Delegation or Collaboration: Understanding Different Construction Stakeholders' Perceptions of Robotization

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ABSTRACT

Recent advances in robotic technologies have stimulated interest in bringing robots onto construction sites, which will in turn bring robots and humans into closer working proximity. Introducing robots requires significant redesign of construction processes, crew compositions, and task allocations, and understanding potential end users' perceptions and expectations of these robots is the critical first step in designing and implementing effective collaborative work between humans and robots. To this end, this study examines trade workers' and managers' perceptions and expectations of construction robots. This study undertook a qualitative content analysis of interviews with thirty-six construction professionals to examine how different stakeholders present their perceptions and expectations of robots, depending on their organizational position and specialized trade work. The analysis results indicate that job

complexity and the perceived safety risk associated with the trade most significantly influence workers' desired capabilities for robots as well as their perceptions of robots' usefulness. Based on these findings, this study establishes workers' fundamental conceptions of construction robots with respect to job characteristics, establishing the groundwork and direction for future construction-robot development.

INTRODUCTION

Over the past decade, there has been a paradigm shift in robotic development and deployment. No longer confined to factory settings, robots are now penetrating everyday activities within diverse domains and interacting with humans at various levels, coexisting with people within the same workspace (Koo et al. 2015; Mahadevan et al. 2018), physically assisting and serving people (Kanda and Ishiguro 2017), and even cooperating or collaborating with humans for surgery (Camarillo et al. 2004) and assembly (Krüger et al. 2009). While robots have been deployed especially in arenas where they perform superiorly—such as with tasks that demand precise repetition of high-strength work—tasks requiring such capabilities as dexterous manipulation and experience-based problem-solving have largely been left for human partners (Everett and Slocum 1994; Hoffman and Breazeal 2004). Human-robot teams that fuse the complementary strengths of both entities may potentially carry out more complex tasks than humans or robots can perform alone and may do so while enhancing organizational performance by maximizing safety, quality and efficiency (Bernold 1987).

The important potential benefits of human-robot partnerships have prompted growing interest in robotic technologies in the construction industry, because the majority of construction activities combine strenuous and dexterous tasks. Although current robotic technologies do not fully support all levels of human-robot interactions (HRI), an increasing number of robots with more advanced capabilities are in development and are expected to be deployed on construction jobsites soon (Bock 2015). As a result, potential robotic solutions for future human-robot collaboration (HRC) in construction are manifold. Among the possible solutions, the appropriate form of human-robot collaboration that leads to high performance demands deeper insights into human perceptions of, and expectations for, robot counterparts.

The introduction of construction robots would significantly change current construction practices—especially with regard to the dimensions of crew compositions, procedures, and process—as well as mandate that project teams consider unprecedented objectives, such as ensuring safe and efficient human-robot interactions and proper task allocation between human and robot. Each robot application will emphasize one specific objective more than others, depending on the construction-task priorities. Thus, those designing and deploying robots should pay attention not only to the technology itself but also to its use contexts and to understanding how end users will interact with robots during various tasks and situations (Davila Delgado et al. 2019). For this reason, monitoring end users' perceptions will help determine which attributes will stimulate an effective human-robot collaborative system. Although past studies in the manufacturing sector—where active collaborative robots have currently been the most adopted—indicate that understanding workers' perception provides valuable insights into robot adoption and thereby contributes greatly to improvements in human-robot interactions (Kildal et al. 2018; Wurhofer et al. 2015b), little research has been conducted to date on humans' perceptions of robots in construction trades.

To this end, this study examined the impact of job context in stakeholders' perceptions around questions of robot adoption. We aimed to verify the job-related factors— i.e., organizational position as well as the safety, dexterity, and complexity characteristics of their work qualitatively, by means of semi-structured interviews with various stakeholders spanning job position (e.g., workers vs. managers) as well as specialization (e.g., structural vs. architectural finishing trades). The resulting outcomes contribute to the body of knowledge by establishing foundational insights into different stakeholders' particular perceptions of robot adoption within the construction industry. Such insights will enable organizations to prepare improved guidelines to better support future human-robot teamwork for various construction tasks.

RESEARCH BACKGROUND

Dimensions of Human-Robot Interaction

HRI is a multidimensional construct that involves varying levels of interaction between humans and robots and spans a range of surrounding environments (Scholtz 2003). HRI is often classified based on whether humans and robots are sharing a workspace (collocated vs. non-collocated) and working at the same time (simultaneous vs. asynchronous) (Helms et al. 2002).

Based on these considerations, there are typically three types of HRI categories: *coexistence* refers to operation within a shared workspace at the same time; *cooperation* refers to operation within a shared task and workspace at the same time; and *collaboration* refers to cooperation with additional direct physical interactions (Schmidtler et al. 2015). Similarly, in construction activities, workers engage in a variety of interactions, ranging from sequential executions with no physical contact to close physical collaborations. Depending on the different type of construction robots— e.g., teleoperated system, programmable work-in-place machines, intelligent systems, (Saidi et al. 2016)—many possible human-robot collaborations (HRC) in construction could occur at different levels. These sets of HRI scenarios describe how humans and robots cooperate to complete a target goal in a given context (Mingyue Ma et al. 2018; Ong et al. 2008).

An important component in determining HRI is the designated role of robots because it influences how people perceive and collaborate with the robot. Prior research in HRI has identified a wide range of robot roles, including tool, teammate, and co-worker. The level of

HRI demands certain capabilities and functionalities from robots, especially in the form of perception of the surrounding environment, predicting human intentions, planning actions with respect to the joint intention, and taking actions accordingly (Bauer et al. 2008). Traditionally, robots have been perceived as a tool designed to empower humans to achieve specific goals. The human sets the goal, while the robot assists the human to achieve the goal (Vicentini 2020). As robots have been equipped with advanced perception, mobility, and intelligence in recent years, collaborative robots have emerged to serve equivalent or complementary roles to human partners (Kwon et al. 2020). The choice of role, that is whether or not the robot fully takes over a specific (sub)task or generally assists a human with a task, influences both the workload distribution between human and robot and, consequently, the overall HRI performance (Parasuraman et al. 2008). Thus, the role of a robot should be selected based on required competencies suited for the task at hand (Hinds et al. 2004).

A robot's ability to carry out its own processes and operation—referred to as "robot autonomy"—also characterizes the level of interaction and interdependencies between humans and the robot (Yanco and Drury 2004). Within the spectrum of shared control between robot and human, robot autonomy sets to whom and when the authority is assigned during the task execution, suggesting the level of required human intervention and control (Beer et al. 2014). Construction robots are usually operated either in an autonomous mode or with some level of interaction with a human. For more complex tasks, robots should exhibit a specific level of autonomy to perform tasks with high variability and complexity. If the autonomy level is too low, humans will waste time attending to the robot instead of undertaking more critical works. For example, a survey robot with a low autonomy may not be able to navigate construction sites without a human operator consistently intervening, whereas a robot with high autonomy would perform its task proficiently with minimal human intervention (Musić and Hirche 2017). However, if the robot is too autonomous, the human may lose situational awareness of the activities, and performance errors of highly autonomous robots could yield severe consequences. Thus, the degree of willingness to delegate authority to robots is situation-specific, and even more so in a safety-critical environment (Hancock et al. 2011), and robots should be endowed with a specific level of autonomy to perform tasks of high variability and complexity.

Based on these dimensions of HRI, this study conceptualized robot types by roles and autonomy levels because these variables fundamentally define the human-robot interaction and, in turn, help determine the functionality of the robot for HRC. Given the capabilities of current construction robots, the HRC scenarios presented throughout this paper may not be, by definition, collaborative because they do not support complex interactions involving high level coordination. For the purpose of this study, however, we define human-robot collaboration as any operation completed through a human-and-robot partnership, not necessarily including joint intention or joint action. Based on this definition, this paper presents various HRI scenarios and explores construction stakeholders' perceptions of HRIs in different construction tasks.

Users' Perceptions of Human-Robot Collaboration

Efforts to support technology adoption aim primarily to acquire users' acceptance of new technologies, a process that is largely affected by individuals' perceptions of the technology (Davis 1989). Because user-perception comprises rational thoughts as well as emotional feelings toward a technology, perception influences whether and how users choose to interact with new technologies. Understanding how people perceive robots is crucial to the design process. In the context of robot adoption, depending on how users perceive the robot (e.g., as a collaborative partner or a tool), the primary focus to consider in the design process will differ. Thus, a proper understanding of users' perceptions will enable roboticists to design robots in a way that aligns with users' expectations and reduces negative attitudes toward robot adoption. Because making changes to comply with user expectations is difficult after the robots have been deployed, understanding users' perceptions in the early phase of robot development is beneficial (Graaf and Allouch 2016). Prior work showed that it is important as well to consider the perceptions of a range of stakeholders (Broadbent et al. 2009).

To this end, prior studies aimed to identify the potential factors that affect perceptions and suggest that user perception exists in relation to its use context. That is generated by an interrelated process that resulted from the interplay of technology, user, and the context (Meissner et al. 2020). For instance, Forlizzi and DiSalvo (2006) showed that user perceptions of service robots in the domestic environment were heavily influenced by dynamics of the robots, the physical environment, and the way users operate the robot.

In a hospital context, Ljungblad et al. (2012) suggested that different stakeholders in the hospital exhibited four interpretations of robot roles—as an alien, a machine, a worker, and a colleague. Mutlu and Forlizzi (2008) revealed that contextual factors, including work definition and physical work location, affected such user perception of robots as well as the way they interacted with robots. Users from different units in the hospital formed different perceptions of identical robot behaviors. For instance, caregivers who had closer interactions with patients tended to exhibit a lower tolerance for interruptions caused by robots and perceived the robots as annoying, whereas users in other units perceived robots as entertaining.

In the case of industrial robots in the manufacturing environment, Wurhofer et al. (2015a) identified factors that accounted for workers' perspectives including perceived usefulness, perceived ease of use, and performance expectancy—many of which were influenced by various individual, systematic, and contextual features. Wurhofer et al.'s study highlighted that individual workers (e.g., operators, maintainers) who performed distinct tasks in a factory developed different perceptions of robots and preferred distinctive working procedures in their HRC based on their own preferences and needs.

In combination, these studies reveal that user perceptions are situated in a specific context and suggest that users learn from the context of use. Because user perceptions are context-sensitive, findings derived in other domains do not map onto the unstructured construction environment, and they are not helpful in predicting how users in the construction domain will respond to the technologies. Although the work of Pan and Pan (2020) examined stakeholder perceptions of future construction robot applications, it did not explore how to these perceptions are influenced by a specific construction context. Thus, this study examined job-related factor dynamics within circumscribed contexts to help technology developers better understand and accommodate a human partner's respective positive and negative expectations in order to achieve fluent human-robot teaming.

METHODOLOGY

We conducted a qualitative research study using in-depth interviews to acquire a comprehensive understanding of how different groups of construction stakeholders perceive robot adoption. A semi-structured interview guide with a series of open-ended questions was developed to explore participants' experiences with and opinions of construction robots in general, followed by targeted questions about the specific designs of the robots. Consequently, the acquired data was analyzed using content analysis method, which allows to infer the relationship of certain themes and access to deeper organizational cognition that may not be discovered readily. The detailed data collection and analysis process are described in this section.

Study Design

Theoretical Models for Robot Adoption

Technology adoption refers to any individual's or organization's decision to use an innovation (Rogers 1995). A number of technology-acceptance models provide a theoretical foundation based on perceptions to understand individuals' behavioral intentions when adopting a technology. For example, one of the earliest models, the Technology Acceptance Model (TAM), uses two primary variables—perceived usefulness (PU) and perceived ease of use (PEOU)—to predict behavioral intentions (Davis 1989). Researchers speculate that the effects of external factors on adoption behaviors are mediated by these variables, and research has been undertaken into the relative importance of TAM constructs including other relevant variables such as social influence (e.g., subjective norms, voluntariness, image) and cognitive perception (e.g., job relevance, output quality) to extend the use of TAM for different systems and users (Venkatesh et al. 2003; Venkatesh and Davis 2000).

Despite the validated usefulness of TAM in the construction domain (Ramanayaka and Venkatachalam 2015; Sepasgozaar et al. 2017; Sepasgozar and Bernold 2012), previous findings may not be directly applicable within the construction robot adoption model because robot systems are significantly more complicated given that robots engage in more complex interaction dynamics than are required for other technologies (Beer et al. 2011). Since different HRI contexts have different robot-systems requirements, the diverse contexts of construction tasks may alter users' perceptions in different scenarios (de Graaf and Ben Allouch 2013; Pan and Pan 2019). In response to this knowledge gap, this study examines job-related contextual factors influencing individuals' perceptions about robot adoption to complement current considerations involved in the process of robot adoption.

Job-related factors are defined as the professional and specialization attributes that induce users' perceptions of robots. The first component, professional attributes, refers to the participants' organizational positions, such as general manager, subcontractor manager, and trade worker. Specialization attributes describe the distinct characteristics of the trades, including safety risk, required dexterity, and job complexity. For example, the risk (e.g., a dangerous vs. safe environment) and complexity (e.g., a complex vs. static environment) associated with a trade job will affect the workers' courses of action during task execution. This may impact their perceptions of what is deemed appropriate for robotization and influence their favorable or unfavorable attitudes toward HRC. As described in Figure 1, using these definitions we incorporated job-related contextual determinants into four selected TAM constructs—see Table 1—and built a theoretical model for construction robot adoption to serve as the basis for our data analysis.

Scenario Development for Human-robot Collaborations in Construction

Over the past decade, various on-site construction robot applications have been proposed across construction trades. While some of them entirely replace a part of human work and perform (sub)tasks such as bricklaying ("SAM100 – Construction Robotics" 2020), painting ("Canvas | The Future of Construction" 2020), earthwork ("Built Robotics" 2020), data capture ("Spot® | Boston Dynamics" 2020) and visual inspection (Kim et al. 2020), others are used as tools to assist completing of (sub)tasks such as preparation and handling materials. These diversified robotic solutions suggest that construction robots can come in varying shapes and sizes, offering a corresponding variety of HRC in construction. To explore how different robotic characteristics—especially robot roles (assistive vs. task executing) and varying levels of autonomy (manual vs autonomous)—are perceived by stakeholders, we developed multiple alternative use scenarios in construction as illustrated in Table 2. Participants were asked to provide their responses by interacting with the robots in an indirect way (Reich-Stiebert et al. 2019) in the given scenarios.

We developed the scenarios using the same principles that underlie human-human collaboration in construction to mimic conventional construction work crews usually consisting of a foreman, specialized workers (e.g., masons), and assistants or laborers (e.g., mason helpers). As with human workers, robots were assigned the responsibilities of either a specialized worker executing a skilled trade job or a general assistive laborer supporting the counter partner. The former is referred as a main task-executing robot, which is designed to fully take over a main trade work that is directly related to the construction of a permanent building part. The latter, in contrast, is referred as an assistive robot designed to perform a subtask to help complete the main tasks, such as preparation and handling materials.

For both robot roles, we provided two alternative scenarios with different levels of autonomy, namely remote or teleoperated and autonomous system. For example, in the case of a task-executing robot that is designed to install a wall, a remote-controlled or teleoperated system has less autonomy and intelligence to take its own initiatives while installing the wall. Thus, a human should act as either an operator or a supervisor with continuous control over the robot regardless of whether or not he has a direct view of the robot. In an autonomous system on the other hand, the robot is capable of perceiving the environment and acting autonomously in response to the dynamic environment to complete the installation task. This type of robot, therefore, requires the least amount of human intervention and a human would not be fully aware of the robot's internal state. We also asked participants to interact with this type of robot as bystanders.

Similarly, we provided two use cases for assistive robots as well. In remote-controlled and teleoperated systems, assistive robots are used as machine-like tools, and they were described as augmenting or helping human partners with physically demanding or dangerous work (e.g., delivering heavy materials). Because these robots possess limited autonomy and intelligence, a human worker is asked to continuously control the robots during operation. In comparison, an autonomous assistive robot is capable of not only sensing the environment but also of understanding a human partner's intent and adapting its action accordingly to deliver the material correctly.

We customized this set of HRC use scenarios for different stakeholder groups based on their trades. These scenarios were delivered with relevant videos and photos of sample construction robots and offered as examples to interviewees who had little knowledge of and experience with robots.

Data Collection

Participants

After obtaining an Institutional Review Board (IRB) exempt determination for this study (IRB2020-1292M), we interviewed 36 construction professionals who have 6 to 40 years of work experience and sufficient domain knowledge in the areas of building construction engineering. To acquire more robust interview results, all participants were recruited through industrial organizations currently working on residential and commercial high-rise building projects. High-rise building projects encompass various complex and collaborative construction activities that could benefit greatly from the implementation of robotic technologies (Cai et al. 2019), which made them suitable candidates to reflect diverse HRC scenarios. The research team purposefully recruited a balanced sample of interviewees from the selected high-rise building projects with diverse backgrounds that ranged from general contractors to specialized subcontractors and researchers. The overall sample consisted of high- and lower-level managers as well as superintendents and workers from civil, concrete, structural steel, façade/windows, drywall, paint, masonry, plastering, stone, tile, waterproofing, mechanical, electrical, and plumbing trades, as described in Table 3. While the research team aimed to conduct the recommended number of 10 to 50 interviews, (Charmaz 2006; Francis et al. 2010), the actual sample size was determined by the saturation point, or when new data no longer revealed any new or relevant perspectives.

Interview Procedure

To collect participants' various perceptions of and opinions on future construction robots, the research design employed semi-structured, in-depth interviews to allow interviewees to freely answer the questions with sufficient leeway to invoke new perspectives.

The research team developed an interview guide with a series of open-ended questions to identify perceptions of HRC in construction and to explore related contextual factors that may have potentially influenced the users' perceptions.

Each interview began with an explanation of the interview's purpose before obtaining participants' consent to participate. Each interview lasted between a half hour and two hours and was audio-recorded for subsequent analysis.

The first part of the interview included questions to identify the job-related factors in play for each interviewee. Questions encompassed individual demographic information and any previous experience and/or knowledge about robotic technologies. The interviewees were then asked to describe and evaluate their job conditions in terms of perceived safety risks, required dexterity, and job complexity. To collect these data, the interview used a Likert scale from 1 to 10 with 1 representing "no risk" and 10 representing "extremely risky".

The questions in the following part of the interview explored the interviewee's perception of robot characteristics. The interviewer described the possible future construction robot scenarios identified in Table 2, and then the interviewees freely articulated their thoughts and feelings about each HRC scenario and explained the reasons for their response. As we detail below, these descriptions were later coded and analyzed to understand the interviewees' PU, PEOU, PJR, and POQ related to a specific HRC. In addition to robot role and autonomy, other attributes of robotic systems—e.g., robot morphology and interface modality—were also brought up during the discussion.

The final portion of the interviews remained open-ended in order to grasp the interviewees' overall attitudes toward and perspectives on robot adoption. Interviewees named any robot application perceived to be useful in their jobs. Then, they shared their assessment of the perceived feasibility of robot adoption and their willingness to adopt a robot in their own job setting. They also freely shared their opinions on related opportunities and challenges for construction robots in general. Finally, we ended the interview by thanking the participants for their contributions to the study. The list of interview questions is illustrated in Table 4.

Data Analysis

The research team analyzed the data to explore the effect of influencing contextual factors on construction stakeholders' perceptions. Upon completion of the interview sessions, each conversation was transcribed by the researchers based on the audio data to ensure accuracy. The raw data were reviewed and analyzed using a content-analysis method (Hsieh and Shannon 2005), a widely accepted approach to exploring individual or organizational perceptions such as values, intentions, and attitudes in the field of management research (Duriau et al. 2007). Under this content-analysis procedure, repeatedly emerging phrases or themes were derived directly from the transcribed data and labeled with relevant codes. Accordingly, such phrases as, *"[...] my job, like assembling formwork by nailing, cannot be standardized. The intervals are impromptu, which I doubt a robot can handle"* were labeled as "complex construction work process unsuitable for programmable robots." Thereafter, per the content-analysis method, these codes were reviewed and grouped into related subcategories within the research framework (See Figure 1).

For instance, here, "complex construction work process unsuitable for programmable robots" was categorized under "low adaptability to high variability in operation process." We then developed higher-level categories to expand the analysis by combining the generated codes from our previous analysis in keeping with the established methodology. For instance, the subcategory "low adaptability to high variability in operation process" was organized under the category, "negative perceived output quality (POQ)"; the set of categories derived from our analysis is summarized in Table 5. Lastly, the frequency of each category was counted, and key insights and implications were drawn from the coded data to further enhance our understanding of the stakeholders' perceptions. In order to ensure the reliability and validity of the data analysis, the initial codes were thoroughly discussed and selected by multiple coders with multiple inclusion and exclusion processes (Syed and Nelson 2015). Then, the results—including transcription, coding analysis, and interpretation of data—were reviewed for consistency and accuracy by other researchers who had not participated in the coding procedures.

RESULTS

To explore contextual influence on stakeholders' perceptions of robot adoption, we provided two comparative analyses: (1) among different trade workers, and (2) between manager and worker groups. We aimed to identify the similarities and dissimilarities among groups and speculated on any job-related factors that may have contributed to these differences. Figure 2 depicts the overall summary of the interview results between the groups with regard to robot role and autonomy.

Different Perceptions between Structural and Architectural Finishing Trade Workers

In this section, we paid attention to individual workers who would make the most use of robotic technologies and investigated whether different perceptions of robot adoption existed within worker groups, and if so, which aspects of the job-related factors caused the difference. To compare workers' perceptions with respect to specialization, we divided construction trades into two groups based on the observed characteristics of their jobs, which are namely safety risk, required dexterity, and job complexity. Using the interviewees' self-evaluations of their job conditions (Table 6), a Wilcoxon test indicated that the structural group (n=9) is characterized by a higher perceived level of safety risk, higher job complexity, and a relatively lower perceived level of required dexterity, whereas the architectural finishing group (n=8) is characterized by higher levels of required skills and lower levels of safety risk and job complexity.

Desired Robot Role and Perceived Output Quality

First of all, the structural and architectural worker groups differed as to which robot role they deemed ultimately more appropriate for their jobs; in the context of this study, the research team designated robot roles as either a main task–executing role (TER) or an assistive role (AR). Although both groups (n=6/8, n=8/8) appreciated the deployment of AR robots to ease their workloads, some respondents in the architectural finishing group thought their job conditions make a TER a more reasonable option (n=4/8). The architectural worker group's overall evaluation of job conditions was not as adverse or unpredictable compared to that of the structural group. The less unstructured job condition was associated with positive POQ, which they perceived as making the work more viable and cost-efficient by deploying robots to perform the actual task rather than just the assistive work. They also presumed that the high precision of robot work could improve productivity and quality, as illustrated in the following comments:

> *"My job has not much physically demanding work to be assisted with. Maybe carrying around paint drum? But, does it make sense to build a robot to just do that? […] the robot should perform the main work, replacing workers (R1)."*
> *"Some of our works are very repetitive like fixing ceiling panels over and over again. That can be automated by robots (R2)"*

The structural group, on the other hand, did not agree that current or near-future robots were capable of performing their main tasks and deemed an AR more appropriate (n=6/8). They agreed that robots would a ameliorate dangerous and difficult job environment; nonetheless, most respondents believed that robots could not perform main tasks well because current robotic technologies are unlikely to be able to handle their job complexities. Structural works tend to take place in different locations and a large number of crews work on the task together simultaneously. As these conditions requires robots to be endowed with high mobility and adaptability, most respondents were skeptical about the robot functionality capacities. One respondent in the structural group exhibited very negative POQ, stating, as follows:

> *"Unless the entire process of building construction changes, no kind of robot will be helpful for the current reinforced concrete practices (R3)."*

Another responded said,

> *"The actual site condition is very, very congested and complex. I'm very skeptical robot can work in such environment. Also, my job, like assembling formwork by nailing, cannot be standardized. The intervals are impromptu, which I doubt a robot can handle (R4)."*

Because of the nature of uncertain and dynamic construction conditions, most structural group participants claimed that an assistive robot was more suitable for on-site implementation and that humans should still carry out the main work to handle any out-of-scenario conditions and deviations.

Desired Robot Autonomy and Perceived Usefulness

In addition, the two groups exhibited different views on robot autonomy—or to what extent the tasks performed by humans should be taken over by robots. In particular, the structural group preferred high-autonomy robots (n=6/8), whereas the architectural finishing group preferred low-autonomy robots (n=6/8). This disparity coincided with the perceived usefulness of robots: For the structural group, the most critical driving force for automation was that it would enhance their own work environment by mitigating occupational hazards and adverse working conditions. Because this group perceived direct benefits from robot adoption, they preferred robots that feature a high level of autonomy if the technology is fully-fledged to deal with an unknown or dynamic environment. They were not afraid of having highly autonomous robot and changing to supervisory role. In the following excerpt, a structural steel worker describes his preference for high robot autonomy:

"The goal is to finish work efficiently and go home early. As long as I know the robot is doing its job right, I do not want to supervise it at all. (R5)"

On the contrary, the architectural finishing group preferred to have control over robots and were more discerning about which technologies to adopt depending on whether they could manipulate the robots. Unlike the structural group, the architectural finishing group primarily perceived benefits related to robots to be improving the quality of work. Although robots can perform repetitive work with higher precisions, they believed it is more reasonable to have control over the robotic system because their job tends to not follow a strict, predefined sequence of operations and requires human knowledge of and expertise in the process. Thus, it is preferred that workers be able to choose the appropriate action based on the situation and that the robot react to the worker and plan for the next action accordingly. The following excerpt illustrates how the architectural finishing group's high required dexterity shaped their preferences for low robot autonomy:

"The work (drywall installation) I do has very little tolerance. If your wall is off by ¼ inches, the furniture that comes in next will not fit in. But concrete walls usually have some errors beyond that tolerance. It's the human skill that can improvise in such situations and finish the work within the tolerance. (R6)"

The architectural finishing group was also worried about their works becoming less meaningful after the introduction of robots and desired to maintain their professional autonomy over their work. One respondent stated that highly autonomous robots might compromise her autonomy, and she was afraid of losing her control over work-related decisions such as work speed and process flexibility, saying "*if a robot autonomously delivers bricks for me, I will end up adjusting my speed at the speed of the robot, which is definitely demotivating (R7).*"

Findings 1 and 2 observed among trade worker groups suggest that job characteristics generated different expectations toward robot adoption, resulting in different preferences for robot roles and autonomy.

Different Perceptions between Managers and Workers

In this section, we analyzed how different positions within the organizational hierarchy perceive robot adoption by comparing the combined worker group with the manager groups consisting of subcontractor managers (architectural finishing group: n=6, structural group: n=6) and general contractor managers (n=7).

Desired Robot Role/Autonomy and Perceived Usefulness

Unlike the worker groups, which exhibited different preferences for robot autonomy based on their jobs, both manager groups preferred a high level of robot autonomy for all trades (n=4/6, n=4/6, n=5/7), regardless of the perceived safety risks and required skill levels of the trade. In contrast to the worker groups, which specifically mentioned that the cost-benefit ratio should not be the primary driving factor for automation, for the manager groups, the cost-benefit ratio played the most critical role in the technology adoption decision-making process. In their views, robot adoption could reduce not only the number of on-site personnel required but humans' error-prone behaviors as well. Robots would more strictly follow safety regulations and carry out quality monitoring in a more consistent and reliable manner.

In terms of robot roles, the general contractor managers showed a tendency to prefer TER robots (n=5/7), while the subcontractor managers showed a similar, yet weaker, tendency to the worker group (n=3/6, n=2/6). From a project-management standpoint, both manager groups perceived robotization as a means of managing projects in a more efficient way, especially for tasks that are expensive when carried out manually. They presumed that TER robots could abate current workforce-related issues, including the shortage of skilled workforce, the rising cost of unskilled labor, stagnant productivity, and so on. Thus, the manager group perceived construction activities that are heavily labor-dependent and yet suffering from a lack of skilled laborers, such as reinforcement-concrete and bricklaying work, to be most appropriate for robotization.

Our findings illustrate that an individual's role in an organization shapes his or her perception of technology adoption and results in divergent preferences for particular robot characteristics.

Technological Anxiety and Perceived Ease of Use / Job Relevance

Another significant difference between the worker and manager groups was the perceived level of technological anxiety and concerns about job displacement. This anxiety was most apparent in the worker group (n=11/17). Both the general contractor managers (n=0/7) and the subcontractor managers (n=4/12) expressed little concern about job displacement. Such a finding indicates that the different levels of technological anxiety across different groups positively relates to their PEOU.

Respondents in the worker groups acknowledged that widespread robot adoption would not be immediate and were not apprehensive about the pace of technology adoption; nonetheless, threats of technological unemployment were still discussed as a serious concern during the interviews. Their worries primarily focused on the potential impact of robots to instigate job loss rather than the impact of robots affecting the job task—e.g., reducing the value of their skillset. They exhibited low levels of PEOU for working with robots and were worried that they would not be able to acquire the required skills to adjust for automation. They were also afraid that this type of technological change would favor only educated workers and that job training would not completely resolve such skill biases.

In addition, our results indicate that technological anxiety positively relates to PJR. In particular, workers who perceived their job as emphasizing "low-skilled" tasks reacted most negatively, while those who perceived their job as demanding "high-skilled" tasks showed far less concern about robots. The latter group expressed low perceived job relevance and believed that they are not at risk of job displacement, or at least that displacement would take years. Interestingly, respondents who had actual experience using robots showed less technological anxiety, as they believed there would still be human jobs left after robot adoption.

Perceived Challenges Incorporating Robots into Current Practice

Most respondents (n=33/36) still showed negative attitudes toward the feasibility of a fully automated system, and those at all levels of organization raised concerns about the various challenges robot adoption would bring to the current workplace. At the top management level, the largest hurdles for robot adoption were perceived to be the costs pertaining to robot adoption, mainly due to a lack of infrastructure and manpower. Robotization would necessitate changing organizational structures, with new staff required to mobilize robot deployment as well as systems operations and maintenance. Robotization would also mandate changes to infrastructure to include the necessary equipment for robot operation, such as pathways or charging stations. These respondents expressed that the level of automation would thus be determined using a cost-benefit ratio. Another concern was the potential internal resistance from workers, in that managers feared potential labor-management issues, especially as managers anticipated that robot adoption would elevate tensions within labor unions. One manager noted that some robotic solutions were ready for immediate adoption but that those solutions would not be adopted in the near future due to resistance from labor unions.

From the worker group's perspective, the major concern related to workflow and that work processes would be affected by robot adoption. Workers worried that their daily work routines would be obstructed due to work-practice reconfigurations, slow robot movements, and congested project areas. Workers also highlighted the importance of taking a holistic approach to robot adoption because most construction activities are interdependent. These respondents suggested that robotizing one task may not be effective because the precedent activity determines the work conditions for the subsequent task. Thus, HRC would not be fluid due to the disjunction between what humans expect robots to perform and what robots actually can perform. Because of this limitation, some respondents (n=3) predicted that robotization should take place only over the long term.

DISCUSSION

The results of this study illustrate how different construction stakeholders exhibit different perceptions toward robot automation within construction trades and how job-related factors appear to shape these perceptions. In addition to the above-mentioned findings, we can draw additional inferences to deepen our understandings of construction stakeholders' perceptions of construction-robot adoption.

Perceived Safety Concerns with Regard to on-Site Robot Adoption

The introduction of robots in human-populated environments inevitably will present new physical and psychological safety issues (Lasota et al. 2017). Although previous literature identified various mental stresses and fears induced by physically working in vicinity of robots (Izadi Moud et al. 2021), our results show that perceived safety is constituted by multiple factors, such as the size of robots and any previous personal experience with a robot. Based on our findings some workers may not in fact be threatened by the introduction of robots in the workplace. For instance, except for one respondent who witnessed a fatal incident with an industrial robot, all workers responded that the presence of UAVs or mobile robots in the workplace have not and would not pose significant safety threats. Even in consideration of safety-critical events—e.g., when risks of falling objects exist—stakeholders' perceived risk levels were not influenced by the co-existence of proximate robots. In fact, several workers (n=4) worried instead that the robots would get damaged. This result suggests that the introduction of robots may not induce severe additional psychological safety threats to bystanders whose jobs have only occasional interactions with a robot from a distance. This interesting finding may be due to stakeholders' constant exposure to construction machines and heavy equipment on contemporary jobsites. However, there is always a chance that robots' sensors or other collision-avoidance systems may fail (Hou et al. 2020), so such low perceived risk may lead to unsafe human behaviors and result in a serious or fatal accident. Thus, future studies must both enhance workers' vigilance when they are in proximity to robots and improve collision-avoidance measures.

Perception of Robot Capability in Relation to Initial Orientation

In terms of perceived and actual robot capabilities, our results indicate that, in general, respondents do not accurately estimate robots' actual functionality and capabilities due to a lack of experience and knowledge. Responses in our interviews were mixed, with high and low levels of perceived robot capacity. For those in our study who tended to over-trust robots, our discussions with them revealed perceptions of robots endowed with intelligence, as depicted in the media. For example, one respondent who did not worry about the physical danger of robots said, "*Robots are smart enough to avoid collision*." Although current technologies have been advancing, such perceptions may not reflect reality in uncertain environments such as those found on construction sites. In contrast, other interviewees underestimated robots' physical and cognitive abilities, saying, "*Robots cannot lift such heavy materials*" and "*Robots cannot detect deviation between the installed building components with the drawing.*" Neither of these contradictory perceptions are congruent with the current capabilities of robots, and should be calibrated to avoid any misuse or disuse (Bryson and Kime 2011). Such inaccurate perceptions of robot capability are also not helpful in promoting effective human-robot collaboration. Komatsu et al. (2012) suggest that if the gap between the perceived and actual capability of robots is large it will compromise trust in robots. Therefore, it is important to understand how people perceive robot capabilities and to correct any misperceptions they might have.

The interview results suggest that workers' general orientation regarding robotic technology can be an important indicator in predicting biased perceptions of robots. Predispositions based on an individual's previous experiences with robots seem to trigger a relative preconception of robot capability. For example, workers who had previous experiences with other types of robot applications—such as a vacuum cleaning robot at home, a serving robot at a restaurant, or an autonomous driving car—exhibited the same perceived capability for construction robots as robots in general. Thus, based on stakeholders' general orientations toward robotic technologies, organizations can correctly inform individuals of the exact functionality of robots to achieve an effective level of HRC and coordination. One limitation of this finding is that itis only applicable to workers' perceptions prior to the actual use of a robot, and their perceptions are subject to change over time as they interact with robots.

Worker Perception of Robot's Human Likeness

When considering teaming humans with robots, whether or not a robot should incorporate social behaviors is often discussed (Seeber et al. 2020). During our interviews, several comments related to this question were brought up repeatedly. Respondents appeared to prefer robots endowed with social abilities in order to maintain a level of HRC similar to human-human collaboration. One potential reason for this preference is that a significant number of construction activities are performed by crews, thus making social relationships a critical factor in job satisfaction (Welfare et al. 2019). Therefore, respondents may prefer to establish similar social interactions with robots as those they have with other human colleagues. A verbal communication mode was most frequently preferred for ease of use. For example, one respondent wanted to give verbal instructions to robots because he would like to "communicate" with the robot teammate. Thus, to build an effective human-robot collaboration, a robot's communication capabilities will be critical not only for exchanging information regarding the goal and intention—which is a prerequisite for effective coordination—but also for social interaction. To achieve this high-level interaction, one challenge to address will be how to map from a human command to the appropriate control command for the robot to be able to perform the task.

Moreover, this propensity for anthropomorphism manifested itself in interviewees' preferences for robots' appearances as well. Robots' human-likeness levels divide robots into three broad categories: humanoid, resembling a human in appearance; anthropomorphic, imitating human characteristics; and non-humanoid, not resembling or imitating humans (Naneva et al. 2020). Such different robot appearances can affect a user's expectation, perception, and evaluation of a robot (Li et al. 2010). Our results revealed that the degree of human-likeness is indeed influential in respondents' attitudes toward robots. For several trade workers who had high work experiences (n=3), the similarity between humans and robots provoked positive attitudes toward robots. These workers felt discomfort in the appearance of four-legged, dog-looking robots and thought it would be more comfortable to be around humanoid robots. One respondent commented that humanoid robots would perform better because they could work like humans. This result is consistent with findings from previous studies: that human likeness can contribute to notions that a robot can perform human tasks (You and Robert Jr. 2018). As real construction jobsites are usually crowded, such biped robots may also be advantageous because they can perform tasks at heights despite their small size—although this feature has limitations of its own that will require further study.

Implications for Future Construction Robot Adoption

In terms of a general attitude toward robot adoption, our findings are consistent with the previous literature that describes managers' tendencies to welcome technology adoption to achieve efficiency and cost reduction compared to those at lower levels on the hierarchy [7] [21].

Despite the envisioned benefits of HRC, our results indicate that a genuine HRC is not feasible at present because the state of the art of construction robotic technology does not support the required level of reasoning, perception, and adaptability for complex construction tasks especially in dynamic construction environments. Instead, it is more plausible to gradually deploy robots for tasks that current robotic solutions can support while implementing an appropriate level of HRI to supplement the incompetence of robots. Immediate or near-future robots may be employed for simple and small sub-tasks, preferably when such tasks as are unrelated to actual construction work. Accordingly, possible applications may be data capture, surveillance activities like checking PPE for safety, monitoring construction progress, delivering materials, and housekeeping. Independent unmanned ground vehicles and unmanned aerial vehicles would be appropriate for this type of application. In fact, most respondents who already used these types of robots responded that the robots were satisfactory and well-integrated into the current workflow (n=30).

Subsequent adoptions may take over simple construction tasks that are typically performed in relatively structured work setting by a single or small number of worker(s). For instance, single-task robots could be applied to architectural finishing works with simple work processes that takes place within more controlled and static work environments and that does not require close coordination with humans. In contrast, structural work characterized by more unstructured environments may not be able to be fully automated any time soon. During the transition, robots may undertake supportive roles, taking on dangerous and demanding work while humans perform dexterous and/or problem-solving activities. The final adoption group includes intelligent autonomous robots capable of performing flexible tasks as a true collaborative partner.

CONCLUSIONS

This study provides cross-profession (workers vs. managers) as well as cross-specialization (structural vs. architectural finishing) comparisons of stakeholders' perceptions of HRC in the construction domain to examine which contextual factors may influence stakeholder perceptions of robot adoption. Performing qualitative analyses on responses to semi-structured interview questions, we found notable differences in perceptions of construction-robot adoption between manager and worker groups as well as among different trade workers as well as the moderating role of job-related factors in shaping stakeholders' perceptions. While most participants acknowledged the benefits of robot adoption and did not express fear of physical and psychological danger from working with robots, each group's unique job-related factors influenced their PU, PQO, PJR, and PEOU of a robotic technology, which altered their views on desired robot abilities and preferred levels and types of HRI. In particular, we found the desired robot role, which is related to PQO, depends on the variety of skills and subtask required to complete the job. In addition, the safety risk associated with the job influenced their desired level of autonomy, which is related to PU. Based on these findings we derived practical implications for construction-robot deployment in varied construction situations.

The findings of this study contribute to a better understanding of the organization of future robot-human teams in a construction project by highlighting relevant job-related factors and how they should be considered in the design/selection of robot partners for current human trade workers. The findings regarding workers' perceptions and preferences regarding robot autonomy and roles offer a basis upon which to address certain labor issues (e.g., workers' resistance to technology and workers' distrust of robotic partners) in initial adoptions of robotic technologies in a construction organization.

Although our findings offer noteworthy insights for organizing human-robot team interactions, the implications are limited to a certain extent. Firstly, at the time of the interviews, the majority of participants in this study did not have much experience with robots except for unmanned aerial vehicles. Thus, their perceptions of the usefulness of robots may change as these stakeholders gain actual hands-on experience with robots (Venkatesh and Bala 2008). In this regard, future work should identify post-use perceptions of robots to explore whether perceptions would be moderated by experience and if so, which other factors may influence any disparities in stakeholders' perceptions. Furthermore, the background of the participants was limited to the domain of high-rise building projects only, excluding small-scale residential buildings or civil infrastructure projects. Although the residential and commercial high-rise building sector provides various complex and collaborative construction activities and reveals a great need for robotic technologies, it exhibit very distinct environmental and job-related factors as compared to other types of construction projects. Thus, the findings of this study may not be directly applicable to other construction sectors. Lastly, this study was conducted using one-to-one HRI scenarios and did not explore the various types of human-robot team dynamics (e.g., one-to-many, many-to-many) despite the fact that actual construction practices will involve multiple interaction scenarios. Given that our findings were based on one-to-one HRI, it would be beneficial to focus future work on multiple-HRI scenarios, such as single worker–to–multiple robots interactions and crews of workers–to–single and/or multiple robots.

DATA AVAILABILITY STATEMENT

Some or all data, models, or code that support the findings of this study are available from the corresponding author upon reasonable request.

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Table 1. Definitions of TAM variables

Variable	Definition
Perceived Usefulness (PU)	The extent to which a person believes that using the technology will enhance his or her job performance (Davis 1989) e.g., The robot will be useful for heavy lifting. Using this robot will enhance my job performance.
Perceived Ease of Use (PEOU)	The extent to which a person believes that using the technology will be free of effort (Davis 1989) e.g., It will be easy to operate robots with a control pad, so the interaction with this robot will be easy.
Perceived Job Relevance (PJR)	The extent to which an individual believes the technology applies to his or her job (Venkatesh and Davis 2000) e.g., For my job, I will use the robot a lot and it is pertinent to my job tasks.
Perceived Output Quality (POQ)	The extent to which an individual believes the technology will perform tasks well (Venkatesh and Davis 2000) e.g., The mobile robot navigation seems robust enough to travel around the construction site; thus, the quality of the output I will get from this robot will be high.

Table 2. HRC Scenarios in Construction

Task Responsibility	Level of Autonomy	Example scenario
Task-Executing Role	Remote/Teleoperated	Remotely controlled/Teleoperated Installation (e.g., bricklaying) Robot
	Autonomous	Autonomous Installation (e.g., bricklaying) Robot
Assistive Role	Remote/Teleoperated	Remotely controlled/Teleoperated Delivery Robot
	Autonomous	Autonomous Delivery Robot

Table 3. Overview of Participants

<table>
<tr><th rowspan="2">Variable</th><th colspan="2" rowspan="2">Group</th><th rowspan="2">Specialization</th><th colspan="2">Sample Size</th></tr>
<tr><th>Worker</th><th>Manager</th></tr>
<tr><td rowspan="16">Job Classification</td><td colspan="2" rowspan="3">General Contractor</td><td>Project management</td><td>-</td><td>5</td></tr>
<tr><td>Tech Development</td><td>-</td><td>2</td></tr>
<tr><td>Sub-total</td><td>-</td><td>7</td></tr>
<tr><td rowspan="13">Subcontractor</td><td rowspan="5">Structural</td><td>Civil</td><td>0</td><td>1</td></tr>
<tr><td>Concrete</td><td>6</td><td>2</td></tr>
<tr><td>Structural steel</td><td>3</td><td>2</td></tr>
<tr><td>Façade/windows</td><td>0</td><td>1</td></tr>
<tr><td>Sub-total</td><td>9</td><td>6</td></tr>
<tr><td rowspan="6">Architectural</td><td>Masonry/Stone/Tiles</td><td>2</td><td>3</td></tr>
<tr><td>Plastering/Painting</td><td>1</td><td>1</td></tr>
<tr><td>Drywall</td><td>1</td><td>1</td></tr>
<tr><td>Waterproofing</td><td>1</td><td>0</td></tr>
<tr><td>M&E</td><td>3</td><td>1</td></tr>
<tr><td>Sub-total</td><td>8</td><td>6</td></tr>
<tr><td rowspan="3">Work Experience</td><td colspan="3">~10 years</td><td colspan="2">8</td></tr>
<tr><td colspan="3">11~20 years</td><td colspan="2">17</td></tr>
<tr><td colspan="3">21 ~ years</td><td colspan="2">11</td></tr>
</table>

Table 4. Overview of Interview Questions

Main Topic	Sub-topic	Questions
Job-related factors	Self-introduction	Please introduce yourself. Please describe your work experience in the field. Please describe your job and position.
	Evaluation of job conditions	Please assess your job in terms of safety risk, required dexterity, and job complexity using a scale from 1 to 10, with 1 representing “no risk” and 10 representing “extremely risky”.
	Any experience with and knowledge of robots	Have you ever physically used/seen any robots at the construction jobsite/anywhere else? Have you ever heard/seen any construction robots in news articles, movie, or other media?
Preferred Robotic System	Robot autonomy	What level of robot autonomy do you prefer/think is appropriate for a construction task in your job context? What is the reasonable level of human intervention a construction task in your job context?
	Robot role	What robot role (e.g., main task-executing or assistive role) do you prefer/think is appropriate for a construction task in your job context?
	Appearance of robots	What do you feel about a specific appearance of robot?
Attitude toward Robot Adoption	Robotization task candidate	In your daily work routine, which task do you prefer/think is appropriate for robotization? Why?
	Attitude toward robot	How do you feel about sharing the workspace with a certain type of robot or robots in general? How do you feel about working collaboratively with a certain type of robot or robots in general?
	Intention to use	Are you willing to adopt the robots we discussed in your workplace? Why or why not?
	Challenges and benefits	What you do think is the main challenge for robot adoption? What do you think is the main benefit for robot adoption?
	Others	Feel free to share any concerns and/or opportunities you have regarding robotic technology.

Table 5. Categories and Sub-categories of Data Analysis Results

Categories	Sub-categories	Respondents' Comments
Positive PU	• Improve efficiency/productivity/quality • Improve work condition	*"We as humans inevitably make mistakes when we do repetitive work over and over again. Robots don't make mistakes"* *"My job is physically very demanding. If robots can eliminate that, it will be great"*
Negative PU	• Inadequate for dexterous and cognitive task • High cost of robot error	*"My Roomba is dumb. I'm not sure if construction robot can be any smarter to do my job"*
Positive POQ	• Simple repetitive tasks • High level of trust in technology	*"Some of our works are very repetitive […] can be automated by robots."*
Negative POQ	• Immature technology • Low adaptability to high variability in operation process • Lack of trust in technology	*"Robots can only do what it is programmed for. Construction does not work that way. I'm highly skeptical if the robot can ever do the way human does."*
Positive PJR	• Low skilled job • Job securities	*"Everything is being automated these days. Construction will not be an exception."*
Negative PJR	• High skilled job	*"For my job, robots cannot perform like humans"*
Positive PEOU	None	None
Negative PEOU	• Technological anxiety • Lack of infrastructure/personnel	*"People told me I can still keep my job even after robot are deployed on sites. Just a different one. However, it's only for those tech-savvy people."*

Table 6. Wilcoxon Test Results of Structural and Architectural Finishing Groups' Likert Scores for Job-related Factors Evaluation.

Accident occurrence	W	p-value
Safety Risk	43.5	0.0087*
Required Dexterity	12	0.0599
Job Complexity	38.5	0.0403*

* *Significant at the* $p = .05$ *level*

List of Figure Captions

Figure 1. Overview of Theoretical Framework for Robot Adoption (adapted from TAM [Davis 1989])

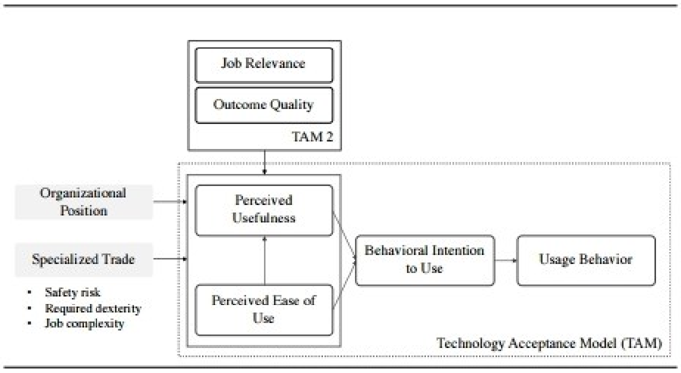

Fig. 2. Group Perceptions of Desired Robot Role and Autonomy