tasks instead of humans in dangerous environments, which can reduce the risk of human exposure to physical dangers or risks that make tasks safer (Llale et al., 2020).

4) Repeatability: Robots can perform the same tasks repeatedly without changes in quality, freeing human workers from boring tasks. This is very useful for tasks that require a lot of repetitive work (Helms et al., 2002).

5) Flexibility: Robots can be programmed to perform a variety of different tasks, which makes them some level of flexible operations (Kortenkamp et al., 2016).

Based on these advantages, robotics has attracted the attention of researchers in various domains, including for the construction industry.

1.2 Robotics in Construction

A construction robot is a robot capable of performing various tasks on a construction site, such as excavation, concrete placement, laying walls, cleaning, and inspection. They are usually controlled by computers and use devices such as sensors and cameras to sense their surroundings and mission requirements (Bock and Linner, 2016). 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 or handling hazardous materials (Wong Chong et al., 2022). Current construction robots are used in a wide range of applications and sectors, including residential construction, commercial construction, road and bridge construction, mining, and energy projects.

There are still many challenges in the construction industry that robots may be able to help address. These challenges include:

1) The construction industry is a labor-intensive industry with high labor costs, and it is also prone to worker fatigue and mistakes (Wan et al., 2013).

2) Most of the work in the construction industry needs to be performed manually, such as building walls, concrete placement, so the construction duration is often relatively long (Ibrahim et al., 2021).

3) As the construction relies on manual operation, the construction accuracy is often difficult to guarantee, resulting in low project quality (Nguyen et al., 2020).

4) There are various dangers in the construction industry, such as high-altitude operations or handling of hazardous materials, which can lead to injury or even death of human workers (Rafindadi et al., 2022).

5) There is a lot of waste in the construction industry, such as material waste, energy waste, which have a negative impact on the environment (Arshad et al., 2017).

6) The lack of a standardized management system in the construction industry makes it difficult to guarantee the construction quality (Z. You and Wu, 2019).

Beyond the adverse effects these challenges have on development and competitiveness of the construction industry, they further impact the environment and society. Therefore, the construction industry needs to innovate and improve, specifically by strengthening technology applications to improve efficiency, ensure quality and safety, and reduce resource waste and environmental pollution.
The application of robotics in the construction industry is a potential solution to these deficiencies. And with the shortcomings of the construction industry and the advantages of robots, the reasons for the application of robots in the construction industry include:

1) Construction robots can perform tasks more quickly and improve construction efficiency (Ding et al., 2020).

2) Construction robots can replace part of the work that requires a lot of labor, thereby reducing labor costs as well as current worker shortages (Han et al., 2006).

3) Construction robots can perform tasks accurately and reduce errors, thereby improving construction quality (Goh and Goh, 2019).

4) Construction robots can perform tasks instead of humans in dangerous environments, ensuring construction safety and avoiding worker injuries (Davila Delgado et al., 2019).

5) The construction robot can record the construction process through sensors, cameras and other equipment, realize the visualization of the construction process, and facilitate later management and maintenance (Feng et al., 2015).

6) Construction robots can accurately control the amount and waste of materials, thereby reducing environmental pollution (Bock and Linner, 2016).

Therefore, the application of construction robots offers many benefits, they can improve construction efficiency, reduce costs, improve quality, ensure safety, visualize the construction process, and reduce environmental pollution. All these benefits offer great significance to the development of the construction industry and broader society.

1.3 Human-Robot Cooperation in Construction

Human-robot cooperation (HRC) is when humans and robots work together to complete tasks in a workplace or other setting. This cooperation can be physical or cognitive (Simões et al., 2022). HRC has many potential advantages, such as increased productivity, reduced labor intensity and risk, and reduced errors (Matheson et al., 2019). To achieve effective HRC, new technologies and algorithms need to be developed, as well as to design more intelligent and human-like
robots. In addition, adjustments in workflow, training and culture will be needed so that humans and robots can work better together.

Automated construction requires HRC because existing robotics technologies and algorithms cannot fully replace human roles and capabilities for the foreseeable future. Although robots can perform simple and repetitive tasks, they still present many challenges in complex and irregular environments, such as construction sites (Leng et al., 2023). In building construction, robots can perform some simple tasks, and for tasks that require complex judgment and a high degree of flexibility, human participation is required. In addition, robots also need human supervision and maintenance on the construction site to ensure their safety and stability. Therefore, human-robot cooperation can combine the advantages of robots and humans for more efficient and safer construction (R. Zhang et al., 2022). For example, robots can be responsible for repetitive and simple tasks, while humans can be responsible for more complex and judgment-requiring tasks. In addition, humans can monitor and guide the actions of robots, ensuring they meet safety and quality standards.

1.4 Schema and Data Needs for Robotics in Construction

A data schema refers to the methods and principles of organizing, designing, and managing data to ensure that the data can be stored, accessed and used effectively. Data schema includes the logical structure, physical structure and metadata of the data, as well as the processing rules and security controls related to the data (Tupper, 2011). Data schema is designed and implemented to support the integration, management, and analysis of data to meet business needs and objectives. Establishing a good data schema can ensure the quality, reliability, consistency and maintainability of data, and provide organizations with a basis for better decision support, enhanced application processes and improved efficiency (Loshin, 2010). Meanwhile, the data schema also needs to be able to be continuously optimized and upgraded to adapt to the changes and development needs of the organization.

When applying robots in the construction industry, it is necessary to understand the information and data needs for planning robots. Robot information and data can help the construction industry with task planning and task adjustment (Wolf et al., 2022). For example, when the construction activities involve the robot, the sequence and time of planning activities can be
determined according to the functions of the robot and the work efficiency of the robot. If the construction environment changes, such as obstacles or changes in the weather, it can be determined whether to make changes to the tasks performed by the robot based on the data of the robot. The construction industry needs to understand the functional characteristics of the robot, such as the shape, size, mass, workload, and freedom of movement of the robot. This data can help the construction industry plan suitable construction environments and tasks for robots to ensure that robots can work normally (Buchli et al., 2018). The power system of the robot has a great influence on the performance and ability of the robot. The construction industry needs to know the power supply type and battery capacity of the robot. This data can help the construction industry evaluate the energy consumption and battery life of the robot, to determine the scope and task to use of the robot (Gerling and Von Mammen, 2016). Understanding the performance, characteristics and limitations of robots can help the construction industry to better plan and manage construction tasks and improve construction efficiency and quality.

1.5 Research Goal

The goal of this study is to create a Construction Robot Schema (CRS) for construction planners to better understand and use construction robots at jobsites. It is a data structure with parameters used to collect and exchange robotics data based on the data needs of the construction domain and factors of human-robot cooperation (HRC) to facilitate planning, analyzing, and operating construction robots on a project site.

When manufacturers of construction robots introduce and demonstrate robots to the outside world, different manufacturers provide different types of data. For the construction domain, there is little consistency. In addition, when these robots are applied in the construction domain, some data are too detailed beyond the scope needed for the application, and some data that the construction domain requires to support planning are not readily available. In summary, the data provided by these manufacturers cannot currently meet the demand for robot data in construction planning. The CRS developed by this study is intended to begin to make up for this gap by organizing and establishing a set of robotic data and initial structure from the perspective of users (construction domain) to help the construction domain better plan the use of robots.
1.6 Research Questions:

1. What are the data needs of robots for the construction planning and operations on construction sites?
2. How should the data be organized for a schema?

1.7 Research Objectives

The study is based on the literature review method and achieves the goal through four steps including literature filter, systematic literature review, structure and defining parameters, and validation. For the literature filter, the objective is selecting the literature on the application or research of robots in the construction domain. For the systematic literature review step, the objectives are to identify the data needs for the robot and the HRC factors from the construction planning perspective. For the structure and define parameters step, the objective is to organize the parameters and categories. For the validation step, the objective is to validate the correct terms used, determine the reasonable relationships, and identify information missed.
Chapter 2 Literature Review

This chapter presents the literature review. It includes the introduction of robotics, robots in construction, human-robot cooperation in construction, and data needs for robotics. The content explores the definition and previous studies on these topics and their limitations. Based on a review of the literature, the study identifies the current knowledge gap which is the lack of a consistent structure covering the HRC factors and the robot data needs of the construction domain, used to collect and exchange data to facilitate analyzing and applying various construction robots. This knowledge gap is the motivation behind the research process.

2.1 Introduction of Robotics

A robot situated in the world is a machine that senses, thinks, and acts (Bekey, 1998). The robot is a physical agent that performs actions by manipulating the physical world and has effectors and sensors (Kunze et al., 2011). A robot is an automated device capable of performing pre-programmed tasks or through sensory perception and autonomous decision-making. Robots usually have mechanical structures, electronic components, sensors, and control systems, and are capable of physical manipulation, data processing, and human-robot interaction (Mukherjee et al., 2022). Robotics is currently defined as an interdisciplinary field of study involving the task areas of mechanical engineering, electrical engineering, computer science, and robot (Correll et al., 2013). There are several potential benefits to humans from the use of robots. Robots are relevant in the domain of production and manufacturing, providing increased productivity, flexibility, versatility and safety (Sherwani et al., 2020). The birth of robots and their advantages have brought convenience to human social life and production. The reason for these advantages is that robots have the potential to be applied in different industries.

For increased productivity, robots can operate continuously without breaks or interruptions (Agostini et al., 2011). This means they can potentially be utilized 24 hours a day, longer than manual operations. Robots can perform tasks with precision and without human error (Charalambous and Stout, 2016). They can continue to perform tasks in a highly consistent manner, so that each product is of the same standard and quality. In terms of providing flexibility, the robot can be easily reprogrammed to perform new tasks, which allows users to flexibly adjust the operation mode of the robot to adapt to changes in the production line and
different production needs (Andersen et al., 2014). Robotic systems typically consist of multiple 
modules that can be added or removed as needed to expand the robot's capabilities (Gilpin and 
Rus, 2010). Some mobile robots can move freely and perform tasks in different locations. This 
robot can move between different production lines to adapt to changing production needs.

Given the versatility of robots, some robots can perform multiple tasks at the same time (Bravo-
Palacios et al., 2020). This makes robots useful in busy production environments where they can 
perform multiple tasks simultaneously, increasing efficiency and productivity. Robots with 
perception functions can perceive the surrounding environment through technologies such as 
sensors and computer vision systems, and adapt to different tasks and contexts (Sanfilippo et al., 
2017). Some robots can use artificial intelligence and machine learning techniques to learn and 
adapt to new tasks and environments (Kunze et al., 2018). This allows the robot to continuously 
optimize how it operates, increasing efficiency and precision.

In terms of safety provided by robots, in certain dangerous or harmful production environments, 
robots can replace human workers, thereby reducing the risk of personal injury (Yang et al., 
2022). For example, robots can work in high temperature, high pressure or toxic gas 
environments without worrying about the safety of personnel. Robots can be equipped with 
sensors to perceive the surrounding environment, and to identify and avoid potential dangers in 
time (Vasic and Billard, 2013). For example, robots can be equipped with technologies such as 
lidar, cameras, and infrared sensors to identify and avoid obstacles and ensure safety. Robots 
equipped with sensors and monitoring systems can track their operating status and automatically 
identify and report any abnormalities. This allows potential security issues to be detected and 
corrected in a timely manner. Robots can use computer vision and machine learning techniques 
to predict and plan safety measures (Akinosho et al., 2020). For example, robots can forecast the 
movements of people and machines to adjust their actions accordingly to avoid potential hazards. 
Based on the advantages of robots and the conditions of the construction industry, these merits 
can also benefit construction projects. With the development and application of robots, robots 
have been focused on the construction industry, and discussions and research on them have 
gradually thrived.

In 1961, the first industrial robot Unimate was installed in General Motors' factor (Gasparetto 
and Scalera, 2019). After that, robot technology was brought to Japan by the United States in
The late 1970s and 1980s were a rich period of industrial-driven development in Japan. Due to labor shortages caused by the aging population and the influx of young workers into high-tech industries, many Japanese companies, such as Shimizu Corporation and Takenaka Corporation, invested in automation and robotics to develop robots for various construction tasks (Bock and Linner, 2016). However, so far, the construction industry is still one of the industries with the lowest degree of digitization and automation (Oesterreich and Teuteberg, 2016). Promoting robotics in construction benefits the development of the construction industry.

### 2.2 Robots in Construction

In previous studies, many researchers have devoted themselves to defining construction robots or developing robot schemas. In terms of the definition of construction robots, Whittaker (1986) considers that construction robots are a kind of robots that construct, meaning to build, they show flexibility in the roles they play and the equipment they use, and they perform complex tasks that previously required human control. In addition, Lee et al. (2007) define a construction robot as a field robot that executes commands while operating in a dynamic environment with changing structures, operators, and equipment. Yahya et al. (2019) pointed out in the paper that a construction robot is defined as a reprogrammable multifunctional manipulator designed to move materials, parts, tools, or special equipment through variable programmed movements to perform the production processes that occur in the construction industry’s various tasks. Apart from this, it is interesting that, as some researchers believe in the domain of construction, there is no consensus on a clear definition of construction robots (Pan et al., 2020). These researchers define construction robots from different aspects. However, these definitions are too general to help users better understand construction robots. The construction industry needs a new way to understand robots to better apply robots in projects.

The reason for applying robotics in construction is that construction robots have the potential to revolutionize and transform the construction industry and have a positive impact on the construction industry (Pan et al., 2018). Robots can be used for dangerous, laborious jobs. For example, bricklaying and paving are repetitive and labor-intensive, and despite repetitiveness, bricklaying can still lead to construction accidents. Bricklaying robots can perform this type of repetitive work in place of workers (Maali Esfangareh, 2022). Robots are especially useful on
dirty and dangerous construction sites. For example, when a worker paints the wall upright for a long time, it will cause harm to the worker's body and eyes. Therefore, painting robots can help humans perform painting work and ensure the physical safety of workers (Cousineau and Miura, 1998). Inspecting tunnels, bridges, roads, and pipelines is one of the biggest challenges facing engineers due to aging, environmental factors, increased loads, changes in usage, human/natural damage, insufficient or poor maintenance, and delayed repairs. Inspection robots can replace humans to perform inspections in these dangerous and human-inaccessible areas (Lou et al., 2019). The participation of construction robots can help the construction industry reduce the workload of workers, improve worker safety, and reduce the risk of accidents. However, when developing robotics in the construction industry, the role of human workers in robotic applications also needs to be considered.

Recent research on construction robots has conducted in-depth research on the specific application and performance measurement of robots in construction activities. For example, Zandavali and Jimenez Garcia, (2019) established a machine learning model based on image-to-image translation to study the accuracy of brick placement by bricklaying robots at work. C. Lee and Chu (2019) developed an obstacle-climbing robot with three modules mainly to clean the windows on the exterior walls of buildings. The paper evaluates the robot's performance based on the size of the obstacle and the time it takes the robot to cross the obstacle. Quintana et al. (2021) introduced an autonomous navigation monitoring robot named ComfBot. Since the robot's task is to monitor the comfort of the building, the robot includes a variety of sensors to collect data such as temperature, humidity, light, etc. in the building. The performance of the robot is analyzed by evaluating its navigation ability and data collection ability. However, these studies focus on the applications and performance of robots in construction. These studies have varied performance measurements of construction robots and use different structures or methods to describe robots. They don’t have a consistent structure or method for describing construction robots and their performance.

Apart from the construction robots that are under development, there are many construction robots that are already in use today that can help the construction industry with different tasks. PictoBot is an intelligent painting robot that can work safely near human colleagues, performing repetitive and cumbersome painting tasks at high elevations. The robot's modular system
includes: a mobile robot, a long-distance jack-up mechanism, an industrial robot arm, an airless paint pump, paint head system, and computer control system. Pictobot is able to achieve higher spray transfer efficiency compared to manual spraying, resulting in less paint dust, paint waste and human exposure to harmful chemicals (E. Asadi et al., 2018). Semi-Automated Mason 100 (SAM 100) is an intelligent construction robot developed and manufactured by the American company Construction Robotics. Its main function is to lay bricks automatically. The SAM 100 bricklaying robot has a high-precision sensor and computer vision system, which can identify and locate the position on the wall and the size of the bricks according to architectural drawings and 3D models, thereby automatically laying bricks. The robot is also equipped with an adaptive control system, which can adjust the way of laying bricks according to the characteristics of the size, shape and color of the bricks, ensuring the accuracy and consistency of the masonry effect (Ding et al., 2020). Jaibot is an intelligent construction robot developed by German company Hilti whose main function is to automate concrete drilling. Jaibot automates drilling using laser scanning and computer vision to identify concrete surfaces and determine drilling locations and depths based on architectural drawings and 3D models. The robot is equipped with a high-precision positioning system and an adaptive control system, which can realize a high-precision and high-efficiency drilling process, and can automatically adjust drilling parameters to adapt to different concrete densities and hardness (Xu et al., 2022). To facilitate users to better understand these robots, their manufacturers provide different types of parameters to demonstrate the performance of the robots. However, there is no consistent data structure that can be used to describe different robots, and some parameters provided by manufacturers cannot fully help the construction industry understand and apply robots.

2.3 Human-Robot Cooperation (HRC) in Construction

In the construction industry, integrating robots and humans is an imperative trend (Brosque et al., 2020). Human-Robot Cooperation is the study of robotic agents and humans working together. The two achieve common goals through communication and coordination. HRC requires joint attention, information exchange, task sharing, and collaboration between human and robotic agents performing work to be efficient (Mutlu et al., 2013). HRC has a wide range of applications in manufacturing, medical, home, office, space exploration, and, more recently, in construction (Hoffman and Breazeal, 2004). HRC is an interdisciplinary research field which
includes robotics, human-computer interaction, artificial intelligence, and cognition (Bauer et al., 2008). When developing and applying HRC, researchers found that HRC has many advantages, which are also the reasons for its application in different domains.

The merit of HRC is that it combines the strength and efficiency of robots with the high dexterity and cognitive abilities of humans into a flexible overall system. This combination facilitates the safe, robust and efficient realization of the target (Lenz and Knoll, 2014). In some complex production tasks, the technology and ability of robots are still limited, while humans have rich experience and flexibility and can adapt to different situations, thus making production more efficient (Villani et al., 2018). The advantage of human-robot cooperation is to complement the advantages of robots and humans. Robots can complete some operations that require high precision and high speed, while humans can complete some operations that require flexibility and judgment (Wilson and Daugherty, 2018). Robots can ensure the consistency and precision of the products produced, while human assistance can carry out inspection and quality control of the products, thereby improving the quality of the products (Wang et al., 2020). Communication and cooperation between humans and robots bring high efficiency, high quality, and safety to production, which means that these advantages can also benefit the construction industry that relies on production. The participation of robots reduces the production burden and safety risks of humans in construction, and human assistance makes up for the flexibility and experience of robots. In addition to the advantages brought by HRC to the construction industry, the application of HRC in the construction industry also depends on the limitations and deficiencies of the industry.

In addition to the advantages of HRC in construction, the application of HRC in construction also depends on the automation limitations of the construction industry at this stage. The degree of automation in the construction industry is low, and as previous attempts at full automation in the construction industry have failed, the robotics and automation in construction has shifted from full automation to semi-autonomous HRC (Stumm et al., 2017). The craftsmanship and engineering methods of the construction industry are usually relatively traditional, and the lack of application of digital technology and automation equipment means that the application of robots in construction is still limited (Feldmann, 2022). Many construction sites still require manual operations and a lot of human intervention, so human workers are needed when robots
are faced with these tasks (Kadir et al., 2018). The application of robotics in the construction industry still faces some challenges, such as the research, design, and production costs of robots are still high, which may make it difficult to use highly autonomous robots on a large scale in the construction industry (Nagy et al., 2021). In addition, the operation and maintenance of robots also requires operators with professional skills and rich knowledge. Such positions cannot be separated from the addition of human workers (Adami et al., 2021). Based on the advantages of HRC in construction and the limitations of automation in the construction industry, factors related to HRC must be considered in the development of construction robots.

According to the understanding of HRC, many researchers are devoted to the research of HRC in construction. Liang et al. (2021) reviewed the development of HRC over the past 20 years and classified HRC into five levels: preprogramming, adaptive manipulation, imitation learning, improvisatory control, and full autonomy. Subsequently, the current knowledge gap and future development directions are proposed according to the development trend of HRC. Liu et al. (2021) focus on coordination and security issues in HRC. They developed a framework for worker-centric collaboration. The research uses wearable electroencephalographs to capture workers' brain waves, which can be used to assess workers' cognitive load on the task and adjust the robot's performance accordingly. S. You et al. (2018) developed an immersive virtual environment using virtual reality technology to simulate the work of HRC in construction. Subjects and robots perform bricklaying work in a virtual environment. The study assessed and examined the perceived safety of working with the robot through feedback from the subjects. Regarding HRC in construction, these studies have focused on the factors related to HRC including the level of autonomy of the robot, the contribution of both humans and robots in cooperation, and the corresponding safety issues. They study and understand HRC in construction from different perspectives, but there is no consistent structure to integrate these factors.

2.4 Schema and Data Needs for Robotics in Construction

Data schema refers to the overall structure and design principles used to manage and organize data, aiming to achieve data consistency, integrity, security, availability and scalability, and to meet application requirements and performance requirements for data access (Siddiqa et al., 2016). Database schema refers to 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 schema can help different systems and applications share and exchange data better to support data integration and sharing. By studying the theory and method of database schema, it can be better facilitated data sharing and exchange, so as to promote the cooperation and integration between different applications (Vanlande et al., 2008). In addition to being applied to the domain of data and databases, patterns are also applied to the construction domain. The most typical research and application of the schema in the construction industry is Industry Foundation Classes (IFC).

IFC is an open data schema for Building Information Modeling (BIM). IFC is designed to serve as a neutral, object-based standard for the exchange of building and infrastructure information to facilitate interoperability between different software applications (Panteli et al., 2020). The IFC data schema is based on an entity-relationship model, using an object-oriented approach to describe the geometric and non-geometric properties of building and infrastructure models (Hu et al., 2022). The IFC data schema defines a set of concepts and rules that describe the structure and content of building and infrastructure models, and the relationships between building and infrastructure models and other models (Theiler and Smarsly, 2018). The IFC data schema is widely used in the architecture, engineering, and construction industries to provide a standardized data format for BIM (Dhillon et al., 2014). IFC helps multiple actors, including architects, engineers, building owners and operators, better manage construction and infrastructure projects. IFC also improves interoperability between BIM software, reducing development costs and time for building and infrastructure projects (Costin et al., 2018). The successful development and application of IFC reflects the great demand for data and data exchange in the construction industry. Then when the construction industry applies robots, it also needs a schema to help the construction industry collect and exchange robot data to better analyze and apply construction robot.

There are many researchers working on developing robot schemas to analyze and develop robots. Hoffmann et al. (2010) developed a body schema for humanoid robots based on biological body
representations to describe and study the motion of such robots. Based on the navigation of mobile robots, Arkin (1989) described and studied the trajectory of mobile robots using the motor schema. Weitzenfeld et al. (1998) propose a neural-based schema system for developing and executing autonomous robots in simulation and the real world. In these past studies, for the development or application of schema, some are only aimed at a specific robot, some are aimed at specific functions of the robot, and some lack descriptive functions. However, for the construction domain, a descriptive robot architecture is needed for users to better understand and apply construction robots. At the same time, based on the wide variety of construction robots in the construction domain, the schema needs to cover construction robots broadly and comprehensively.

When robots are applied in the construction industry, relevant data support of robots is needed. Descriptive data about the structure, function, and behavior of construction robots can be incorporated into building information models. These data can be used to build detailed digital models, so as to better realize the digitization and automation of buildings and construction (F. Zhang et al., 2022). In the construction site, interaction and cooperation between robots or between robots and human workers are required, and robot data can provide support for interaction and collaboration between robots (Ajoudani et al., 2018). Meanwhile, robots or robot operators need to make corresponding decisions and actions according to different tasks and environments, and the data of robots 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). Therefore, the robot data supports the construction industry to analyze and apply construction robots in many aspects.

The research and application of robot technology is inseparable from the support of relevant data. Many researchers have demonstrated through their research that the analysis and application of construction robots in different aspects require different robot data support. Xu and de Soto (2020) mentioned in the paper that the unstructured and dynamic characteristics of the construction site bring challenges to the localization and navigation of the robot. 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. Bock et al.
(1996) introduced a robot assembly system including an offline database and a robot database. The system is used to plan complex assembly tasks and generate robot motion. These databases included in the system contain data such as architectural design, original installation parts, and motion planning of construction robots. They suggest that the database must model all this data to analyze the robot environment and robot activity. Zhou et al. (2022) present a collision avoidance system developed for a construction robot manipulator. The system stores the movement trajectory data of the human arm into the data pool and classifies the data into pattern groups according to the similarity of movement patterns, to promote the machine learning of the robotic manipulator for different pattern groups. Previous researchers' research on robot data focused on specific robots or specific functions of robots, but research on the classification and structuring of different data types of construction robots is lacking. So, there should be a robot schema which is used to integrate, manage, and structure the needed data from robots.

2.5 Summary

This chapter includes studies on robotics, construction robots, HRC in construction and data needs for robots. The construction industry has noticed on the advantages of robotics, and more and more research has focused on the application and development of construction robots. However, the previous data structure of construction robots lacks the combination of construction operations and robotic elements, so that it is hard to conduct data collection of construction robots in more detail based on the current stage of construction. In addition, when describing the construction robot and its corresponding performance, there is a lack of a consistent structure to describe the robot. Based on the advantages of HRC and the limitations of automation, complicated craftsmanship and participations requirements of human workers in the construction industry, this consistent structure also needs to include HRC factors. In terms of data needs for robots, previous data research and schema research focused on specific robots or specific functions of robots, and few people focused on the studies of classification and structuring of different data types of various construction robots. Therefore, there should be a robot schema containing a consistent structure can be applied on diverse construction robots for collecting and exchanging data based on the data needs from the construction domain to better analyze and apply construction robots.
Chapter 3 Methodology

The goal of this study is to create a Construction Robot Schema (CRS) for construction planners to collect and exchange robotics data based on the data needs of the construction domain and factors of human-robot cooperation (HRC) to facilitate better understand and use construction robots at jobsites. Figure 1 shows the process of CRS development through a specific literature review. The method of this study is divided into four steps, which are literature filter, systematic literature review, structure and define parameters, and validation.

![Figure 1 CRS Development Process]

Table 1 summarizes the four steps and their corresponding objectives and tasks. This study uses the method of literature review to index 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. Finally, a qualified CRS is obtained through validation. This chapter describes in detail the operation of each step and how to achieve the goal through these steps.
<table>
<thead>
<tr>
<th>Development Step</th>
<th>Objective</th>
<th>Task</th>
</tr>
</thead>
<tbody>
<tr>
<td>Literature Filter</td>
<td>➢ Select the literature on the application or research of robots relevant to the construction domain.</td>
<td>Access to Web of Science database.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Search keywords.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Filter by published year and domain.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Manually filter by scanning abstract.</td>
</tr>
<tr>
<td>Systematic Literature Review</td>
<td>➢ Identify the data requirements of construction for the robot.</td>
<td>Confirm categories.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Upload literature to Nvivo.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Review literature.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Code the literature to a specific confirmed category.</td>
</tr>
<tr>
<td>Structure and Define Parameter</td>
<td>➢ Organize parameters into a structure and relationships.</td>
<td>Classify parameters into categories.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Define the parameter.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Exemplify the parameter.</td>
</tr>
<tr>
<td>Validation</td>
<td>➢ Correct terms used.</td>
<td>Validate CRS through robot constructability simulation experiment.</td>
</tr>
<tr>
<td></td>
<td>➢ Determine the reasonable relationships.</td>
<td>Validate CRS by interviewing experts from the construction industry and construction research.</td>
</tr>
<tr>
<td></td>
<td>➢ Identify information missed.</td>
<td>Validate CRS through robot database implementation.</td>
</tr>
</tbody>
</table>

### 3.1 Literature Filter

To advance the first research question raised by this study regarding the data needs for robots from the construction domain the study reviewed and captured the relevant literature to explore the data needs of robots for the construction domain. At the beginning, the study needed to filter the papers which were applying, analyzing, or developing construction robots.

The study used literature databases to filter past papers. The database used in this study is Web of Science (WoS). The database platform can provide access to six online indexing databases, including academic journals, and conference proceedings. The research considers that during the development of the CRS, parameters need to meet the requirements from the construction domain of robots. Therefore, to cover as much literature as possible related to the indexing requirements the keywords selected in this study are robotics and construction.

Before filtering the papers, it is necessary to determine the scope of the selected papers. The scope is determined according to two parts, the first part is the date of publication of papers and the second is the domain. The study selected those papers published from 2018 to 2022. The
reasons for selecting papers in this period are that there was a forecast for increasingly developing automation in construction in the past five years (Bock, 2015) and another reason was that the study needed to focus on the state-of-art achievements of construction robots. The domain chosen for the study before filtering the papers is construction applications of robotics. Based on such considerations, when indexing papers, the relevance of construction tasks or applications ranks at the highest level compared to other domains for considering parameters.

To make the literature screening process more clearly displayed, the study introduces the details of this process in the following. Figure 2 shows the detailed process of literature filtering. The text in the box indicates the steps of the operation, and the numbers indicate the results of the number of literatures displayed by WoS. To capture the scope proper papers, that are the analysis, development and application of construction robot, keywords were used, specifically robotics and construction. When indexed with these two keywords, WoS shows 6,225 papers related to the keywords. Based on the need to index the most advanced research results of construction robots, the publication period of selected papers in WoS for this study is locked from 2018 to 2022. In addition, since some papers were published in other languages, the study constrained the language of the papers in English to facilitate review. Based on these two criteria, WoS showed that the remaining 2,206 papers met the requirements. At the same time, WoS also provides a screening function for research areas. By reviewing the research areas of these selected papers, the study found that some of the research areas covered by these papers are irrelevant to this study, such as agriculture, biology, and chemistry. Therefore, this study further
constrained the research area through WoS to construction. After this step, WoS narrowed to 126 papers.

To ensure the search parameters were not overly narrow, additional keywords were searched in the focused domain to check whether for missing papers. The original keywords were supplemented with synonyms, such as replacing robotics with robot and robot technology. Similarly, construction was supplemented with architecture and building construction. Another method used was the addition of 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. The criterion for the end of this step is that when no new papers appear after three consecutive newly input parameters or keyword are automatically filtered by WoS, this step can be ended. After this step, WoS identified 293 papers. Finally, it is necessary to manually filter the abstracts of these papers to eliminate papers that are not relevant to the research.

The specific method of manual filtering is to exclude papers that do not meet the requirements from the selected papers by scanning the abstracts. After automatic filtering from WoS based on keywords entered, period of publication and domain confirmed, the displayed papers need to be manually screened. Some papers only mention robotics and construction but are not the subject of the paper. In some instances, the meaning of “construction” used in the paper does not match the required meaning of construction industry, resulting in the filtered papers not related to the domain of construction but often the assembly of the robots or something similar. In addition, during the process of manual filtering of papers, this study also considers the number of citations of selected papers. Based on the consideration of the scientific research value of some papers, this study decided that the number of citations of selected papers published before 2022 must be greater than or equal to one, and the number of citations of papers published after 2022 can be zero. The reason for this decision is that the papers published before 2022 have enough public time, based on the consideration of their research value, the papers published in this period with zero citations need to be filtered out. However, papers published after 2022 have not had time to be cited due to the limited publication time, so papers with zero citations can be retained. Ultimately, 279 eligible papers were considered.
3.2 Systematic Literature Review

Through a systematic literature review, this study was able to extract the parameters used to build the data structure from the selected articles. The idea of a systematic literature review is to gather available evidence from the literature and then evaluate the evidence against predetermined criteria (Linnenluecke et al., 2019). After the papers are filtered, all the qualified papers are saved. Before literature reading and parameter extraction, several categories for these parameters to be extracted were defined. The purpose of this is to facilitate the identification and classification of data from these papers, provide a clear direction for extracting parameters, and facilitate the classification and structure of parameters in subsequent steps.

In total, four overarching categories are defined in the study, the first being the Ontological Property of construction robots. In ontology, a robot is a device composed of many mechanical parts (Prestes et al, 2013). In the study, the Ontological Property includes the parameters of the robot body, manipulator, and various mechanical hardware as well as related functional parameters needed for a functioning robot. The second is the Operational Requirement of construction robots. Operational Requirement refers to the strict constraints necessary for a robotic system to complete a mission (Smart, 2007). Operational Requirement in the study includes such parameters as necessary environmental conditions, necessary construction site supports or necessary human assistance. The third is the Activity performed by construction robots. The Activity in the study refers to the construction activities in which the robot participates, which is the function that the construction robot exhibits while performing the prescribed task. Activity contains parameters related to the construction tasks in which the construction robot is involved. The fourth is Safety related to construction robots. The study chose Safety as the last category because the use of robots in construction has the potential to reduce exposure to hazards, increase worker safety, and benefit the construction industry (García de Soto et al, 2022). Safety includes parameters that describe construction robots helping humans stay away from danger and the cautions when human works or operates robots. These four categories provide an initial and high-level grouping for the corresponding parameters, which focus on aspects of construction robots.

After determining the categories, these qualified papers were imported into Nvivo. Nvivo is a qualitative data analysis software that helps researchers analyze unstructured or qualitative data
such as interviews and journal articles (Dhakal, 2022). Before browsing papers, the study defined these four categories into Nvivo as coding categories. When reading one of the identified papers housed in the Nvivo database, it is possible to code text in the article corresponding to the named categories. When reviewing each paper, the study focused on the content of the paper that mentions construction robots and corresponding attributes. This content often appears in the chapters on methodology, case studies, and validation. Based on the aspects of construction robots that these articles present, these aspects are captured, grouped, and summarized into corresponding parameters.

After reading, coding, and categorizing the selected papers, this study obtained a statistical result through Nvivo. Among the 279 papers obtained from WoS, there were 183 research papers and 96 review papers. In this study, research papers refer to papers that have developed, analyzed, and discussed the functions, performance, and applications of construction robots. Review papers refer to the introduction, discussion, and summary of various past research on construction robotics. The study also obtained the number of papers indexed in each category from Nvivo. Among them, 113 papers mentioned ontology property, 50 papers mentioned operational requirement, 147 papers mentioned activity, and 47 papers mentioned safety. It should be noted that many papers are classified into multiple categories due to the research content, so the total number of papers in the four categories is greater than 279.

Table 2 Number of Papers in Different Categories

<table>
<thead>
<tr>
<th>Categories</th>
<th>Number of Papers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ontological Property</td>
<td>113</td>
</tr>
<tr>
<td>Operational Requirement</td>
<td>50</td>
</tr>
<tr>
<td>Activity</td>
<td>147</td>
</tr>
<tr>
<td>Safety</td>
<td>47</td>
</tr>
</tbody>
</table>
3.3 Structure and Define Parameters

The study has structured the acquired parameters at this step. According to the paragraph of the paper to which the parameter belongs and the category to which the paragraph belongs, the parameter is classified into the corresponding category. The parameter has been defined and based on the parameter's introduction in the paper, the study has conceptualized the paragraph as a definition of the parameter. To facilitate users' further understanding of this parameter, the study needed to extract the application of this parameter in the paper as an example and add it to the structure. Finally, the reference of this parameter was given to facilitate the user to quickly guide the example paper of the parameter. After completing the above steps, drew all the information into the table to show the structured parameters, which was the preliminary CRS.

To facilitate the understanding of the parametric structured process, this study introduces the details of the structured practical process. CRS contains four categories, which are ontology property, operational requirement, activity, and safety. The study located paragraph in selected papers that mentioned and described this parameter and extracted this parameter from the paragraph. There were two criteria when the study categorized this extracted parameter:

1) Review the specific category of which the paragraph contained the parameter was coded.

2) Review the requirements of the category, and the extracted parameter must fully meet the requirements of the category for the belonging parameters.

After structuring parameters, the preliminary data structure has 4 categories and 35 parameters with corresponding definitions. Among them, the ontology category contains 19 parameters, the operational requirement category contains eight parameters, the activity category contains three parameters, and the safety category contains five parameters.

3.4 Validation

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 three parts including database testing, simulation, and expert interviews. The role of these three steps is to validate the following aspects of the CRS data structure (Di Zio et al., 2016):
1) Correct use of terminology, data type, parameters and categories when naming schema elements. (Validate through interview)

2) The parameters in the data structure are correctly categorized. (Validate through interview and database testing)

3) The definition of parameters can clearly explain the parameters. (Validate through interview)

4) Usability of parameters. (Validate through interview and simulation)

5) The data structure is comprehensive, including all important parameters. (Validate through interview and simulation)

6) The data structure does not contain parameters that are not relevant to the scope of the study. (Validate through interview)

If the CRS data structure is to be modified after validation, the modification methods include the following three changes:

1) Modify the terms, definitions, and categories of parameters in the data structure.

2) Add new parameters or categories,

3) Delete existing parameters or categories.

When developing acceptance criteria for revisions, the study needs to review the scope of the study to ensure that every change is inside the scope. This study develops a CRS data structure based on the requirements of robots in the construction field and the factors of human-robot cooperation, which is used to collect and exchange data about construction robots, to help the construction field to develop, analyze and apply construction robots. Based on this scope, the modification criteria of the data structure include the following two aspects:

1) Modification opinions must come from knowledge and experience in the development, analysis, and application of robots in the construction site or research.

2) When making modifications, it is necessary to be able to find corresponding literature or cases of applications and experiments to support changes.

After the validation process, the study added 6 new parameters and deleted 2 parameters. In total, the CRS has 4 categories and 39 parameters.
3.5 Summary

This chapter demonstrated the four steps of this study. The study filtered and selected the eligible papers published from 2018 to 2022 by accessing to Web of Science database. These papers introduced the construction robotics in practical applications or relevant research. After collecting these papers, the study reviewed the papers by using Nvivo to identify the data needs from the construction domain and extracted the parameters from the corresponding paragraphs of these papers. To structure these parameters, the study categorized and defined each parameter, provided corresponding data type, and exemplified each parameter to facilitate understanding each parameter and the corresponding definition. In terms of validation, the study conducted database implementation validation, constructability validation and expert interview validation to correct terms used, determine the reasonable relationships, and identify missed information. As a result, the data needs of the CRS are formed in a table which can be further demonstrated in next chapter with the detailed validation process.
Chapter 4 Results and Validation

After literature filtering, systematic literature review and structuring parameters, the study obtained a preliminary construction robot schema (CRS). This chapter contains the demonstration of the CRS and the validation process. The CRS is presented in the form of a table, which contains category, parameter, definition, example, and reference. While in the validation process, the study has corrected the terms used, determined relationships, and identified information missed through the initial schema development.

Figure 3 Categories of CRS

Figure 3 shows the categories included in CRS. For each category, the parameter requirements defined by this study, based on their definition:

1) Ontological Property: It contains the parameters of the functional parameters needed for a functioning robot, such as the robot body, manipulator, and various mechanical hardware.

2) Operational Requirement: It includes the parameters necessary to address environmental conditions, necessary construction site resources, or necessary human assistance.

3) Activity: It contains parameters related to the construction tasks in which the construction robot is involved.

4) Safety: It includes parameters that describe construction robots’ attributes or constraints to ensure humans stay away from danger and cautions when human works with or operates robots.

After categorizing parameters, this study defines each parameter. According to the paragraph of the parameter in the selected paper, the paragraph is summarized and refined, and the core information is extracted for each parameter. Then, to facilitate the understanding of the
parameters and their definitions, this study exhibits the data type for each parameter and finds the corresponding examples of construction robots to further explain the parameters. The Appendix C shows the slides used in the interview. 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, edit the source paper of the parameter as a reference to help users trace the source of the parameter.

4.1 Construction Robot Schema

The paper shows the contents in the CRS in the form of tables. As shown in Table 3, four categories are included in this data structure, which are ontology property, operational requirement, activity, and safety. According to the source paper of the parameter and the coded category in which the parameter text appears, the parameter is classified into the corresponding category. For each parameter, the data structure gives a concise definition. At the same time, to assist users in understanding each parameter, the data structure shows an application case of an actual robot and corresponding data type. Finally, the source of the definition is given in the reference section to facilitate the literature review of the definition.

To correctly match 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 database (Chamberlin, 2012). 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.”
<table>
<thead>
<tr>
<th>Table 3 Construction Robot Schema</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Category</strong></td>
</tr>
<tr>
<td><strong>Name</strong></td>
</tr>
<tr>
<td><strong>Weight</strong></td>
</tr>
<tr>
<td><strong>Dimensions</strong></td>
</tr>
<tr>
<td><strong>Power Source</strong></td>
</tr>
<tr>
<td><strong>Run Minimum</strong></td>
</tr>
<tr>
<td><strong>Productivity</strong></td>
</tr>
<tr>
<td><strong>Precision</strong></td>
</tr>
<tr>
<td><strong>Accuracy</strong></td>
</tr>
<tr>
<td><strong>Load Capacity</strong></td>
</tr>
<tr>
<td><strong>Manipulator</strong></td>
</tr>
<tr>
<td><strong>Degree of Freedom</strong></td>
</tr>
<tr>
<td><strong>Coordinate Reach</strong></td>
</tr>
<tr>
<td><strong>Range of Motion</strong></td>
</tr>
<tr>
<td><strong>Manipulator Installation Position</strong></td>
</tr>
<tr>
<td><strong>Lifting Capacity</strong></td>
</tr>
<tr>
<td><strong>End Effector</strong></td>
</tr>
<tr>
<td><strong>Internal Sensor</strong></td>
</tr>
<tr>
<td><strong>External Sensor</strong></td>
</tr>
<tr>
<td><strong>Mobility</strong></td>
</tr>
<tr>
<td><strong>Speed</strong></td>
</tr>
<tr>
<td><strong>External Sensor</strong></td>
</tr>
<tr>
<td><strong>Autonomy Level</strong></td>
</tr>
<tr>
<td><strong>Navigation</strong></td>
</tr>
<tr>
<td><strong>Number of Operator</strong></td>
</tr>
<tr>
<td><strong>Number of Coworker</strong></td>
</tr>
<tr>
<td><strong>Operator's Responsibility</strong></td>
</tr>
<tr>
<td><strong>Coworker's Responsibility</strong></td>
</tr>
<tr>
<td><strong>Site Preparation</strong></td>
</tr>
<tr>
<td><strong>Grade</strong></td>
</tr>
<tr>
<td><strong>Humidity</strong></td>
</tr>
<tr>
<td><strong>Number of Operator</strong></td>
</tr>
<tr>
<td><strong>Number of Coworker</strong></td>
</tr>
<tr>
<td><strong>Activity Type</strong></td>
</tr>
<tr>
<td><strong>Material</strong></td>
</tr>
<tr>
<td><strong>Task</strong></td>
</tr>
<tr>
<td><strong>Emergency Stop</strong></td>
</tr>
<tr>
<td><strong>Safe Distance</strong></td>
</tr>
<tr>
<td><strong>Objective Detection</strong></td>
</tr>
<tr>
<td><strong>Safety Barrier</strong></td>
</tr>
<tr>
<td><strong>Minimum WorkspaceP</strong></td>
</tr>
</tbody>
</table>
According to statistics, CRS contains four categories and 39 parameters. Among them, the ontology category contains 22 parameters, the operational requirement category contains 8 parameters, the activity category contains 3 parameters, and the safety category contains 6 parameters.

### 4.2 Database Schema Validation

For the database validation, CRS needs to be validated from the database schema development for the construction robot. Implementing the CRS structure into an instance of a database can facilitate the data collection of construction robots, which also ensures that CRS can support the design of the construction robot database and corresponding data needs. After validation of the database schema, a qualified CRS needs to meet the requirements for database establishment.

To validate the CRS by database validation, the study created a data sheet through Microsoft Excel to conduct construction robot data collection. In the data sheet, using the parameters from CRS to indicate the data needed. As shown in Appendix A, the data sheet includes various types of construction robots which are from different robot manufacturers or construction robot literature. As for the constraints of the data sheet, the study add unit for each parameter. If a parameter has a specific unit, it means the cell behind the parameter needs to be a numeric value. If a parameter does not have a unit, it means the cell behind the parameter will be text. In addition, for a specific robot, if the study currently cannot find data corresponding to a parameter, the cell of this robot in the data sheet needs is temporarily filled in as a question mark to indicate that this data is currently unavailable. If a robot does not have this data according to the parameter, the cell of this robot in the data sheet indicates ‘None’. For example, a fixed robot does not have speed data, so this cell should be filled in as ‘None’.

After collecting data from different construction robots, the study created a database based on these robots’ collected data. The tool for establishing construction database is Structured Query Language (SQL). SQL is a standard language for managing relational databases and is widely used in various types of data management systems. SQL can be used to perform various operations such as querying, inserting, updating, and deleting data from a database, as well as creating, modifying, and deleting table objects (Bjeladinovic et al., 2020). The database
establishment validation aims to test the parameter usability, relational rationality, and parameter comprehensiveness. As a result, so far, CRS has not limited the establishment of the database.

### 4.3 Simulation Validation

For the simulation validation, the CRS is validated through the application of sample robotic data for analysis of constructability of the construction robot. In the practical validation operation, this research demonstrates the CRS data structure’s applicability and use to a researcher in our research group who is doing a constructible simulation of construction robots. Through this part, this study expects that the CRS can meet the data requirements of the simulation experiment for the robot. For now, the selected construction robot, the Canvas painting robot, is studied and the selected experimental method is the simulation experiment. When the simulation experiments obtain data 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.

The simulation experiment needs to validate the accessibility of the robot. When the simulated robot passes through the passage or the entrance, the length, width, and height data of the robot are required to support it. Such data is already 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 is also simulated to pass through temporary floors in the construction environment. In an unstructured construction environment, temporary facilities such as temporary floor cannot allow heavy objects to pass through, so the weight of the robot is required for simulation. The 'Weight' parameter is also covered by the CRS.

When the simulation experiment verifies the area of the wall that the Canvas robot can touch, the required data cannot be provided by the CRS. Since the distance between the mobile robot Canvas and the wall can be artificially determined, therefore 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 include 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 et al., 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.

### 4.4 Interview Validation

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 implementing robots and roboticists from relevant construction robotics firms. The interviews will present the CRS structure and parameters in small parts. Then in the open section, respondents will be asked for their feedback regarding the scope, clarity, and comprehensiveness. The slides used in the interview are included in Appendix C.

The first interviewee was an expert from Construction Robotics whose professional experience came from developing the Semi-Automated Mason (SAM) 100 and Material Unit Lift Enhancer (MULE) robots. Referring to SAM as an example, the modification suggestions given were in the safety section. He pointed out that the wide sides of the SAM robot have metal doors. When the SAM is performing tasks, the two doors are locked by the operator to separate the SAM from the worker. This external physical security measure is also applied to other robots. For example, the CyBe 3D printer needs to be installed a fence after arriving to a specific work position, to separate the robot and the worker. Based on this, this research refers to this new parameter belonging to safety as 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.
The second interviewee has extensive experience in the application of various construction robots. He 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. His suggestion is that the construction planners can consider buying, leasing, or giving up the use of the construction robot according to the price. Another suggestion is 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 chose to reject 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. He also suggested to add a parameter about the ability of robots for reporting the position to construction teams. This ability has included in the navigation parameters, so the study decided to reject this change.

However, for another part of his suggestion, he said that the sensor in the ontology attribute cannot well 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 construction site and had literature supports, which conformed to the criteria of modification acceptance, the study decided to accept the three new parameters.
4.5 Results of Validation

Table 4 New Parameters

<table>
<thead>
<tr>
<th>New Parameters (Category)</th>
<th>Reason</th>
<th>Validation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coordinate Reach (Ontological Property)</td>
<td>From construction robot application research and with literature support.</td>
<td>Simulation</td>
</tr>
<tr>
<td>Range Of Motion (Ontological Property)</td>
<td>From construction robot application research and with literature support.</td>
<td>Simulation</td>
</tr>
<tr>
<td>Manipulator Installation Position (Ontological Property)</td>
<td>From construction robot application research and with literature support.</td>
<td>Simulation</td>
</tr>
<tr>
<td>Safety Barrier (Safety)</td>
<td>From construction site robot application and with literature support.</td>
<td>Interview</td>
</tr>
<tr>
<td>Internal Sensor (Ontological Property)</td>
<td>From construction site robot application and with literature support.</td>
<td>Interview</td>
</tr>
<tr>
<td>External Sensor (Ontological Property)</td>
<td>From construction site robot application and with literature support.</td>
<td>Interview</td>
</tr>
</tbody>
</table>

Table 5 Deleted Parameters

<table>
<thead>
<tr>
<th>Deleted Parameters (Category)</th>
<th>Reason</th>
<th>Validation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reach (Ontological Property)</td>
<td>The movement space and position of the manipulator cannot be fully described.</td>
<td>Simulation</td>
</tr>
<tr>
<td>Sensor (Ontological Property)</td>
<td>It cannot distinguish between internal and external sensors indicate to miss information.</td>
<td>Interview</td>
</tr>
</tbody>
</table>

Table 4 and Table 5 show the new parameters and deleted parameters after validating CRS. As a result of validation, the study added 6 new parameters and deleted 2 parameters. Both tables exhibit the name of each parameter with corresponding category, reason for adding or deleting and the validation type.
4.6 Summary

In this chapter, the study demonstrated the CRS including the categories, parameters, definitions, data types, examples, and corresponding references. Then based on the validation, the study validated the CRS through database validation, simulation validation and experts interview validation. According to the validation, the study modified the CRS by adding new parameters and delete some parameters.
Chapter 5 Summary and Conclusions

5.1 Summary

In previous studies, researchers have contributed to the study of construction robots. Their contributions and results in this domain became the cornerstone of this study. However, the research of previous scholars also has limitations. The main limitation is that the lack of a consistent data structure for collection and exchange of operational data specific to the needs of construction robots. This study proposed a new data structure, the construction robot schema (CRS), by utilizing a systematic literature review.

There is a large amount of literature on construction robots. In these literatures researchers have developed, analyzed, and applied different construction robots. Besides that, there are many articles that mention some of the attributes, such as the body, manipulator arm, hardware device, function, performance, operating condition, and safety of construction robot. When reviewing this content, the study translated them into different parameters and organized, categorized, and structured these parameters into a consistent data structure, forming the CRS.

5.2 Conclusions

The method and process of this study have answered the two research questions posed at the beginning of the study. The answers to these two questions are:

1. This study explored and parameterized the need for robotic data in the construction domain through a literature review.

2. The study structured parameters and established CRS through the extraction, classification, and definition of parameters.

For the first research question, this study used a literature review method to explore the content of the demand for robot data in the construction industry. This study used the Web of Science database to index the literature on construction robots. Eligible papers were then found and saved through automated and manual screening. Before reading the paper, this study established four categories namely ontology property, operational requirement, activity, and safety, which can help this study to code papers and structure parameters. After obtaining the papers, this study
utilized Nvivo qualitative data analysis tool to read and code the selected papers. When the construction robot was mentioned in the paper, the mentioned paragraphs are converted into parameters and saved.

For the second research question, the study plotted the parameters extracted while reading the literature into a table. During the literature review, four categories were established in this study, and passages in the literature describing robots were organized into corresponding categories. Based on the paragraph and paragraph category in which each parameter appears in the literature, this research classified the parameter under the corresponding category and adds it to the table. Then, the study condensed the paragraph describing the parameter into a definition and add it to the table. To help users better understand this parameter, the study found the case of the corresponding construction robot as an example and added it to the table. At the same time, to facilitate the review of parameters and definition sources, this study added references to the table. Through this series of processes, the data structure is finally established.

To validate the data structure, the study conducted database testing validation, simulation validation and expert interview validation. The aim for the three validations was to correct terms used, determine the reasonable relationships, and identify information missed. Finally, the study added 7 new parameters and deleted 2 parameters. For each new additional parameter, the study showed the definition, reason for addition and type of validation. For each deleted parameter, the study showed the reason for deleting and type of validation.

5.3 Contributions

The goal of this study is to create a Construction Robot Schema for construction planners, which is a data structure used to conduct robot data collection and data exchange based on the data needs of the construction domain and factors of human-robot cooperation to facilitate analyzing, and operating construction robots. Unlike previous data structures, the advantage of CRS is that it is a consistent data structure. When construction planners need to do data collection on construction robots, they don't have to spend hours referencing literature and discussing data needs. This data structure can help the construction planners collect data from a variety of construction robots, without having to make modifications to different robots when collecting data as in the past. In addition, CRS can demonstrate the data requirements for robot
manufacturers when applying robots in the construction industry, thereby providing a
standardized form when manufacturers display product parameters to users. In terms of data
exchange, like IFC, CRS contains necessary and important information required by robots in the
construction field, and CRS can be used as a standardized form for data exchange for different
analytical studies of construction robots.

5.4 Limitations

This study established the CRS data structure through literature review, but this method has the
following limitations:

1) The sources of information about construction robots in this study are all from the literature,
did not use real observation of the working status of construction robots when performing
construction tasks. This single information acquisition method reduces the available data to
content captured by other studies with different purpose.

2) The literature review of this study focuses on papers published from 2018 to 2022. There are
also many excellent papers before 2018 and after 2022. This limitation caused this study to
ignore many excellent studies, which made the data structure omit some important parameters,
thus affecting the integrity of CRS.

3) The validation process of this study is limited due to the small number of robots currently
used in construction, which reduces the opportunity to modify the data structure.

5.5 Future Work

While this study was developing the data structure, several issues were identified that were
outside the scope of the study and could serve as potential future research work. The first is
about the level of autonomy of robots. On this topic, many researchers are currently discussing it.
For example, Beer et al. (2014) proposed a level of autonomy framework for robot autonomy in
the article. They categorized robot autonomy into 10 levels, ranging from the lowest manual
teleoperation to the highest full autonomy. Also Melenbrink et al. (2020) mentioned a 0 to 5
level of robot autonomy developed by the Society of Automotive Engineers, from the lowest no
autonomy to the highest full autonomy. They believe this is the widely accepted taxonomy.
However, when construction robot manufacturers introduce their products, the description of autonomy is often reduced to fully automatic, semi-autonomous and teleoperated, without clear classification. Therefore, future work in this regard can be based on the characteristics of the construction industry to develop a robot autonomy level classification method that can be widely recognized by the construction industry, to better evaluate the autonomy level of construction robots.

The second is a database about construction robots. The study will keep going on improve the database schema development based on the CRS. Currently, CRS has captured parameters and initially categorized them. However, the relationships still need to be further designed for the database schema. The construction robotics database is important for the industry because when this study wanted to obtain data related to construction robots, it had to obtain data from different sources and in different ways. Usually, the data obtained in this way is not complete, and it takes a lot of time to obtain the data. Therefore, this study suggests that a comprehensive database can be established for construction robots in future work, and this database needs to contain a variety of construction robots and have corresponding complete data. The contribution of this work is to save the cost of data acquisition and facilitate the analysis and application of construction robots.
References


### Appendix A Construction Robots Data Sheet

<table>
<thead>
<tr>
<th>Entity Property</th>
<th>Unit</th>
<th>PictoBot - PBA 300</th>
<th>PictoBot - WAHPR</th>
<th>CyBe</th>
<th>TyBot</th>
<th>Line Dragon</th>
<th>DXR 315</th>
</tr>
</thead>
<tbody>
<tr>
<td>Name</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Weight</td>
<td>lb</td>
<td>881.85</td>
<td>6613.87</td>
<td>8818.49</td>
<td>7260</td>
<td>1325</td>
<td>4453</td>
</tr>
<tr>
<td>Power Source</td>
<td></td>
<td>Battery</td>
<td>Battery</td>
<td>?</td>
<td>Battery</td>
<td>Battery</td>
<td>Battery</td>
</tr>
<tr>
<td>Run Duration</td>
<td>hour</td>
<td>4</td>
<td>8</td>
<td>?</td>
<td>12</td>
<td>?</td>
<td>12</td>
</tr>
<tr>
<td>Productivity</td>
<td>quantity/hour</td>
<td>538.19ft²/h</td>
<td>7086.61ft/h</td>
<td>590.55~7086.61ft/h</td>
<td>?</td>
<td>?</td>
<td>?</td>
</tr>
<tr>
<td>Precision</td>
<td>in</td>
<td>0.017</td>
<td>0.04630.040.04</td>
<td>715</td>
<td>3</td>
<td>7</td>
<td>1</td>
</tr>
<tr>
<td>Reach</td>
<td>ft</td>
<td>1.30*18.61</td>
<td>8.60*11.33</td>
<td>7</td>
<td>?</td>
<td>204.72/216</td>
<td>7</td>
</tr>
<tr>
<td>End Effector</td>
<td></td>
<td>Spray Gun</td>
<td>Nozzle</td>
<td>Breaker/Bucket/Cut/Cut/Cut</td>
<td>?</td>
<td>?</td>
<td>?</td>
</tr>
<tr>
<td>Manipulator</td>
<td></td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>Degree of Freedom</td>
<td>DOF</td>
<td>6</td>
<td>7</td>
<td>?</td>
<td>?</td>
<td>?</td>
<td>?</td>
</tr>
<tr>
<td>Reach</td>
<td>ft</td>
<td>?</td>
<td>1.97~24.61</td>
<td>8.69~11.48</td>
<td>?</td>
<td>?</td>
<td>204.72/216</td>
</tr>
<tr>
<td>Lifting Capacity</td>
<td>lb</td>
<td>440.92</td>
<td>?</td>
<td>15</td>
<td>?</td>
<td>?</td>
<td>?</td>
</tr>
<tr>
<td>Sensor</td>
<td></td>
<td>laser scanner, sonar sensor, 3D camera, laser, IR sensor, force sensor</td>
<td>pressure sensor, temperature sensor</td>
<td>pressure sensor, temperature sensor</td>
<td>?</td>
<td>?</td>
<td>?</td>
</tr>
<tr>
<td>Mobility</td>
<td></td>
<td>Wheel</td>
<td>Tracked</td>
<td>Wheel</td>
<td>Tracked</td>
<td>Wheel</td>
<td>Tracked</td>
</tr>
<tr>
<td>Safety</td>
<td></td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>?</td>
<td>?</td>
<td>?</td>
</tr>
<tr>
<td>Activity</td>
<td></td>
<td>Painting</td>
<td>Painting</td>
<td>?</td>
<td>?</td>
<td>?</td>
<td>Demolition</td>
</tr>
<tr>
<td>Material Type</td>
<td></td>
<td>Concrete mortar</td>
<td>Rebar</td>
<td>?</td>
<td>?</td>
<td>?</td>
<td>?</td>
</tr>
<tr>
<td>Task</td>
<td></td>
<td>Print Concrete</td>
<td>Rebar</td>
<td>Concrete Placing</td>
<td>?</td>
<td>?</td>
<td>?</td>
</tr>
<tr>
<td>Safe Distance</td>
<td>ft</td>
<td>2.6</td>
<td>2.6</td>
<td>?</td>
<td>?</td>
<td>?</td>
<td>?</td>
</tr>
<tr>
<td>Minimum Workspace</td>
<td>7</td>
<td>7</td>
<td>7</td>
<td>7</td>
<td>7</td>
<td>7</td>
<td>6.81</td>
</tr>
</tbody>
</table>

Figure 4 Construction Robots Data Sheet
Appendix B Constructability Simulation
Appendix C Experts Interview Slides

Goal for Meeting

- Confirm the information about robots corresponding to the data needs of construction applications.
- Identify missed information that is important for robots.
- Suggest other considerations about robots that can enrich the information

Ontological properties

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Description/Definition</th>
<th>Data Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>Name</td>
<td>The official name is given by the manufacturer.</td>
<td>ANYmal (Inspection Robot)</td>
</tr>
<tr>
<td>Weight</td>
<td>Body weight</td>
<td>110.2~122.8 lb</td>
</tr>
<tr>
<td>Dimension</td>
<td>Length<em>Width</em>Height</td>
<td>36.61<em>20.87</em>35.04 inch</td>
</tr>
<tr>
<td>Mobility</td>
<td>It is the method and ability of a robot to move from one place to another.</td>
<td>Leg</td>
</tr>
<tr>
<td>Speed</td>
<td>The transport speed of the robot when it is normally performing work.</td>
<td>4.27 ft/s</td>
</tr>
</tbody>
</table>
### Ontological properties

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Description/Definition</th>
<th>Data Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power Source</td>
<td>Battery/Power Line/Fuel</td>
<td>Battery</td>
</tr>
<tr>
<td>Run duration</td>
<td>The working duration of the robot under the power supply.</td>
<td>8 hours</td>
</tr>
<tr>
<td>Load Capacity</td>
<td>The maximum allowable force that the robot can withstand for a long time when it is performing work.</td>
<td>880lb</td>
</tr>
</tbody>
</table>
Ontological properties

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Description/Definition</th>
<th>Data Example (Oscar 1000 Glazing Robot)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manipulator</td>
<td>An electronically controlled structure consisting of a series of links and joints that perform tasks by interacting with the environment. (Robot Arm)</td>
<td>Yes</td>
</tr>
<tr>
<td>Degree of Freedom</td>
<td>The number of geometry axis that can be rotated or extended.</td>
<td>6</td>
</tr>
<tr>
<td>End Effector</td>
<td>A device attached to the end of a manipulator is designed to allow the robot to interact with the task environment.</td>
<td>Suction Cup</td>
</tr>
</tbody>
</table>

Ontological properties

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Description/Definition</th>
<th>Data Example (Husqvarna DXR)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reach</td>
<td>The maximum distance the manipulator can attach.</td>
<td>204.72 in (top)/216 in (forward)</td>
</tr>
<tr>
<td>Lifting Capacity</td>
<td>The maximum weight that the robot can lift during operation.</td>
<td>683 lb</td>
</tr>
</tbody>
</table>
### Ontological properties

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Description/Definition</th>
<th>Data Example (CyBe 3D Concrete Printer)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Accuracy</td>
<td>The degree of quality defines how correctly the robot normally performs works.</td>
<td>0.0059 inch</td>
</tr>
<tr>
<td>Productivity</td>
<td>The amount of work or production of the robot per unit time.</td>
<td>19.69 inch/s</td>
</tr>
<tr>
<td>Precision</td>
<td>The degree of refinement of the robot when normally performs works.</td>
<td>0.039/0.039/0.039 inch</td>
</tr>
</tbody>
</table>

### Operational Requirements

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Description/Definition</th>
<th>Data Example (SAM 100)</th>
</tr>
</thead>
<tbody>
<tr>
<td># of Operator</td>
<td>The person who controls the robot.</td>
<td>1</td>
</tr>
<tr>
<td># of Coworker</td>
<td>A person who performs a task with a robot.</td>
<td>1</td>
</tr>
<tr>
<td>Operator’s Responsibility</td>
<td>The operator’s work contents when the robot is performing tasks.</td>
<td>On-site robot setting, robot inspection.</td>
</tr>
<tr>
<td>Coworker’s Responsibility</td>
<td>The coworker’s work contents when the robot is performing tasks.</td>
<td>Extra motor shovel away.</td>
</tr>
</tbody>
</table>

https://www.msn.com/en-us/privacy/images/robotics.jpg
### Operational Requirements

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Description/Definition</th>
<th>Data Example (Clapa Floor Master)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Site Preparation</td>
<td>The preparations required for the robot to work properly on the site.</td>
<td>Semi-dry sand/material needs to be laid on the floor prior to work. (Clapa Floor Master Screed Robot)</td>
</tr>
</tbody>
</table>

### Operational Requirements

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Description/Definition</th>
<th>Data Example (ANYmal)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grade</td>
<td>It is used to describe the acceptable flat level of the ground for the mobile robot.</td>
<td>Walk on a slope less than 30° cross a gap of fewer than 11.81 inches and climb a step less than 9.84 inches.</td>
</tr>
</tbody>
</table>

- **GAP** *30 CM*
- **STEP** *25 CM*
- **SLOPE** *30°*

## Operational Requirements

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Description/Definition</th>
<th>Data Example (CyBe 3D Concrete Printer)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature</td>
<td>The temperature range required for the robot to work properly.</td>
<td>21 - 122°F</td>
</tr>
<tr>
<td>Humidity</td>
<td>The humidity range required for the robot to work properly.</td>
<td>Max 95%</td>
</tr>
</tbody>
</table>

## Activity

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Description/Definition</th>
<th>Data (Semi-Automated Mason 100)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Activity</td>
<td>The name of the activity that the robot is involved.</td>
<td>Bricklaying</td>
</tr>
<tr>
<td>Material</td>
<td>Specific material needed for the activity.</td>
<td>Bricks and Mortar</td>
</tr>
<tr>
<td>Task</td>
<td>The task performed by the robot under this activity.</td>
<td>The SAM100 can do the tasks of grabbing bricks, applying mortar, and placing bricks.</td>
</tr>
</tbody>
</table>
## Safety

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Description/Definition</th>
<th>Data (PictoBot)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Emergency Stop</td>
<td>The robot stops automatically and immediately when specific conditions are triggered.</td>
<td>PictoBot’s collaborative robot has a safety system that performs a protective stop if the arm accidentally hits a structure or person.</td>
</tr>
<tr>
<td>Safe Distance</td>
<td>The minimum distance needs to be maintained when humans and robots work together.</td>
<td>Keep 80cm (2.6ft) between people and PictoBot to keep workers safe and robot performing.</td>
</tr>
<tr>
<td>Objective Detection</td>
<td>The robot’s ability to detect and recognize objects within a specific range.</td>
<td>Laser obstacle scanning, 3D point cloud collision checking.</td>
</tr>
</tbody>
</table>

---

## Safety

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Description/Definition</th>
<th>Data (Husqvarna DXR)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Additional PPE Requirements</td>
<td>Personal protective equipment required when humans operate or work with robots.</td>
<td>Earmuffs Required</td>
</tr>
<tr>
<td>Minimum Workspace</td>
<td>The minimum space required by the robot to avoid collisions while operating.</td>
<td>81.9 in</td>
</tr>
</tbody>
</table>

[Image of construction site with robots and workers]
Vita

Fangxiao Li is a currently second-year Ph.D. student, and his major is Architectural Engineering with a focus on Construction. Fangxiao gained his Master of Science Degree in Civil Engineering at Northeastern University in Boston in 2020. Fangxiao is interested in human-robot cooperation in construction and the development of construction robot schema. Fangxiao was born in China. His hometown Zibo is famous for silk and ceramics. After Fangxiao got his bachelor’s degree in China, he decided to continue studying in America and embrace a different kind of culture and environment. He got some internship experiences working as an assistant superintendent in a local construction management company in his hometown for several months. His main works were assisting the superintendent to inspect the production quality in the construction site and track staged costs and construction progress. His hobbies are badminton and video games. In addition to this, he also like to seek and watch movies, especially historical movies.