Customer Satisfaction in Construction Robots: A Multi-Stakeholder Perspective

Siwei Chang[1] Kwok Tai Wai[2] Ching-Wei Chang[1] Yixing Yuan[1] Juhao Su[3]

[1]Hong Kong Center for Construction Robotics, Hong Kong
[2]Wah Tung Façade Company Limited, Cheung Sha Wan, Hong Kong
[3]Academy of Interdisciplinary Studies, The Hong Kong University of Science and Technology, Hong Kong S.A.R.

siweichang@ust.hk, davidkwok@wahtungfacade.com, ccw@ust.hk, yixing@ust.hk, jsuan@connect.ust.hk

Abstract

Construction robotics, regarded as a key trigger to reshape the traditional construction industry, has continuously emerged. Although various construction robot prototypes have been developed, only some of them are widely adopted for on-site practices. To improve users' acceptance of this novel technology, this research aims to investigate customers' satisfaction levels utilizing construction robots to address construction constraint factors from a multi-stakeholder perspective. Specifically, ten constraint factors were identified through a systematic literature review. The satisfaction level for each constraint factor was then scored using a 1-5 Likert scale through a questionnaire survey. Based on the satisfaction scores, six key stakeholder groups were first segmented using the k-means algorithm to target acceptance patterns. Mean score ranking of the scores marked by stakeholders unwilling to adopt construction robots was conducted to identify current concerns. Results indicate that acceptance is more probable among experienced stakeholders and those familiar with construction robots, signifying the market's readiness for broader adoption. High costs and a lack of partnership cooperation emerged as primary constraint factors. Recommendations to solve these concerns are detailed. The results contribute to speeding up the development of construction robots by investigating and improving customer acceptance of this novel technology.

Keywords –

Construction robotics; Customer satisfaction; technology acceptance

1 Introduction

Construction robots, defined as intelligent machines equipped with sensors, actuators, and advanced control systems tailored for construction activities, have evolved significantly since the late 20th century [1]. This technological evolution has led to diverse applications, ranging from inspection and excavation to on-site construction and demolition.

For example, [2] developed a robotic vehicle system for unmanned excavations (depicted in Figure 1 (a)). This unmanned excavation paradigm integrates a vehicle chassis and 6 degrees of freedom (DOF) manipulators, augmented by sensor suites comprising cameras, real-time kinematic positioning (RTK), global positioning system (GPS), and inertial measurement unit (IMU) that are used for comprehensive position and attitude measurement. A 5G communication module was developed to facilitate the transmission of control signals. [3] advanced the field with a polyarticulated robot featuring an articulated arm affixed to an automatic guided vehicle (AGV) for precision-controlled automated concrete pouring tasks (Figure 1 (b)). Executing its operations based on trajectories derived from Building Information Modeling (BIM) geometry information, the system manipulates the articulated arm and AGV, facilitating precise concrete pouring at predetermined positions. [4] introduced a retractable robot for automated wall spraying (Figure 1(c)), demonstrating meticulous engineering to balance the imperatives of a compact robot and a large working area. Controlling algorithms, including a surface-to-surface parallel adjustment mechanism relying on laser ranging and a polar coordinate transformation method leveraging LiDAR data, confer the ability to maintain parallelism to the wall during spraying and autonomously identify working areas. Concurrently, [5] developed a robotic system tailored for the sorting of construction demolition waste (Figure 1(d)). This system, featuring a wheeled mobile chassis for precise navigation and a robot manipulator for waste handling, incorporates computer-vision technology to recognize and locate waste.

Rigorous validation through both laboratory testing and on-site validation substantiates the system's capacity for the autonomous execution of envisioned high-efficient construction processes. However, despite the development of these pioneering prototypes, the on-site integration of construction robots remains gradual [6-7]. The examples mentioned are still in the initial design or field-testing stages and are yet to be accepted for practical uses.

This study aims to enhance users' acceptance of this novel technology by examining its customer satisfaction from a multi-stakeholder perspective. Here, customers refer to the one who may pay for the construction robots and then use or interact with them. The findings reveal an in-depth recognition of various customer requirements and expectations, which is an important foundation for the design and evolution of construction robots. These findings also provide insights into facilitating the strategic prioritization of features and functionalities that hold the utmost significance for users.

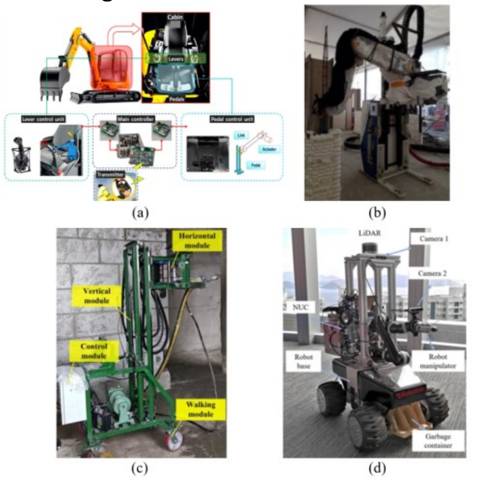

Figure 1. Construction robot prototypes. (a) Unmanned excavator. (b) Polyarticulated concrete pouring robot. (c) Wall painting robot. (d) Demolish waste collection robot

2 Literature review

In accordance with the Technology Acceptance Model (TAM), customer satisfaction, regarded as an indicator of perceived usefulness and ease of use, is increasingly employed to measure the acceptance level of advanced technologies [8]. For instance, [9] conducted a study to identify influential factors that affect customer satisfaction with building information modeling (BIM). to evaluate the success of BIM implementation. To stimulate user's acceptance of BIM, [10] employed the entropy method to establish a quantitative model for the measurement of BIM user satisfaction. The significance of examining customer satisfaction to enhance technology acceptance has been underscored by existed research studies [11]. Therefore, this study intends to enhance users' acceptance of construction robots by comprehensively understanding customer satisfaction, focusing on mitigating critical constraint factors within construction works.

In particular, this study explores customer satisfaction from a multi-stakeholder perspective, aiming to consider diverse needs and expectations across roles in the construction industry. A proactive approach to addressing concerns and barriers from a broad perspective is also expected to explore potential collaboration patterns that promote the integration of robotic technology into the traditional construction industry.

3 Methodology

An in-depth literature review was initially conducted to identify these constraint factors, such as time, cost, and quality [12]. Subsequently, a survey was conducted among six distinct stakeholder groups. The invited experts were asked to score their satisfaction with implementing construction robots for mitigating constraint factors using a 1–5 Likert scale. The experts were selected using the Delphi method [13]. The reliability of questionnaire responses was verified using Cronbach's α. During the data analysis phase, stakeholder groups were first clustered into segments based on similar scoring patterns using the k-means algorithm. This segmentation facilitated a focused and targeted finding by refining observations from individual stakeholder groups. Further, factor scores within stakeholder segments were ranked using the mean score ranking to elucidate primary concerns and interests. The detailed research methodology and findings are explained below.

3.1 Identify constrain factors

A systematic literature review was conducted in this section to search for constraint factors. The constraints are the factors that prevent construction process from progressing smoothly. Scopus was chosen for the following reasons: 1) Scopus has frequently been employed in construction-related review studies [14]. 2) Scopus covers a broader range of disciplines, including engineering, construction, and management, and has the potential to index construction constraint management papers [15]. 3) Scopus contains more recent citations and provides the most recent research findings, which is critical for staying current in rapidly evolving fields [16]. To narrow the search scope of construction constraints, the following search keywords were used: "construction," "industry," and "constraint." The search string used was "article title, abstract, keywords." A total of 1925 papers with constraint analysis were chosen to identify constraint factors.

VOSviewer, a popular bibliometric analysis tool, was employed to extract and classify constraint factors efficiently. The searched literature was specifically exported from Scopus into a ".csv" file, then imported into VOSviewer for keyword analysis. The VOSviewer's keywords co-occurrence analysis section was used to extract and summarize keywords from the 1925 papers automatically. Figure 2 depicts the visualization of keyword occurrences. As can be seen, a comprehensive visualization of constraint words, such as "cost," "time," and "quality," can be obtained.

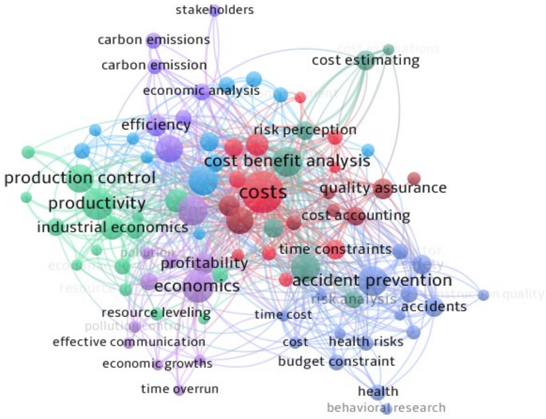

Figure 2. Keywords co-occurrence map

From the keyword co-occurrence map, a total of ten constraint factors were identified. Table 1 lists and describes the identified factors. The factor "time" refers to time delays that affect the smooth construction process. The factor "cost" refers to budgetary constraints and cost overruns that affect project profitability. The factor "quality" refers to the issue of quality compromise, which causes safety concerns. The factor "environment" includes concerns for the environmental impact of construction activities. The factor "safety" is concerned with ensuring the well-being of construction workers in order to prevent accidents and injuries. The term "labour shortage" refers to the shortages of skilled workers. The factor "communication" involves difficulties in the insufficient exchange of information among project stakeholders, which is critical for coordinating activities. The factor "partnership" refers to concerns about collaboration and coordination among various entities caused by the fragmented and diverse nature of construction activities and a lack of trust in cooperation. The factor "production" refers to the problem of inefficient material and machinery production to meet project demands. The factor "logistics" refers to the problem of inefficient material, equipment, and personnel transportation, which is critical for the timely delivery of resources to the construction site and minimizing disruptions to the workflow.

Table 1 Constraint factors and their description

ID	Factor	Description
F1	Time	Schedule delay problem
F2	Cost	Budgetary limitation and cost overruns
F3	Quality	Quality compromise problem
F4	Environment	Concerns related to the ecological impacts
F5	Safety	Hazardous caused by accidents and injuries
F6	Labour shortage	Lacking availability of skilled workers
F7	Communication	Inadequate exchange of information
F8	Partnership	Hesitations on the collaboration and coordination
F9	Production	Inefficient production of materials and machinery
F10	Logistics	Lacking efficient movement and transportation

3.2 Score satisfaction

To investigate customer satisfaction with employing construction robots to alleviate the identified constraints, a questionnaire survey was conducted. In Hong Kong in 2023, an electronic questionnaire was generated using Google Form and distributed to invited experts via e-mail and mobile messaging with a web link. Using a five-point Likert scale, the experts were asked to express their professional views on whether they satisfied with using construction robots to alleviate the ten constraint factors (1 = strongly agree; 2 = agree; 3 = neutral; 4 = disagree; 5 = strongly disagree). The Likert scale method was chosen due to its ease of quantifying and rating the level of satisfaction with individual constrain factors based on the opinions of multiple stakeholders.

56 effective respondents were collected. The 56 responses can be considered sufficient because it has been proven that a median of 32.5 to 40 participants is acceptable in phenomenological studies [17]. The response rates of government departments, developers, consulting firms, main contractors, sub-contractors, and universities are 40%, 35%, 40%, 40%, 65%, and 60%, respectively.

The invited experts involve six stakeholder groups: consulting firms, government departments, main contractors, real estate developers, subcontractors, and universities. The distributions of the six stakeholder groups are shown in Figure 3. All the stakeholder groups are regarded as the prominent participants in the construction industry [18]. Only those with experience in construction technology and advanced construction technology, including construction robotics, were invited. The reliability and credibility of the research can be ensured because: 1) Most of them, especially the university professors, have both industry and academic experience. Survey participants with multiple backgrounds across organizations provide more valid responses [19]. 2) 82% of the experts held top positions in their organizations, such as senior or executive level (30%). 3) 82% of the experts have more than five years of working experience in the construction industry and grasp knowledge of construction robotics.

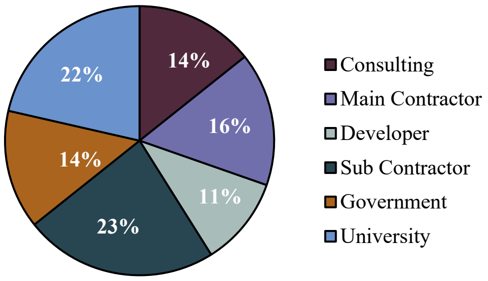

Figure 3. Distribution of investigated experts

3.3 Data analysis

3.3.1 Reliability testing

Cronbach's alpha coefficient was first measured to test the reliability of the collected response. Cronbach's alpha presents response reliability by measuring the internal consistency of the satisfaction scores on each constraint factor. Cronbach's alpha measures the degree of consistency on a standardized scale ranging from 0 to 1. A higher Cronbach's alpha indicates higher reliability because a participant is likelier to provide similar scores for the assessment items [20].

The responses were first imported into the SPSS software to compute the Cronbach's alpha index. A Cronbach's alpha value of 0.89 was obtained, indicating the acceptable reliability of the responses.

3.3.2 Stakeholder segmentation

Stakeholder groups with similar characteristics were segmented to investigate overall concerns and interests among different stakeholder groups, explore potential collaborative possibilities, and provide targeted solutions. K-means, a widely used unsupervised machine learning technique, was employed to do so. The k-means clustering algorithm divides a dataset into distinct and non-overlapping groups by assigning data points to clusters iteratively based on their proximity to each cluster's mean (centroid). The k-means algorithm has been widely used in customer segmentation due to its simplicity, versatility for clustering numerical data, and intuitive approach. For instance, [21] utilized a k-means algorithm to cluster customers to study how well a specific product performs in terms of marketing. The findings were proven more accurate by introducing the k-means algorithm, an unsupervised learning-based processing method. Because of the scattered nature of the scoring data, this study employed the k-means algorithm to cluster the six stakeholder groups to find hidden satisfaction patterns.

Specifically, the initial cluster centroids were determined by randomly selecting several K points from the dataset. Second, each data point was assigned to the cluster centroid that was closest to it, and the distance between the data point and the assigned cluster centroid was calculated using Euclidean distance (see Equation (1)). Finally, the centroid points were updated, the data points were reassigned, and the distance was calculated again. Steps 2 and 3 were repeated until the sum of the distances (computed using Equation (2)) reached the minimum to determine the cluster centroid and the specific cluster of each point.

$$d(d_i, c_i) = \sqrt{(x_{di} - x_{ci})^2 + (y_{di} - y_{ci})^2} \tag{1}$$

$$dj = \sum_{i=1}^{k} d(d_i, c_i) \tag{2}$$

Here: $d(d_i, c_i)$ refers to the distance between the data and centroid points. d_i and c_i refer to the $i-th$ data point and centroid point, respectively. x_{di} and x_{ci} refers to the $i-th$ x coordinates of the data point and the centroid point. y_{di} and y_{di} refers to the $i-th$ y coordinates of the data point and the centroid point. dj refers to the sum of the distance. k means there are $k-th$ centroid points in total.

To determine the optimal number of clusters, the elbow method was employed. First, the within-cluster sum of squared errors (SSE) for various centroid point values was calculated. When the SSE value first begins to decrease, the optimal number of centroid points appears.

The algorithm was coded using the Python language. The KMeans package of the sklearn.cluster library was employed to execute the k-means algorithm.

3.3.3 Mean score ranking

The significance of factors was determined using a widely used data statistic approach, the mean score ranking method [22]. Using Equation (3), the 1-5 Likert scale scores, representing customers' satisfaction with using construction robots to mitigate constraints, are averaged across all score sets. The lower the mean score, the higher the satisfaction because the scoring was presented on a scale of 1 = strongly agree, 2 = agree, 3 = neutral, 4 = disagree, and 5 = strongly disagree.

$$\overline{X_F} = \frac{1}{n}\sum_{i=1}^{n} X_{iF} \quad (3)$$

Here $\overline{X_F}$ refers to the mean score for factor F. n refers to the number of customers in a stakeholder segment. X_{iF} refers to the score for factor F of each stakeholder.

4 Results

Figure 4 depicts the computed SSE values, which indicate the optimal number of clustering centers. As can be seen, when the number of cluster centers reaches 3, the elbow point appears. Before that, the SSE value drops dramatically from 200 to 13.5. After that, the SSE value steadily decreases from 13.5 to 0.05 as the cluster center number increases from 3 to 6, after which the SSE value remains constant. As a result, the optimal cluster center number was determined to be 3, the SSE curve's elbow point.

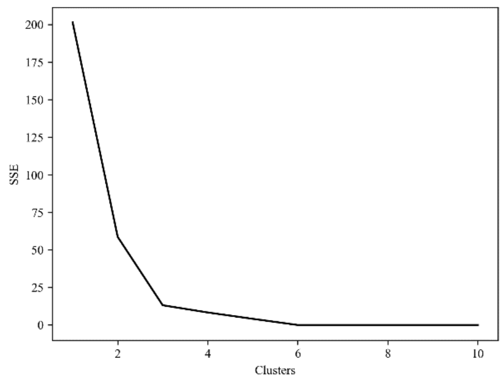

Figure 4. Visualization of SSE result

Figure 5 depicts the results of segmentation for six different stakeholder groups. The initial number of cluster centers was set to three based on the SSE computation result. The six stakeholder groups are represented by the x-coordinate in the following order: 0-consulting, 1-main contractor, 2-developer, 3-subcontractor, 4-government, and 5-university. The mean scores of the ten constraint factors are represented by the y-coordinate. The mean values were used as a representation of all observations [23] and were fed into the k-means algorithm instead of the initial scores. The blue dots represent each stakeholder's mean score, while the red triangle represents the cluster centers.

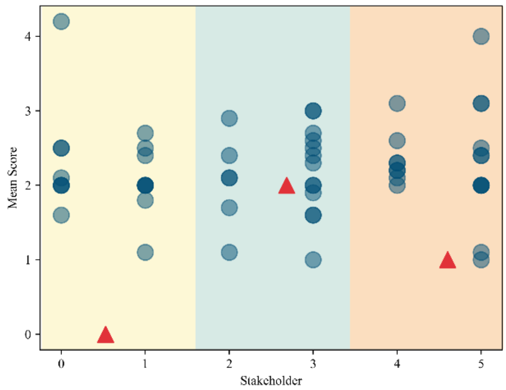

Figure 5. Stakeholder segmentation.

Based on their preferences, the six stakeholder groups were categorized into three groups. Segments 1, 2, and 3 consist of government and university, developer and subcontractor, consulting and main contractors, with (0.53, 0), (2.68, 2) cluster centers, respectively. The majority of the stakeholders are confident of utilizing construction robots to alleviate constraint factors, as indicated by the distribution of their mean scores, which range from 1 to 3. To facilitate an in-depth discussion of customer satisfaction, the distribution of each stakeholder's satisfaction score is detailed below.

5 Discussion

5.1 Satisfaction analysis among stakeholders

Figure 6 demonstrates stakeholders' satisfaction scores for each constraint factor, reflecting how satisfied stakeholders are when employing construction robots to mitigate constraints. Overall, the majority of the stakeholders show a neutral or positive attitude. The areas with satisfaction scores of 2 overlap. the most, with nearly 48% of the stakeholders agreeing that using construction robots can help improve constraints to some degree. It is also worthwhile to be aware of any potential acceptance hesitations. The overlap area of scores of 3 ranks second, with nearly 26% of stakeholders holding a neutral attitude toward the effect of construction robots. A general industry concern about embracing rapid technological changes when there is no apparent productivity or financial benefit may result in neutral attitudes [24]. A lack of familiarity and hands-on experience may also contribute to a cautious attitude [25]. While nearly 7% of stakeholders scored a 5, they strongly opposed the adoption of construction robots.

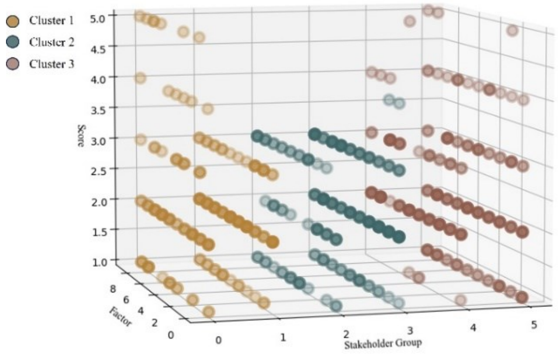

Figure 6. Satisfaction scores of stakeholder groups on constraint factors

It can be seen that stakeholder segment 2 (developer and subcontractor) is currently the most satisfied with construction robots. Almost all of them showed a satisfaction score of 2. It's interesting that experienced experts are more likely to accept construction robots. All of the stakeholders in the second segment are experienced experts who hold senior or executive-level positions in their organizations. Most of them have more than 20 years of experience in the construction industry. Senior-level stakeholders with extensive construction industry experience have most likely witnessed and adapted to various technological advancements. They may be more open to accepting and embracing construction robots because of a history of adapting to new technologies [26]. Senior and executive-level stakeholders are often critical in shaping the strategic direction. Their long-term perspective allows them to see construction robots' potential transformative impact.

Another pattern is that stakeholders more familiar with construction robotics are more likely to accept it. Construction robots are well-known to nearly 84.2% of stakeholders in the second segment. Customers familiar with construction robots are likely to have firsthand knowledge of or exposure to the technology [27]. These customers may have received education or training on using and benefitting from construction robots. This hands-on experience allows them to comprehend the practical benefits, operational capabilities, and potential benefits that construction robots bring to projects.

The satisfaction of experienced and familiar customers may indicate that the market is ready for more widespread adoption of construction robots. Positive feedback from these customers validates the practical benefits and dependability of construction robots, indicating that it is an appropriate moment to invest in the product further. The finding is consistent with [28], which claims that familiar and experienced customers indicate product credibility. If the product, including all the forms of construction robot products, such as mechanical arm, elements, and the services, currently meets the needs of experienced and familiar users, it may be worth investigating possibilities to diversify its applications or functionalities. It is critical to continue collecting feedback to improve continuously [29]. Furthermore, the findings highlight the importance of educating potential users on the benefits and capabilities of construction robots. Increased awareness can lead to increased user satisfaction [30].

5.2 Satisfaction analysis of constraint factors

Although stakeholders in the second segment have a positive attitude, some experts, particularly in the third stakeholder segment, have expressed their unwillingness to accept construction robots. The satisfaction scores of 4 and 5 appear 21 times, indicating that these stakeholders disagree or strongly disagree about the effectiveness of using construction robots to mitigate constraints. This section discusses the mean score ranking of satisfaction scores for each constraint factor provided by the stakeholders in segment 3 (government and university) to identify key concerns that impede the acceptance of construction robots and suggest improvement possibilities.

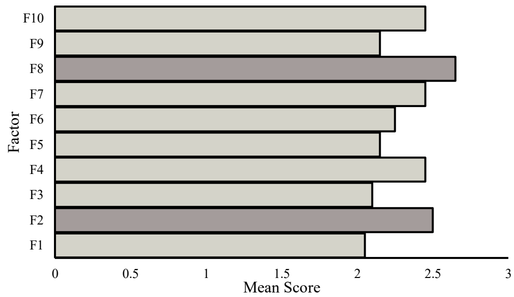

Figure 7. Mean score ranking of satisfaction scoring on each constraint factor

Figure 7 depicts the ranking of satisfaction scores on each constraint factor by mean score. It can be seen that the top two concerns are constraint factors F2 (cost) and F8 (partnership). The findings show that some customers believe there is no obvious benefit to using construction robots to reduce construction costs and increase partnership collaborations. While it may appear counterintuitive for government and universities to be concerned about the high overall cost of using construction robots because they do not directly lead construction projects. There are several reasons behind: 1) Government is subject to budget constraints. Concerns about high costs reflect a sense of responsibility to taxpayers as well as the need to demonstrate responsible use to prevent public resources from overspending [31]. 2) Universities frequently collaborate on research projects with industry partners. If the cost of implementing construction robots is perceived to be high, it may influence industry partners' willingness to engage in collaborative ventures, affecting research opportunities and industry-academic partnerships [32].

Customers in government and universities are dissatisfied with the performance of construction robots in improving partnership collaborations, in addition to the high cost. Building strong social networks and enhancing collaboration is critical for universities to apply for research funding and conduct research [33]. As a result, they expect the construction robots to be able to improve collaboration among various stakeholders to ensure a smooth construction process. Governments are in charge of the regulatory frameworks that govern industries. If construction robots cannot improve partnership collaboration, it may impede the creation of an environment conducive to the successful integration of all participants [34].

Cost-cutting strategies such as flexible leasing and financing options are suggested to alleviate customer concerns about high costs. Offering alternatives to outright purchase can alleviate financial burdens and make construction robot adoption more accessible [35]. Designing construction robots in a modular manner to facilitate adaptability and scalability has the potential to increase customer acceptance. Customers may begin with a smaller investment and scale up as needed, matching the cost to the specific needs of their projects [36].

Focusing on the concept of human-robot teaming, in which construction robots supplement rather than replace human skills, may help address the partnership collaboration issue [37]. It is also suggested that features such as natural language processing, gesture recognition, and real-time communication interfaces be included to improve collaboration and provide advanced communication capabilities to construction robots. Developing construction robots that can adapt to the dynamic and fragmented nature of construction workflows is also recommended. Using machine learning algorithms and artificial intelligence (AI) to enable robots to understand and respond to changes in tasks, schedules, and team dynamics promotes better coordination.

6 Conclusion

Due to the limited adoption of various prototypes, a comprehensive investigation into customer satisfaction and acceptance of construction robots has been conducted. To do so, stakeholders' satisfaction level on using construction robots to mitigate constraints, such as cost and time, were analyzed. Ten constraint factors were identified through a systematic literature review. Their satisfaction scores were given using a Likert scale via a questionnaire survey. To target satisfaction patterns among multi-stakeholders, six stakeholder groups with similar preference were divided into three segments using the k-means algorithm. The average score ranking of constraint factors revealed existing concerns and improvement possibilities. These findings contribute to our understanding of customer satisfaction and acceptance for the developed construction robot prototypes while also providing actionable detailed insights for further improving their functionality. However, the results are more specific to the development of construction robotics within Hong Kong. Although the construction industry in Hong Kong is representative on a global scale, further study intends to extend scopes by conducting investigations across various regions to achieve comprehensive insights.

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