Interface Management of Robots in Construction: A Case Study of Overhead Drilling Robot

Zhida Zhang[1], Mi Pan[1], Sujuan Zhang[2,3], Quan Sun[1]

[1]Department of Civil and Environmental Engineering, University of Macau, Macao, SAR, China
[2]School of Project Management, Faculty of Engineering, University of Sydney, Sydney, Australia
[3]John Grill Institute for Project Leadership, University of Sydney, Sydney, Australia
zhidazzd@um.edu.mo, mipan@um.edu.mo, sujuan.zhang@sydney.edu.au, quansun@um.edu.mo

Abstract –

The introduction of innovative robotics to the traditional construction processes involves complex and multi-dimensional interfaces that could hinder effective technology implementation. This paper aims to identify potential interface problems between construction robots and traditional construction processes, and propose effective strategies for interface management. Drawing on a case study of the implementation of an overhead drilling robot in Macao, the findings indicate various issues related to physical, contractual and organizational interfaces and their causes associated with the integration of construction robots. In particular, contractual interface problems were identified as the most critical factors affecting the real-world application of robots in construction. This highlights the importance of developing new business models and fostering collaboration among stakeholders through innovative contract forms. The developed innovative interface management framework for construction robots provides valuable insights for future research and practice to understand and manage complex interfaces between robots and traditional construction processes. The paper should contribute to the better implementation of robots in construction.

Keywords –

Construction robot; Interface management; Drilling robot; Engineering management

1 Introduction

Construction robots, often refer to sophisticated and intelligent machinery designed for construction processes with robotic features, are emerging as a cutting-edge solution that could address many challenges confronting the industry [1]. The first on-site construction robot was developed by the Japanese Shimizu company for spraying surface materials in the 1980s [2], followed by diverse construction robots springing up during the 1990s. Consequently, many prototypes of single-task robots have been developed in the construction industry, such as those for concrete finishing, wall painting, and ceiling board installation, providing evidence of the potential of robots to assist in performing dangerous, dirty, and difficult construction jobs [3]. Recently, research has also embarked on more general-purpose or human-assisted robotics in construction, such as aerial robots, robotic exoskeletons, collaborative robots and humanoid robots [4, 5].

Previous works have contributed to the development of construction robots and demonstrated technological and economic feasibility in specific cases [6]. However, robots have yet to experience large-scale, real-world implementations in construction. There are still doubts regarding how robots will outperform humans in construction and what new problems they might introduce [4, 7]. One major barrier hindering the effective implementation of robots in construction is the complex interfaces between robots and traditional construction processes. However, there is still limited exploration of these interfaces and how they can be effectively managed.

This paper fills the above knowledge gap by achieving three objectives: 1) identifying the potential challenges related to the complex interfaces between robots and traditional construction processes; 2) examining causes of interface problems; and 3) proposing strategies for effective interface management. The research is based on a case study of a pilot trial of an overhead drilling robot in Macao, drawing on the classification of the interfaces into physical, contractual and organizational (PCO) dimensions [9].

2 Background

2.1 Interface Management in Construction

The term ‘interface’ generally refers to the soft or/and hard interaction of entities (e.g., products, people) with boundary limits [8]. In construction, Pavitt and Gibb (2003) [9] argued that interfaces between different elements and components cause most problems and highlighted the importance of interface management.

Interface management is critical to project success, as it could directly or indirectly affect the time, cost and quality performance of a construction project [10]. Wideman [11] defined it as '*managing the problems that often occur among people, departments, and disciplines rather than within the project team itself.*' Construction Industry Institute (CII) [12] defined it as '*management of communications, relationships, and deliverables among two or more interface stakeholders*'. The effective implementation of interface management could enhance construction processes, reduce the occurrence of rework, and shorten the overall construction period [10].

Earlier research has identified interface problems that emerge in traditional construction projects due to the complex and fragmented nature of the construction industry [13]. In particular, poor communication and coordination among project stakeholders have been widely recognized as key issues leading to interface problems like design errors and construction conflicts [14]. Recent studies examined the problematic interfaces in modern construction methods, like prefabricated and modular construction [15, 16].

However, limited empirical research has investigated interface problems from the adoption of construction robots. The introduction of robots as a disruptive technology to the traditional construction processes often involves complex interfaces and triggers new interface problems. To unleash the full potential of robots in construction, it is essential to understand the potential interface problems and develop effective interface management strategies.

2.2 Physical, Contractual and Organizational Interfaces of Robots in Construction

There are different ways to understand interfaces and interface management. From a systems perspective, interface management can be categorized into four types: time, relational, information, and environmental [17]. Additionally, Pavitt and Gibb [9] classified three types of interface management within construction as physical, contractual and organizational. Specifically, physical interfaces refer to the actual physical linkage between two or more building elements or components; contractual interfaces relate to how the work packages involving processes and people have been formed from a contractual basis; organizational interfaces indicate managerial interactions related to individual and/or group relationships. Building upon Pavitt and Gibb's categorization [9], this research examines the complex interfaces from the three dimensions, with a specific focus on the integration of construction robots.

Physically, the implementation of robots on construction sites necessitates careful consideration of spatial constraints, adaptability to diverse and complex work environments, and the potential impact on construction personnel and existing infrastructure.

Contractually, the introduction of robots could affect traditional contracting and subcontracting practices and result in new issues related to obligations, liabilities, and profitability.

Organizationally, the integration of robots will change the existing workflows, roles, and responsibilities of various parties on construction sites, which require organizational adjustments, such as redefining job roles and fostering an innovative culture to embrace change.

3 Methodology

The research design is illustrated in Figure 1. Initially, a critical literature review was conducted using databases including Web of Science, Scopus, and Google Scholar, with keywords related to "construction robotics" and "interface management". The review aims to examine the application challenges of construction robots and explore the potential interface problems, which enables the preliminary analysis of physical, contractual and organizational (PCO) interfaces of robots.

Then, a case study of the implementation of an overhead drilling robot in Macao was carried out to further analyze the PCO interface problems between the drilling robot and traditional construction processes. The case study utilized multiple sources of evidence, including documents, researchers' observations of the actual application of the robot through site visits, and 7 semi-structured interviews with key stakeholder groups covering principal contractor and mechanical, electrical and pumping (MEP) subcontractors. The interviewees were purposefully selected considering their direct involvement in the case of the drilling robot and work experience in the industry, including 1 project director, 2 project managers, 1 site manager and 3 technical staff. The interview questions were semi-structured, combining both open and closed-ended questions to gather comprehensive insights into the interface problems associated with robot integration. In particular, the interviewees were asked to provide their perspectives on what specific interface problems they encountered, why these problems occurred, and their suggestions for addressing these challenges. Each interview lasted for approximately 20-30 minutes. The data collected from the case study were analyzed using the NVivo 15 software.

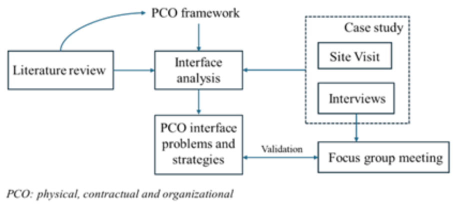

Figure 1. Research design

Finally, the initial findings identified from the case study were further validated through a focus group meeting with the previous interviewees.

4 Case Study Results and Analysis

4.1 Case Background

The case study was conducted with a pilot trial of an overhead drilling robot applied on the construction site of a residential building project comprising 1,566 residential units. The project is in the form of an Engineering Procurement Construction (EPC) contract in which the MEP work is carried out by various subcontractors. The pilot trial was initiated by the principal contractor, while the robot was responsible for the drilling tasks involving MEP engineering.

The overhead drilling robot utilized in the case study project is a semi-automatic construction robot (Figure 2), with a flexible robotic arm for drilling tasks mounted on a mobile vehicle. It is specifically designed for MEP and interior installation work, which is often strenuous, challenging, and time-consuming for construction workers. In the studied case, the operator was an electrician with one hour of training.

During the construction process, the operator needs to move the robot to the designated work area via a controller and utilize a total station for positioning purposes. Then, within the achievable area, the robotic arm can automatically drill holes for one or multiple MEP subcontractors based on the design data from AutoCAD or Revit.

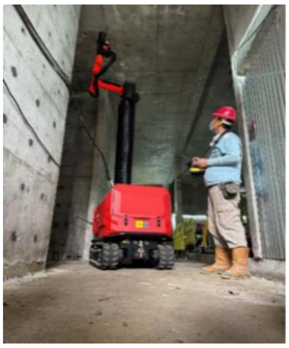

Figure 2. The overhead drilling robot

Compared with traditional manual-based methods, the drilling robot can offer several distinct advantages. For instance, it can eliminate potential risks associated with overhead installation and conduct vacuuming operations during drilling for improved occupational health and safety. Moreover, the robot can enhance productivity and efficiency by autonomously marking and drilling holes according to digital plans.

4.2 Interface Analysis

Drawing on the case project, the identified PCO interface problems, potential causes, and key stakeholders are shown in Tables 1 to 3, and elaborated in the following subsections.

4.2.1 Physical Interfaces

The implementation of the drilling robot may lead to physical interface problems between robot and operator/worker, site environment, and built structure.

Between robot and operator/worker: During the drilling process, human errors by robot operator (e.g., accidentally touching and displacing the total station) may result in construction deviations. Additionally, cross-work and collaboration between the robot and construction workers from multiple trades are inevitable, potentially leading to physical contact and associated problems.

Between robot and site environment: The dynamic and complex construction site presents significant challenges for the robot performance, particularly regarding their interfaces with site environment. For example, as one interviewee noted, "*due to the high reliance on the total station, when facing a space/room with many obstructions, operators must perform multiple positioning operations for the robot, which greatly reduces its efficiency.*"

Between robot and built structure: The robot's primary function is to drill holes in the built structure to meet the installation requirements of MEP engineering. Consequently, it will inevitably encounter the built structure. The robot may face physical interface problems with the rebar or pre-built piping inside the structure and with the finished paint on the surface.

To summarize, potential causes for physical interface problems mainly include the lack of technological maturity of the robot (such as limited mobility, flexibility, and adaptability) and poor engineering management.

4.2.2 Contractual Interfaces

When work elements are grouped into different work packages to meet the needs of the principal contractor, new contractual interfaces may arise between work packages, typically involving specialist contractors [10]. The introduction of the drilling robot may create contractual interface problems in terms of work package reassignment and liability attribution among stakeholders.

Work package reassignment: The drilling robot is designed for a single task with the aim of integrating all MEP drilling tasks, while in the case project, these tasks were undertaken by separate subcontractors. This necessitates the adjustment of relevant tasks at the contract level, which led to contractual interface problems among the principal contractors and MEP subcontractors. Furthermore, due to the limited coverage, areas that the robot cannot reach need to be drilled by workers, which also requires contractual reassignment of work packages.

Table 1. Identified physical interface problems and potential causes

Category	Physical interface problems	Potential causes	Key stakeholders						
			PC	MEP	P	A	S	O	W
Between robot and operator/ worker	• The robot operator or worker may accidentally touch and displace the total station, which could result in localization errors for the robot, potentially leading to subsequent drilling errors	• The localization of the drilling robot highly relies on the total station; no mechanism to avoid or alarm its displacement	√	√				√	√
	• The drilling robot might introduce new risks (e.g., injury) to co-workers	• Workers' unfamiliarity and incompetence in working with the robot	√				√		√
Between robot and site environment	• The drilling robot requires relocalization for different rooms/spaces with obstacles (e.g., columns, walls), resulting in a long setup time	• There should be no obstructions between the drilling robot and the total station	√	√			√	√	
	• Special arrangements are required for the drilling robot to move in a dynamic site environment with steps	• The drilling robot has limited mobility	√	√			√		
	• The drilling robot is incapable of adjusting drilling to construction errors (e.g., discrepancies between actual construction and drawings)	• The robot can't recognize and address construction errors and uncertainties; poor construction management	√			√	√		
	• Uneven ground can affect the drilling quality and accuracy of the robot	• The drilling robot has limited adaptability	√	√			√		
Between robot and built structure	• The robot is unable to make flexible adjustments of drilling when encountering rebar in the structure to meet subsequent MEP installation requirements	• The drilling robot has limited flexibility	√	√			√		
	• The robot may damage the surface of the structure or pre-built piping during drilling	• The drilling robot has a low intelligence level	√	√			√		
	• The drilling robot may cause damage or pollution to the completed ceiling and floor paint	• Lack of measures to protect finished painting for the previous process	√		√			√	

Note: PC = principal contractor; MEP = MEP subcontractor; P = painting subcontractor; A = architect; S = robot supplier; O = robot operator; and W = Worker.

Table 2. Identified contractual interface problems and potential causes

Category	Contractual interface problems	Potential causes	Key stakeholders						
			PC	MEP	P	A	S	O	W
Work package reassignment	• The drilling robot will integrate all drilling requirements of MEP works that are assigned to different subcontractors under separate contracts, with unclear responsibility	• There is no large subcontractor that can provide an integrated MEP engineering solution in Macao	√	√			√		
	• The drilling robot may have limited coverage and require supplementary work by MEP workers	• The robot is unable to access narrow spaces and corners for drilling	√	√			√		√
Liability attribution	• The drilling robot may cause delays (e.g., robot breakdown, maintenance) in project schedule and result in claims	• Improper planning and scheduling with the use of robots	√	√		√			
	• The liabilities are unclear among stakeholders for the drilling errors of the robot due to improper construction works (e.g., uneven ground, construction deviations, problems with drawings), operator mistakes or robot performance that may incur rework and additional cost	• Immature business models	√	√	√	√	√	√	
	• The introduction of the drilling robot necessitates the implementation of additional measures and agreements (e.g., reserve dedicated channels, coordinate working areas) to guarantee robot operating performance	• The drilling robot is integrated into traditional construction as a new element and role	√	√	√		√		

Note: PC = principal contractor; MEP = MEP subcontractor; P = painting subcontractor; A = architect; S = robot supplier; O = robot operator; and W = Worker.

Liability attribution: As a new role introduced in construction sites, the drilling robot requires additional measures and attention to ensure its functional operation. Moreover, factors such as limited robot performance, poor project management, immature business models and improper construction works could result in the misuse of robot that cause project delays, rework, and even additional costs and contract breaches. These circumstances often involve multiple stakeholders in the attribution of contractual liability.

Based on the case study, many respondents considered contractual interface issues as the most critical factors affecting the practical application of robots. Specifically, these issues involve the complex reassignment of tasks and liability attribution resulting from the integration of robots. This could lead to contractual misunderstandings and disputes, and affect the profitability of stakeholders and the overall efficiency of the construction process. Consequently, these challenges could hinder the widespread adoption of robots in the construction sector.

4.2.3 Organizational Interfaces

The implementation of the drilling robot on construction sites involves multiple stakeholders, with various organizational interfaces forming during the communication and collaboration process at project, government and industry levels.

At the project level, with the introduction of the robot and the integration of drilling requirements, the original workflows and responsibilities within the project have been altered, potentially leading to organizational interface issues, such as difficulties in coordination and communication between organizations. Additionally, poor management may result in worker idleness with the introduction of robots on site.

At the government level, the early stages of robot development are characterized by funding shortages and a lack of relevant regulations and standards. Moreover, respondents have argued that the absence of government support in economic and policy aspects significantly hinders the widespread adoption of robots in construction.

At the industry level, organizational interface problems usually involve all stakeholders. These challenges are primarily reflected in industry resistance to adopting robots, which may be driven by a lack of innovative culture. Potential risks posed by robots, such as employment concerns, present additional challenges in the industry.

Table 3. Identified organizational interface problems and potential causes

Category	Organizational interface problems	Potential causes	Related key stakeholders							
			PC	MEP	P	A	S	O	W	G
Project level	• Robotic integration of MEP drilling involves multiple stakeholders, which has more coordination difficulties and is vulnerable to communication problems	• Lack of management and coordination between multiple stakeholders	√	√	√	√	√			
	• There could be worker idling issues during the operation of the drilling robot	• Inexperience of the management team in work arrangements involving robots	√	√					√	
Government level	• There are new legislation and regulation related issues (e.g., additional time for permit approval) with the introduction of the drilling robot	• The development of robots is still in its early stages and lacks standards and practice	√				√			√
	• The drilling robot involves high initial costs, while its development and adoption lack government support and incentives	• The development of robots is still in its early stages and lacks economic justification	√				√			√
Industry level	• The drilling robot may pose a threat to employment opportunities and salaries of workers	• The introduction of the drilling robot will increase efficiency and reduce the need for manual labor	√	√					√	√
	• Multiple stakeholders may have resistance to the adoption of the drilling robot	• Lack of innovative culture and acceptance of new technology	√	√	√	√	√	√	√	√

Note: PC = principal contractor; MEP = MEP subcontractor; P = painting subcontractor; A = architect; S = robot supplier; O = robot operator; W = Worker; and G = government.

4.3 Strategies for Interface Management

Based on the identified interface issues and their causes associated with the integration of construction robots, several strategies are proposed on the technical, contractual and organizational aspects for different stakeholders.

Technical strategies are mainly focused on the design and development of robots to avoid or address technical interface problems, which are particularly important for robot suppliers, including:

- Improve the adaptability and mobility of robots to better interact with unstructured, dynamic and complex construction site environments.
- Enhance the flexibility of robots to handle uncertainties and a variety of construction tasks.
- Design more user-friendly and collaboration-enabled interfaces to allow robots to effectively work with people in a conflict-free manner.

Contractual strategies primarily concern the need to adjust existing contractual arrangements among principal contractors and subcontractors, including:

- Adjust and optimize contracts to reasonably allocate work packages and improve liability attribution. This includes clarifying the new roles and responsibilities of stakeholders considering the introduction of robots and ensuring that contractual terms align with their work requirements.
- Develop new business models to address the potential conflicts and claims arising from robot-related performance issues, foster collaboration among stakeholders with pain/gain mechanisms and better integration.

Organizational strategies primarily consider the requirement of the government and principal contractors' efforts in project management, policy implementation and innovation culture creation to address organizational interface problems, including:

- Principal contractors should embrace potential robot-incurred issues into existing project management practice and enhance the coordination among various stakeholders.
- The government should accelerate the formulation of relevant legislation, regulations and standards to clarify the roles and responsibilities with the introduction of robots in construction. Government support and incentives should be provided during the initial phases of robot development to encourage research and trial projects.
- The industry should cultivate a culture of innovation to increase the acceptance of robots, and take measures to address the potential risks (e.g., worker unemployment) associated with robot integration.

5 Discussion

This paper conducted a case study on the interfaces between the overhead drilling robot and traditional construction processes from PCO perspectives. By analyzing and summarizing the interface problems, their corresponding causes, and preventive strategies, a PCO interface management framework for construction robots is proposed, as shown in Figure 3.

The research has identified potential interface problems when introducing robots in construction environments. Firstly, limitations in the robot's adaptability, intelligence level and collaborative ability impact its performance in the construction process. This results in numerous physical interface problems, primarily occurring between robots and operators/workers, construction site environments, and existing built structures. Secondly, the contractual interface problems, which are identified as the most critical factors affecting the practical application of robots, mainly involve the reassignment of work packages and the attribution of contractual liabilities. On the one hand, the introduction of the robot integrates traditional tasks in a different way, which incurs changes in work processes and requires the reassignment of subcontractors' work packages. On the other hand, potential issues (e.g., rework, project delays) caused by robots require a determination of contractual liability attribution. Finally, organizational interfaces mainly occur among different organizations or individuals. Factors such as poor communication and collaboration, as well as the lack of clear regulations and standards, may lead to interface problems at the project, government, and industry levels. These findings echo with previous studies to highlight the importance of developing new business strategies and stakeholder networks to promote the implementation of construction robots [18].

The findings further indicate the complex interactions among PCO interfaces. Firstly, physical interface problems can affect the contractual interface. For instance, the mobility limitations of the drilling robot in the studied case necessitated the establishment of a dedicated working channel, requiring supplementary contract clauses. Conversely, modifications to the contractual interface can lead to the regrouping of certain work elements into new work packages, which may involve different subcontractors and result in changes in physical interfaces. For example, integrating the drilling tasks using the robot could create additional physical interfaces between the robot and MEP subcontractors. Secondly, both physical and contractual interfaces can influence organizational interfaces. Physical interface problems (e.g. worker idling) can intuitively reflect issues in communication and collaboration between organizations. Meanwhile, contractual interface issues, such as conflicts and liability attribution, can negatively affect inter-organizational collaboration and organizational profitability. Finally, effective coordination of organizational interfaces can address problems related to physical and contractual interfaces, such as coordinating work areas and adjusting contract terms.

This study adapts the PCO classification for interface management in the construction field [9, 20] and pioneers the research of interface management for construction robots. While previous studies mainly focus on technical challenges of construction robots in the implementation [19], this research emphasizes the underlying interface problems in the contractual alignment and division of work that could hinder the real-world application of robots in construction. The developed framework enriches the previous studies by specifying the interface elements and illustrating the complex interrelationship among multi-dimensional interfaces, which contributes to both knowledge fields of interface management and construction robots.

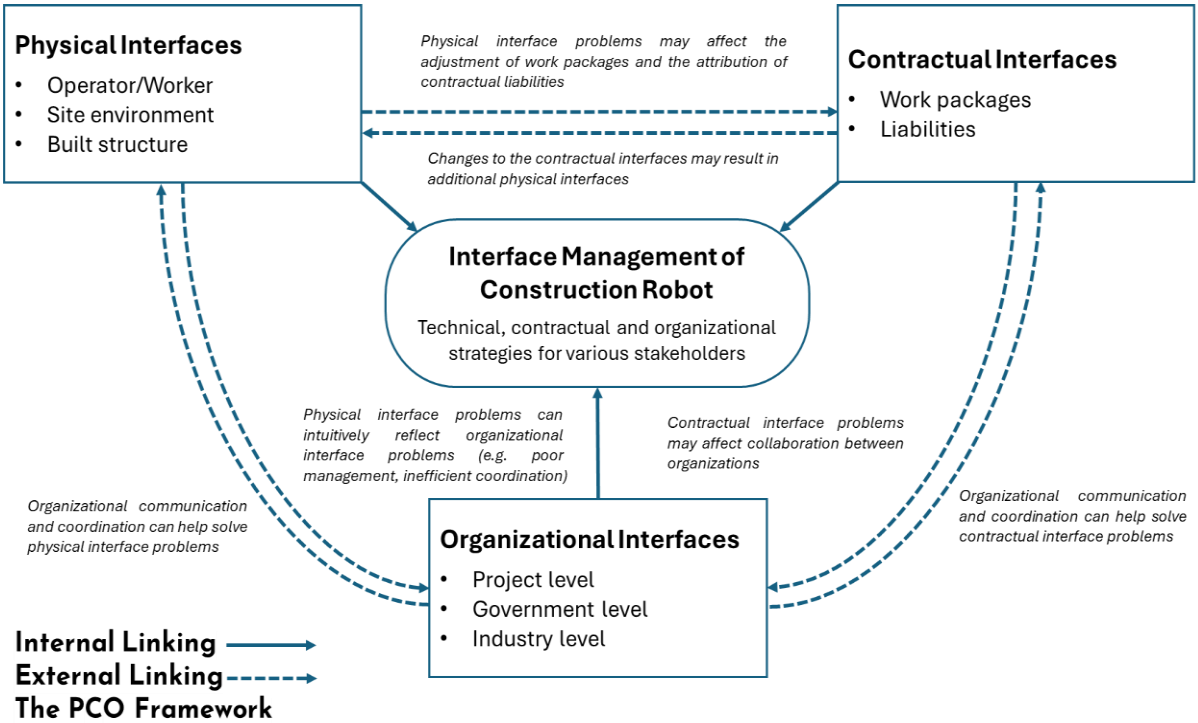

Figure 3. PCO interface management framework for construction robots

6 Conclusion

This paper investigates the interface management of construction robots through a case study of an overhead drilling robot by examining the interface problems, potential causes and preventive strategies. The findings reveal complex interface issues emerging between robots and traditional construction processes, leading to an innovative PCO interface management framework for construction robots. In particular, contractual interface issues are highlighted as the most critical factors hindering the implementation of robots, including work package reassignment and liability attribution. The findings further highlight the importance of developing new business models and stakeholder collaboration schemes with innovative contract forms to address the interface problems involved in construction robot implementation and support effective technology uptake.

This research contributes to the literature on interface management in the construction industry by proposing an innovative framework for interface management specific to construction robots. The PCO framework offers a new theoretical foundation for understanding the complex interfaces with the integration of robots in construction, and provides valuable insights for the industry and academia to address the interface problems derived from the implementation of construction robots. Future research can extend the research by incorporating a broader range of construction robots. Further research can also apply the framework in different institutional contexts to improve its generalizability.

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