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EXPLORING A DESIGN FOR ROBOTIC CONSTRUCTION APPROACH: TWO CASE STUDIES MATCHING ROBOT AND CONSTRUCTION DESIGN FEATURES

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Abstract

As robots become more flexible to operate in unstructured environments, the AEC industry needs to facilitate the deployment of robots from design perspectives. However, today's process of deploying robots typically starts while the construction phase is underway, lacking design methods for robotic construction. This paper explores a Design for Robotic Construction approach. First, a set of metrics was defined to analyze the match between the design features of construction projects and robots. Second, a user interface (UI) was prototyped to visualize these metrics and suggest design decisions for robots and construction projects. The approach was preliminarily validated in two pilot studies.

Introduction

Over the past few years, construction robots have become a technical and economic possibility with the decrease in the cost of machinery relative to labor, recent developments in microprocessors, and the advent of low-cost computers, sensing technologies, AI techniques, and other innovations (Saidi et al., 2016). The robustness and task adaptability of construction robots have been further improved, making the application scenarios more diverse (Melenbrink et al., 2020). Previous case studies demonstrated the effectiveness and advantages of construction robots in steel structure welding, interior decoration, inspection and maintenance, material handling and other scenarios (Melenbrink et al., 2020).

However, the adoption of robotics in the construction industry still faces many challenges due to the unique characteristics of the construction process (Davila Delgado et al., 2019). In manufacturing, robots have already been highly adopted, and their benefits are widely understood (An et al., 2020b,a; Dolinšek and Duhovnik, 1998). The successful adoption of robots in manufacturing is also driving the application of robotics in the construction industry. However, the construction environment has a lower level of standardization and is less controllable (Xiao et al., 2022), which makes the application of construction robots more difficult. In the past, construction robots were often confined to structured off-site environments, reducing complexity by transforming a relatively uncontrollable environment into a factory environment, such as prefabrication (Lundeen et al., 2019). Now, the goal of the Architecture Engineering and Construction (AEC) industry also includes the exploration of how construction robots can be applied to unstructured on-site environments (Lundeen et al., 2019). To understand whether a robot can deliver its intended benefits on a construction site, we often need to consider questions such as: *Are the corners reachable for the robot? Is the space big enough for the robot to turn around? Can the robot surmount the step to get into another room? Is the elevator large enough for the robot to get in?* These questions require us to consider the feasibility of robotic construction from a design perspective.

In previous research (Brosque and Fischer, 2022c; Brosque et al., 2021; Brosque and Fischer, 2022b), challenges in connecting a robot's capabilities to design decisions were identified when evaluating the applicability of robots in unstructured construction environments. In 9 of the 15 cases we studied, there were misalignments between the design features of robots and construction projects. Understanding the construction feasibility and making corresponding decisions during the early design phases of construction projects could effectively avoid potential rework, improve production efficiency, and reduce costs (Bakhshi et al., 2022). However, today's process to deploy robots typically starts while the construction phase is underway. At this time, misalignments between a robot's capabilities and the construction design features are too late to be reconciled. To address this challenge, the AEC industry needs a tool or approach for Design for Robotic Construction (DfRC) that helps to implement efficiencies.

In this paper, we explore a DfRC approach that determines whether robotic construction is feasible by checking the match between the design features of the construction project and the robot or vice versa (i.e., design feasibility). This approach also suggests redesigning decisions for the robots and construction projects to help maximize the benefits of construction robots. This approach is twofold: (1) A set of metrics is suggested to check the design feasibility of the two case studies. (2) A user interface is prototyped to visualize these metrics in 3D and suggest design decisions for robots and construction projects in two case studies. The two pilot studies include an interior grinding robot designed by the HD Lab (Denmark), and a concrete drilling robot (Brosque et al., 2021). The former we focused on the design of the robot, and the latter we focused on the design of the construction project.

Theoretical points of departure

To understand how builders, designers, and robot manufacturers could connect robot capabilities to construction and design decisions, we focus on three theoretical points of departure: 1) Design for Manufacturing and Assembly, 2) Robot-Oriented Design approaches in construction, and 3) Ambient Intelligence Strategies.

Design for Manufacturing and Assembly (DfMA)

In manufacturing, DfMA provides a way to integrate product and machine technology to increase the one-time success rate of design and achieve high efficiency (Yuan et al., 2018). DfMA highlights the need to adapt the product structure to the manufacturing system and technology considering the amount of parts variation, the adjustment of the product structure, and the design of components' interfaces with each other (Bock and Linner, 2015). Learning from the successful adoption of robotics in manufacturing (An et al., 2020b,a; Dolinšek and Duhovnik, 1998), previous authors have extended DfMA to integrate construction project design and robot capabilities. For example, Goessens et al. (2018); Dolinšek and Duhovnik (1998) introduced a feasibility study of drone-based masonry construction. In terms of a robot's design, it considered issues such as the size and weight of the drone for lifting blocks, as well as the tolerance needed for the blocks (Goessens et al., 2018). Design changes to the construction project could facilitate the use of robots in construction as well. For instance, design the openings large enough to facilitate robots' access (Slaughter, 1997), or column spacing that reduces the number of manual robot set-ups. Modifying the construction materials and products could also make them to be easily manipulated by robots, including dimensional changes, special connections, new application methods, or different tolerances (Slaughter, 1997).

Robot-Oriented Design approaches in construction

Robot-Oriented Design (ROD), coined by Bock and Linner (2015), refers to a co-adaptation strategy of the construction products and the robot assembly operations to improve the efficiency of the total construction process. Previous Design for Robotic strategies include changing the construction design. For example, Warszawski (1988) conducted a study focusing on robot accessibility and load limits and changing the building components with prefabricated modular elements that were more easily assembled by robots. Another way proposed by Linner et al. (2019) is to determine how the complexity of the robot can be decreased by shifting some complexity to the overall building system. For example, Linner et al. (2019) proposed to simplify the facade by implementing an ROD strategy. The changes to the facade design allow for a simplified robot axes requirement which makes it more economically feasible to complete the construction phase of the project.

Ambient Intelligence Strategies

Based on industry observations from previous case studies related to robotic construction (Brosque and Fischer, 2022c; Brosque et al., 2021; Brosque and Fischer, 2022b), robots are usually equipped with a series of Ambient Intelligence Strategies to adapt to complex, unstructured construction sites, including strategies such as Bluetooth, Lidar, sound and light sensors, position sensors, etc. (Brosque and Fischer, 2022c). For example, Spot uses proximity and depth sensors for purposes such as avoiding collision between robots and obstacles; CANVAS uses Lidar sensor, vision sensors, rotary encoder, and other strategies to achieve 3D spatial mapping and semi-autonomous movement of the robot (Brosque and Fischer, 2022c). In related literature, Joseph Engelberger's HelpMate robot (Krishnamurthy and Evans, 1992) for hospital material transportation included a set of design guidelines for the unstructured hospital environment, such as parking and battery charging areas for robots. Heilala and Sallinen (2008) also reflected on Ambient Intelligence Strategies to aid robots working in manufacturing. Their approach addressed information processing, signal processing, and production control with high-speed sensing and communication systems in the automation process.

Methodology

This paper explores a Design for Robotic Construction approach that could help builders, designers, and robot manufacturers to check how well a robot matches the design features of a construction project or vice versa. The DfRC approach also helps generate diverse redesign suggestions for robots and construction projects to make robotic construction feasible, and provide the corresponding cost and schedule impacts. We implemented the following two main steps to two pilot studies: (1) First, check how well the robot matches the design features of the construction project or vice versa from the two directions of physical and intelligence metrics. (2) Second, deploy a user interface to visualize these metrics related to design decisions with 3D models and to suggest redesigns for robots and construction projects that may facilitate the use of construction robots.

In previous case studies, we observed that different types of robots need to consider different design factors (Brosque and Fischer, 2022c). For example, Kewazo's Liftbot scaffolding assembly robot uses a vertical rail system to move on a fixed, one-dimensional path to lift heavy objects (Brosque and Fischer, 2022c); while Boston Dynamics' Spot reality capture robot uses a four-legged motion system to capture reality on the construction site, and to ensure that its scanning device would not make direct contact with any building components (Brosque and Fischer, 2022c). Therefore, for the former, we do not take into account its accessibility, as it does not need to move autonomously in or between work spaces. For the latter, no consideration needs to be given to its ability to manipulate physical objects in direct contact. Based on these observations, before the two main steps, it is necessary to adjust the metrics for various types of robots to improve the generality of the approach and avoid inapplicable requirements for the design of robots and construction projects.

Metrics for design feasibility check

There are two main sources of metrics for the design feasibility check. First, we reviewed papers in the fields of Design for Manufacturing and Assembly, Robot-oriented Design, and Ambient Intelligence Strategies in the past three decades. Second, we included industry observations from robot cases involved in Stanford University's Construction Robotics class (Brosque and Fischer, 2022a).

Construction project: Environmental Conditions	**Robot: Capabilities/Limitations**
Access	
Water	Humidity tolerance
Gravel/rocks/other terrain conditions	Mobile units
	Hardwares to withstand adverse terrain conditions
Static Load (including permanent and temporary structures such as scaffolding)	Static Weight
Dynamic load (including permanent and temporary structures such as scaffolding)	Vibration + Weight
Vertical transportation (e.g. elevator, scaffolding)	Dimensions (width, length and height)
	weight
Size of available moving space	Dimensions (width, length and height)
	Turning radius
Workers/Materials/other obstacles	Hardware to clear/avoid obstacles
Slopes / ramps / stairs	Mobile units
Gaps	Dimension of mobile devices
	Mobile units
Reach	
Relative position of the robot and the physical object (orientation, distance, etc.)	Operating units
	Range of reachable distance
Obstacles impeding operation	Hardware to clear/avoid obstacles
Total area/quantity to be reached	Total reachable area/quantity
Accepted threthold of % accessible	% accessible
Manipulate (direct contact)	
Joints and interfaces - Material of building components	Joints and interfaces - Material of robot
Joints and interfaces - Dimensions of building components	Joints and interfaces - Dimensions of robot
Joints and interfaces - Geometry features of building components	Joints and interfaces - Geometry features of robot
Manipulate (general)	
Performance required	Performance provided
Modularity/Customisation/Variability in material specs	Adjustability of operating devices
Modularity/Customisation/Variability in component dimensions	
Modularity/Customisation/Variability in component geometry features	
Number of parts of building components	Number of parts of the robot equipment
Tolerances of building components	Tolerances of robot

Figure 1: Design feasibility check: physical metrics

Construction project: Environmental Conditions	**Robot: Capabilities/Limitations**
Power	
Electrical outlets availability	Distance limitations from electrical outlets
Battery recharge station/Backup battery availability	Battery power capability
Connection	
Type of connection available (WIFI, Bluetooth, Cellular Data, Others, etc.)	Type of connection available
Effective distance	Max distance from the signal
Distribution interval (e.g. every n meters / one)	
Signal strength distribution	Signal strength requirements
Geolocation/sensing	
GPS/Other availability	
GPS signal on site	GPS hardware
On-site sensors/eqquipment/reflector availability (e.g. total station)	
On-site sensors/eqquipment/reflector (e.g. total station)	Corresponding hardware that receives/reflects signals
Functionality of the sensors/eqquipment/reflector	Corresponding requirements/constraints
Effective distance	Range of distance between the robot and the sensors
Distribution interval	
Accuracy/Precision/Tolerance	Corresponding requirements
Robot sensors/eqquipment/reflector availability (e.g. CV sensor, Infrared sensor, etc.)	
/	Robot sensors/equipment/reflector availability
Corresponding requirements/constraints	Functionality of the sensors/eqquipment/reflector
Range of distance between the sensors and the objects	Effective distance
Corresponding requirements/constraints	Accuracy/Precision/Tolerance
Sensory environment	
Sound	Noise tolerance
Heat	Low/High temperature resistance
Light	Low/Strong light tolerance
Autonomous system	
Corresponding requirements/constraints	Task planning capability
	Path planning capability
	NLP capability
	...

Figure 2: Design feasibility check: intelligence metrics

Table 1 summarizes the literature related to the design of robotic construction, including the selected metrics, and the categories of these metrics. In addition, combined with the metrics observed in industry, such as total stations, scaffolding, reflector, gravel/rocks/other terrain conditions, vision, etc., we summarize the physical metrics and intelligence metrics in Figure 1 and Figure 2 respectively. Physical metrics are used to check how well a robot's capabilities, including access, reach, and manipulate, match construction design features, while intelligence metrics are used to check the feasibility of power, connection, geolocation/sensing, and autonomous systems. Each metric checks the match between the environmental conditions of the construction project (first column of Figure 1 and Figure 2) and the corresponding capabilities or limitations of the robot (second column of Figure 1 and Figure 2). For example, when evaluating whether a robot can use vertical transportation (such as elevators, scaffolding, etc.) on a construction site, we need to check whether the weight of the robot is within the load capacity of the vertical transportation, and whether the size of the robot is small enough to get into this vertical transportation. Similarly, when evaluating whether the power supply of the robot is feasible on site, we need to check the availability of electrical outlets on the construction site, and whether the robot has restrictions on the distance from the electrical outlets to its working position.

Case Studies

This section describes the implementation of the DfRC approach based on two pilot case studies. We used Microsoft Excel to record the results of the design feasibility check. Then, we utilized Blender version 3.0.0 and Axure RP 10 to prototype a user interface. Blender 3.0.0 allows users to create complex and detailed 3D scenes and animations, and it also comes with a customizable interface and support for various file formats. Axure RP 10 is a prototyping tool that enables designers and developers to generate interactive and high-fidelity prototypes for websites, mobile apps, and other digital products. Using these tools, we developed a User Interface prototype that can visualize design metrics and provide suggestions for design decisions to demonstrate potential ways to improve the feasibility of robotic construction. In the first case, we explained the design iteration process of HD lab's interior grinding robot, and helped the industry partner understand the feasibility of robot construction, focusing on the accessibility. In the second case, we analyzed a concrete drilling robot and found a series of construction project design features that were not applicable for robot, from which we selected one and redesigned it to better match the robot's capabilities to construction project design features for cost savings.

Case study 1: HD lab's interior grinding robot

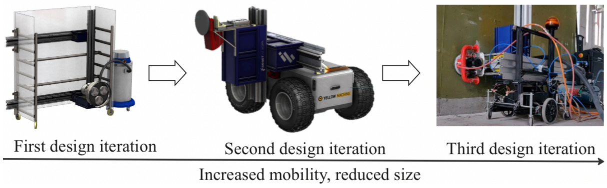


Figure 3: Design iterations of the grinding robot

This interior grinding robot was developed by HD lab in collaboration with two Danish demolition contractors aiming to substitute the manual grinding and blasting work of renovation projects. Given that the robot is deployed for demolition work, the construction project cannot be modified, so the design changes could only be implemented on the robot design to maximize the access and reach of the robot. The first robot design was developed on the basis of a 2m x 2m workspace with a moving platform. The tool was mounted to the platform and could move in vertical and horizontal directions. However, it was found that the first-iteration design could not access most of the desired work, as obstacles prevented the robot from operating efficiently and limited the robot's access to objects above 2m. In addition, the robot had to be small enough for a site elevator, and light enough for two workers to lift it manually if the robot had to be carried up the stairs. Achieving rugged mobility both indoors and outdoors was key to securing the access of the robot to the right locations. The last robot design focused on mobility and modified the tracks for a combination of wheels for additional flexibility. Figure 3 shows the design iterations of the robot. With the last prototype of the robot design, the industry partner still had some issues communicating the robot's capabilities. If the robot cannot grind more than half of the target of the walls, it is not worth taking it to the construction site. Therefore, we used the DfRC approach to understand what is accessible by the robot, and suggest redesigning the robot to improve its ability to access locations. In terms of physical metrics, the robot needs a certain degree of accessibility to move semi-autonomously on the construction site, and its operating unit needs to actively approach and directly contact the building components, so its capabilities for reaching and manipulation also need to be considered. In terms of intelligence metrics, the robot requires on-site power supply. When it disconnects from the internet, it still functioned properly. GPS and field sensors were not available on site, so only the sensors equipped with the robot itself need to be considered. In addition, the robot does not use advanced autonomous systems when conducting construction tasks. Based on the above descriptions, we selected applicable metrics for checking the design feasibility of this robot.

The result of design feasibility check

By checking each of the physical metrics listed in Figure 1, it is found that the HD lab's grinding robot may have design misalignment in terms of reachability, as the robot cannot operate within 0.1m from corners. Therefore, this part of the work needs to be completed with human assistance, or the operating unit of the robot needs to be redesigned. For the intelligence metrics listed in Figure 2, the robot is feasible in terms of power and geolocation/sensing based on current robot capabilities and construction project design features.

User Interface prototyping

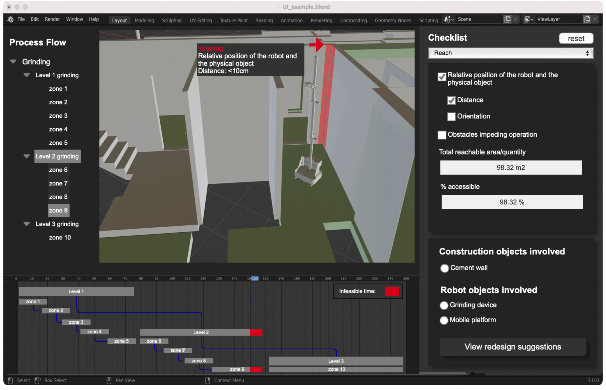
As is shown in Figure 4, in the middle of the UI, the design features of the robot and the construction project are visualized using 3D models, with areas within 0.1m of cor-

Table 1: Metrics for design features related to robotic construction analyzed in previous literature

Author	**Physical**	**Intelligent**	**Comments**
Kunic et al. (2021)	☆ ✪	♦	Degrees of freedom; Sensor for positioning
Rogeau et al. (2021)	★ ☆ ✪		Joints geometry; Assembly process (obstacles, avoid collisions)
Yang and Kang (2021)	★ ☆		Path planning; Collisions avoidance; Degree of freedom
Anton et al. (2021)	☆ ✪		Material; Geometry; Tolerance
An et al. (2020a)	☆ ✪		Geometry; Mating plane; Manufacturing plane
An et al. (2020b)	✪		Geometry; Mating plane; Manufacturing plane
Orlowski (2020)	✪		/
Wagner et al. (2020)	★ ☆ ✪		/
Kontovourkis and Tryfonos (2020)	★ ☆ ✪	◆	Path planning; Dimensions; Material; Geometry
Piroozfar et al. (2019)	✪		Modularity, Customisation
Yuan et al. (2018)	✪		Geometry
Goessens et al. (2018)	✪		/
Jovanović et al. (2017)	✪		/
Turek et al. (2017)	★	♦ ◈	Dimension; Height; Mapping; Path planning; Localization
Correa (2016)	★ ☆		/
Tan et al. (2016)	★ ☆	♦ ◈	Height; Autonomy level; Vision; Autonomy level; Noise level; Light level
Raspall (2015)	☆ ✪		Speed of fabrication; Temperature, Geometry features
Bock and Linner (2015)	★ ☆ ✪	◆	Load limits; Dimensions; Slopes / ramps / stairs; Water; Electricity; Transportation; Conditions on-site (dirt, dust, obstacles on floor, etc.); Tolerance; Interfaces and joints; Number of parts; Product structure; Modular repetition; Payload; Variability in component size
Gambao et al. (2000)	★ ☆ ✪	◇ ♦	Position resolution; Orientation
Bock et al. (2000)	★ ✪		Tolerance; Transportation
Scott Howe (2000)	★ ☆		Location of components and tools; Gaps
Han et al. (1998)	★ ✪		Component design; Tolerances
Dolinšek and Duhovnik (1998)	★ ☆ ✪		Degree of freedom; Obstacles; Material
Navon and McCrea (1997)	☆ ✪		/
Navon (1995)	★ ☆ ✪	◆ ♦	Position resolution
Bridgewater (1993)	☆ ✪		Tolerance; Number of components, Degrees of freedom
Engelberger (1993)	★ ☆	◆ ◇ ♦	Robot intelligence such as power, connection and geo-location/sensing; Workstations; Access; Reach; Charging and parking stations
Paulson et al. (1989)		◆ ◇ ♦ ◈	/

★Access ☆Reach ✪Manipulate
◆ Power ◇ Connection ♦ Geolocation/sensing ◈ Autonomous system

ners marked in red as alerts. On the right side of the UI, a checklist is provided for users to select one or more metrics that need to be checked. The left side of the UI shows the overall process flow of robot construction; the lower part of the UI uses a Gantt chart to mark infeasible time, and the tasks of the grinding robot are decomposed into floor level and zone level to identify infeasible areas/times. Here, the UI shows that the robotic construction in zone 9 on the second floor is not feasible. The overall reachability of the grinding robot is 98.32% (calculated by subtracting the area within 0.1m of the corner from the total area). If the acceptable threshold for the percentage of accessibility is below this value, then using the grinding robot would be feasible in terms of design in this case.



Warning:
Relative position of the robot and the physical object
Distance: <10cm

Checklist reset

Reach

☑ Relative position of the robot and the physical object

☑ Distance

☐ Orientation

☐ Obstacles impeding operation

Total reachable area/quantity: 98.32 m2

% accessible: 98.32 %

Construction objects involved

○ Cement wall

Robot objects involved

○ Grinding device

○ Mobile platform

View redesign suggestions

Figure 4: UI for HD lab's grinding robot

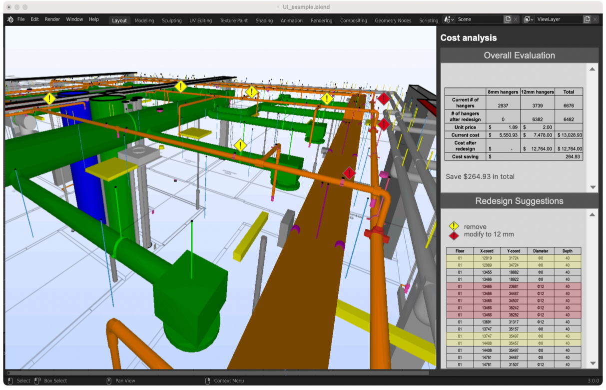
Case study 2: the concrete drilling robot

This is a semi-automated concrete drilling construction robot designed for mechanical, electrical, and plumbing installation work. In terms of physical metrics, considerations for deploying this robot include accessibility to the desired workstations, including site obstacles, scaffolding, elevators, slopes (up to 15 degrees), and weight (750 kg). The robot is maneuvered via a joystick to the workstation where it can drill autonomously. Once at the workstation, reachability aspects like the height and type of ceiling (flat vs. T slabs) become important variables to determine the % of work the robot can accomplish. The variability of building components' material, and geometry also need to be considered. From an intelligence perspective, to achieve the required accuracy, the robot must be in the line of sight of a total station.

The result of design feasibility check

We checked each of the intelligence metrics listed in Figure 1 and concluded that the design of the grinding robot and the construction project is feasible. The result of checking the physical metrics listed in Figure 2 helped to identify the following mismatch between the robot's capabilities and the design features of the construction project: In terms of accessibility, the elevator entrance has a ramp with a height of about 15cm and an angle almost perpendicular to the ground, while the integrated tracked platform of the robot can only handle up to 15 degrees of slope. Outside the building, there is an scaffolding connecting two buildings with a limit of only 300 kg, and the robot's weight of 750 kg exceeded the load capacity of this scaffold. In addition, T-slabs' geometry could present unforeseen issues to the depth sensor in the robot which affects the accuracy of the holes. For variability in construction components' dimensions, a mix of 8mm and 12mm diameter hangers could be used, or we could replace all hangers with 12mm diameter hangers. It would be easier for the robot to operate if every hanger has the same diameter, as it would not need to spend time changing the drill bit. If all the hangers were designed to be 12 millimeters, that could be slightly more expensive, but stronger hangers mean that they could be spread out and use fewer hangers. Therefore, the tradeoff between the number and diameter of the hangers must be considered when making design decisions.

User Interface prototyping



Cost analysis

Overall Evaluation

	8mm hangers	12mm hangers	Total
Current # of hangers	2937	3739	6676
# of hangers after redesign	0	6382	6482
Unit price	$ 1.89	$ 2.00	
Current cost	$ 5,550.93	$ 7,478.00	$ 13,028.93
Cost after redesign	$ -	$ 12,764.00	$ 12,764.00
Cost saving	$		264.93

Save $264.93 in total

Redesign Suggestions

⚠ remove
⚠ modify to 12 mm

Floor	X-coord	Y-coord	Diameter	Depth
01	12919	31724	Φ8	40
01	12989	34724	Φ8	40
01	13455	18882	Φ8	40
01	13466	18922	Φ8	40
01	13466	23681	Φ12	40
01	13466	34467	Φ12	40
01	13466	34507	Φ12	40
01	13466	38242	Φ12	40
01	13466	38282	Φ12	40
01	13691	31317	Φ12	40
01	13747	35157	Φ8	40
01	13747	35497	Φ8	40
01	14408	35457	Φ8	40
01	14408	35497	Φ8	40
01	14761	34467	Φ8	40
01	14761	31507	Φ12	40

Figure 5: UI for the concrete drilling robot

Figure 5 is a prototype of the UI and shows redesign suggestions for the hangers' layout and diameters. In the 3D model on the left, it is suggested to remove the hangers marked with red diamonds, and change the diameter of the hangers marked with yellow diamonds to 12mm. On the right, the UI gives specific redesign suggestions and the cost impacts of this redesign. Cost savings could be realized by modifying or removing about 3,000 hangers with a diameter of 8mm compared to the initial design. Under the presented case, the corresponding requirements of robotic construction could be considered and incorporated from the design phase by using the UI.

Conclusions and future work

In this paper, we explore a DfRC approach that checks how well a robot matches the design features of the construction project, or vice versa, and suggests redesigns for robots and construction projects to maximize the benefits of robotic construction.

In both pilot studies, the metrics for design feasibility check helped identify misalignment between the design features of the robot and construction project, and the user interface visualized these metrics in 3D models. We preliminarily validated the effectiveness of this approach in providing redesign suggestions for construction projects and robots and saw the potential opportunities of this approach in analyzing corresponding cost and time impacts. Although the prototyped UI may provide design insights for robotic construction, there may still be some limitations from an ethics perspective that are not currently understood, and analyzing the safety of design suggestions is still necessary. Future research needs to study the completeness and generality of the metrics with additional case studies, and deploy an accurate 3D simulation system that integrates the detailed information of physical and intelligence design features of robots and construction projects. One direction is to integrate Building Information Modeling and Robot Operating System for deeper and more detailed simulation.

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