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Construction Students' Safety Perception of the Presence of Drones on Job Sites

Zixian Zhu, Jiun-Yao Cheng, Idris Jeelani, Ph.D. and Masoud Gheisari, Ph.D.
University of Florida
Gainesville, Florida

Drones are increasingly being utilized in the construction industry, offering a wide range of applications. As these drones have to work with or alongside construction professionals, this integration could pose new safety risks and psychological impacts on construction professionals. Hence, it is important to understand their perceptions and attitudes towards drones and evaluate the cognitive demand of working with or near drones. Limited research has explored individuals' perceptions of drones, particularly when engaged in construction activities at job sites. This study specifically targets construction students, the future professionals in the field, to understand their responses to drone interactions on job sites. An immersive virtual reality construction site was developed using a VR game engine, allowing construction students to interact with drones while engaging in typical construction activities. Through a user-centered experiment, the influence of drone presence on construction students' attitude, cognitive workload, and perceived safety risk was evaluated. The results suggest that presence of drones did not significantly elevate cognitive load or foster significantly negative attitudes among construction students. Instead, they perceived only mild safety risks, suggesting a general acceptance and adaptability towards drone technology in construction settings.

Key Words: Human-Drone Interaction, Virtual Reality, Construction Safety, Safety Risk Perception

Introduction

Drones, also known as unmanned aerial vehicles (UAVs), have become increasingly popular in the construction industry, which has shown the highest adoption rate of drone technology. Over 80% of drone users in the construction industry intend to expand or maintain their investment in drones (DroneDeploy 2021). Drones can accomplish tasks more efficiently and at a lower cost on construction sites, performing construction activities more cost-effectively and with greater control (Zhou and Gheisari 2018). However, construction consistently ranks as one of the most dangerous industries, resulting in more than 5,000 fatal work injuries in the US in the past five years (Bureau of Labor Statistics 2022). As drones become more prevalent on construction job sites, there are increasing safety concerns for construction practitioners in such a dynamic and complex environment. In the near future, drones with various responsibilities will collaborate with human workers to carry out a wider range of construction-related tasks (Zhu et al. 2023). Given the foreseen ubiquity of worker-drone interaction on construction sites, workers' perceptions of drones while working on site could critically affect their safety. Specifically, if workers perceive drones as a potential threat rather than a valuable tool or friendly colleague, they may experience heightened stress and anxiety, reduced job satisfaction, and other negative impacts on worker well-being (Jeelani and Gheisari 2022). However, limited research has investigated the detailed relationships between the presence of drones on job sites and the various dimensions of perception among individual construction practitioners, particularly when they are engaged in construction activities around drones and exposed to potential negative safety impacts. This study specifically targeted construction students who will become construction professionals and work with drones on job sites in the future. An immersive virtual reality construction site was developed in a game engine where the construction students could interact with drones. Results of post-surveys were assessed quantitatively and qualitatively to investigate how the presence of drones on the site impacts construction students' perception of negative attitudes, cognitive load, and expected risks.

Background

Drones have been increasingly utilized throughout the entire construction lifecycle, with applications including building inspection (Eiris et al. 2021), damage assessment (Calantropio 2019; Li and Liu 2019), site surveying and mapping (Irizarry et al. 2016), progress monitoring (Martinez et al. 2020), and safety inspection (Zhou and Gheisari 2018). However, increasing interactions between human workers and drones raises novel occupational safety and health concerns for construction practitioners (Jeelani and Gheisari 2021), especially regarding the psychological and cognitive outcomes resulting from negative perceptions. These outcomes, such as mental fatigue and cognitive impairment, can lead to unsafe behavior (Namian et al. 2018) and deficient work performance. Existing research about perception of drones in construction industry are mainly focus on surveys and interviews for perception of drone overall applications barriers (Sabino et al. 2022; Umar 2020). In these studies, the participants did not directly interact with drones and perceived the presence of drones when they were working on job sites. For acceptable human-robot interaction, there may be a discrepancy between actual situation and user perception, that a robot must avoid taking actions that might create an unpleasant situation for humans even if its actions do not cause any physical harm (Akalin et al. 2022). As drones will be increasingly involved in construction operations requiring a shared working space with humans on site, it is crucial to investigate if construction practitioners perceive drones as a support, a team member or a flexible part of construction activities (Bonci et al. 2021). Negative safety perceptions of drones can lead to worker fear and privacy concerns regarding surveillance while working with or around drones (Chang et al. 2017), leading to cognitive distraction and heightened accident risks (Jeelani and Gheisari 2021). Multidimensions of perception for robots have been studied through user-centered experiment, such as attitude (Xia and LeTendre 2021; Zafari and Koeszegi 2021), workload (Kaufeld and Nickel 2019; Nenna et al. 2023), and risk perception (Hanoch et al. 2021).

Research Methodology

This study is aimed to assess the influence of drone presence on construction students' attitude, cognitive workload, and perceived safety risk on job sites. As illustrated in Figure 1, this study first developed a virtual reality (VR) scenario in which construction students can perform construction tasks while perceiving the presence of drones on construction sites. After the development, a user-centered experiment was conducted by disseminating demographic surveys and post-surveys measuring participants' perceptions, which covered cognitive load, negative attitudes, and risk perceptions.

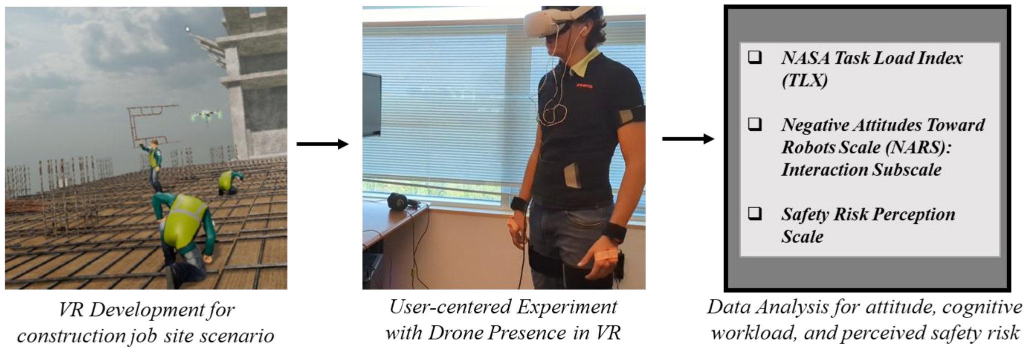

Figure 1 Research Methodology

Experiment Scenario Development

A fully immersive VR scenario was developed to facilitate subject interaction with drones within a construction site context. People tend to perceive interacting with drones on a construction site as unsafe, especially for workers who already face a hazardous working environment daily. This concern is particularly significant given the high risks associated with falls, slips, and trips, which account for 46.1% of fatal injuries and 31.4% of non-fatal injuries recorded in the construction industry (Bureau of Labor Statistics 2022). Furthermore, fatalities resulting from falls are most commonly associated with work locations such as roofs, ladders, and scaffolding (Brown et al. 2020). Therefore, a construction scenario was designed to involve an inspection task on a platform located near scaffolding at heights. To replicate a range of potential interactions, two distinct types of drones were introduced into this VR scenario: an inspector drone, responsible for monitoring work progress by following a predefined flight path around the virtual site, and a delivery drone, tasked with collecting toolboxes and delivering them to specified locations on the platform. To replicate this construction scenario within the VR environment, all necessary assets were imported and animated using the Unity3D® game engine. This included static objects such as buildings and temporary structures, dynamic objects like drones and equipment, and virtual workers, enabling a comprehensive construction site simulation that allows users to interact with virtual drones in a realistic manner (Figure 2).

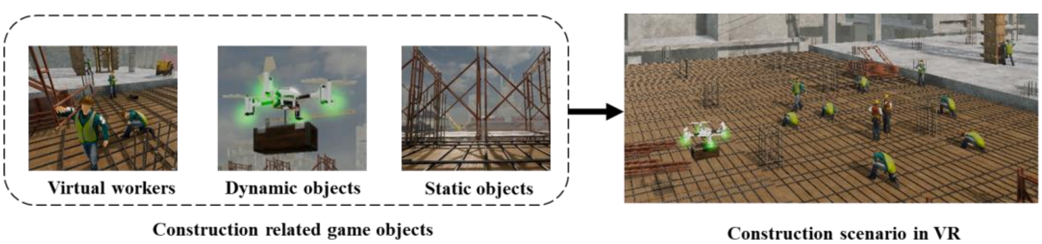

Figure 2 Experiment Scenario

User-Centered Experiment Procedure

The user-centered experiment was approval from the University of Florida Institutional Review Board (IRB #202300203). 15 subjects who are students from Rinker School of Construction Management were recruited. In the experiment, subjects initially reviewed and consented to the study by completing a consent form. Subsequently, they were required to fill out demographic surveys that collected data regarding their individual experiences, including age, work experience in the construction industry, knowledge levels related to construction (including major and educational status), knowledge levels of VR, and knowledge levels of drones. After completing the experimental tasks in the VR scenario, participants filled out a post-experiment perception survey on negative attitudes, cognitive loads, and risk perceptions.

Study Metrics

Negative Attitudes Toward Robots Scale (NARS) Interaction Subscale (Nomura et al. 2006): NARS is a validated tool widely used in HRI studies, which was designed to determine human attitudes toward robots when interacting with them. In this study, the subscale of NARS specifically focusing on "negative attitude toward interaction with robots," was employed. This subscale includes six items, and each item is scored on a five-point Likert scale. *Cognitive Workload by NASA-TLX* (Hart and Staveland 1988): NASA-TLX is a widely used instrument for assessing cognitive and mental workload during or immediately after performing a task. It comprises a multidimensional score based on a weighted average of ratings on six subscales: mental demand, physical demand, temporal demand, performance, effort, and frustration level. In this study, each subscale was scored on a seven-point scale from very low to very high. *Safety Risk Perception Scale* (Hallowell and Gambatese 2009; Pandit et al. 2019): the safety risk perception score was calculated using the formula: Safety Risk = Incident Frequency × Incident Severity (Fortunato et al. 2012). In this study, this metric was adapted from a safety risk perception quantification survey instrument developed by Pandit et al. (2019). The validated safety risk perception score for each risk classification is provided in Table 1 (Hallowell and Gambatese 2009). To compute an individual's score, the scores for each risk classification are summed. For instance, if a participant perceives all levels of incident injuries as "likely" to occur, the total score would be 0.19 (i.e., 0.01 + 0.03 + 0.04 + 0.05 + 0.06).

Table 1

Scores for safety risk perception survey

Severity \ Injury Frequency	Not Possible	Unlikely But Possible	Likely	Very Likely	Almost Certain
Discomfort/Pain	1.25×10^{-4}	1.25×10^{-3}	0.01	0.06	2.5
First Aid	2.75×10^{-4}	2.75×10^{-3}	0.03	0.14	5.5
Medical Case	3.50×10^{-4}	3.50×10^{-3}	0.04	0.18	7.0
Lost Work Time	4.00×10^{-4}	4.00×10^{-3}	0.05	0.20	8.0
Permanent Disablement or Fatality	4.75×10^{-4}	4.75×10^{-3}	0.06	0.24	9.5

Results and Discussion

The results from the demographic survey, which collected individual experience data, are presented in Table 2. Most subjects were male (60%), aged between 20 and 30 (66%), and are graduate students (80%). Furthermore, almost every subject had previous work experience on construction sites (93%), and nearly half of them have more than two-year of professional experience in the construction industry (47%). Most subjects possessed different levels of knowledge based on their previous experience of VR (93%) and drone (93%).

Table 2

Demographics of the participants

Variable	Category	Number (Percentage)
Gender	Male	9 (60%)
	Female	6 (40%)
Age	≤20	2 (13%)
	>20 and ≤25	5 (33%)
	>25 and ≤30	5 (33%)
	>30	3 (20%)
Educational Status	Undergraduate Student	3 (20%)
	Master Student	7 (47%)
	PhD Student	5 (33%)
Work Experience in Construction Site	None	1 (7%)
	Less than 6 months	3 (20%)
	6 months to 1 year	1 (7%)
	1 to 2 years	3 (20%)
	More than 2 years	7 (47%)
Knowledge Level of VR	None	1 (7%)
	Some Knowledge of	6 (40%)
	Fair	6 (40%)
	Competent	2 (13%)
Knowledge Level of Drone	None	1 (7%)
	Some Knowledge of	8 (53%)
	Fair	5 (33%)
	Competent	1 (7%)

Table 3 presents the findings related to the NARS interaction subscale, which has an overall neutral score of 2.78. The data reveals that participants provided negative ratings (> 3) for the statement "I felt uneasy when I worked on site and drones came close to me" (3.47), and "I felt nervous when working around drones on site" (3.13). These results suggest that when drones were flying in close proximity to the participants, they experienced slightly increased discomfort and anxiety. This sentiment aligns with qualitative feedback from some participants. For example, one expressed feeling uneasy when drones approached them, stating "*I was very uneasy having the drones come near me and near other workers on site. The presence of the drones was very distracting too.*" Similarly, another one specifically mentioned that the sounds of drones would make them feel nervous by stating, "*The buzzing of the drone was annoying and nerve-wracking because I could sense it getting closer.*" However, the participants tended to disagree that they would feel nervous working with drones in front of other people on site (2.87). Their agreement decreased further when confronted with statements using stronger negative language, such as "Drones meant nothing to me when I performed the task on site" (2.47) and "I hate drones performing tasks automatically and making decisions on site" (2.47). These results suggest that although participants may experience uneasiness and nervousness when drones operate in proximity, they do not perceive drones as inconsequential or harbor a strong aversion to drones autonomously executing tasks and making decisions on site. Finally, the participants scored the lowest score on the agreement of the statement: "I felt paranoid when I tried to communicate with drones on site" (2.27). This result could be because they did not feel necessary to communicate with the drones all the time during the experiment.

Table 3

NARS: Interaction Subscale results

NARS: Interaction Subscale Questions*	Mean ± SD
1: I felt uneasy when I worked on site and drones came close to me.	3.47 ± 1.36
2: Drones meant nothing to me when I performed the task on site.	2.47 ± 1.13
3: I felt nervous working with drones in front other people on site.	2.87 ± 1.25
4: I hate drones performing tasks automatically and making decisions on site.	2.47 ± 1.30
5: I felt nervous when working around drones on site.	3.13 ± 1.25
6: I felt paranoid when I tried to communicate with drones on site.	2.27 ± 0.88
Overall	2.78 ± 0.63

** Likert Scale: Strongly Disagree (1) to (5) Strongly Agree*

Table 4 presents the outcomes for NASA-TLX, encompassing various subscales such as mental demand, physical demand, temporal demand, performance, effort, and frustration. In summary, the participants reported an overall neutral score of 3.24 for NASA-TLX scale. They perceived working around drones was characterized by a slightly low to moderate level of mental demand (3.60) and a slightly lower degree of physical demand (2.93). They also noted that the task's pace was not excessively hurried or rushed (3.27). Furthermore, they perceived a somewhat high level of performance in accomplishing the task (5.00), with a perception of needing to apply a slightly low level of effort to achieve their performance level (3.33). Additionally, the participants reported a slightly low level of frustration performing tasks around drones (3.33). Overall, the results show that the participants did not experience a notably high cognitive load across various dimensions. However, it is worth noting that they perceive slightly higher mental demand than physical demand. This perception difference could be caused by the participants having not had full knowledge of the drones' flight paths and the ability to control them to prevent potential risks, such as physical contact between drones and workers. For instance, one participant expressed concerns, stating, "*I felt like the drones were doing their job … Only worry was that drones would collide or cause damage*." Such uneasiness can be aligned with the results of NARS scale, where most of the participants agreed that they feel uneasy when working on site and drones came close to them. Furthermore, some participants also mentioned that they thought they needed to be more vigilant to avoid safety risks while working with or around drones, stating, "*I think it was important to stay vigilant about your environment because I did not (know) if the drone was going to collide with anything*." This perception may also contribute to extra mental demand for the participants working around drones on job sites.

Table 4

NASA-TLX results

NASA-TLX Questions*	Mean ± SD
1: **Mental demand**: How mentally demanding was the task?	3.60 ± 1.35
2: **Physical demand:** How physically demanding was the task?	2.93 ± 1.44
3: **Temporal:** How hurried or rushed was the pace of the task?	3.27 ± 1.34
4: **Performance:** How successful were you in accomplishing what you were asked to do?**	5.00 ± 1.37
5: **Effort:** How hard did you have to work to accomplish your level of performance?	3.33 ± 1.29
6: **Frustration:** How insecure, discouraged, irritated, stressed, and annoyed were you?	3.33 ± 1.58
Overall	3.24 ± 0.94

** Likert Scale: Very Low (1) to (7) Very High*
*** Statement worded reversely, and the overall score was calculated with the reversed score*

The participants' collective risk perception score averaged 2.73 based on the scores in Table 1. This score is slightly higher than the risk score for Discomfort/Pain, indicating that, overall, the expected safety incidents of working around drones on site can only result in the mildest safety consequences. A distribution of their responses is detailed in Table 5. The results reveal that most of the participants (53%) perceived experiencing discomfort and needing first aid as highly probable when working with or near drones. When it comes to the risk perception of medical case incidents, participants exhibited a divided perception, with 33% deeming them as unlikely but still possible and another 33% viewing them as highly probable. As for incidents leading to lost work time, more participants (33%) perceived that it is very likely to happen while working with or near drones on site. Finally, when it came to incidents resulting in fatalities, a majority (40%) perceived them as unlikely but possible to happen based on their experience on the virtual site. It is also worth noting that none of them perceived that fatalities were almost certainly to happen during such experiences.

Table 5

Percentage response results for safety risk perception scale

Injury Frequency / Severity	Not Possible	Unlikely But Possible	Likely	Very Likely	Almost Certain	Total
Discomfort/Pain	7%	13%	0%	53%	27%	100%
First Aid	0%	33%	0%	53%	13%	100%
Medical Case	7%	33%	20%	33%	7%	100%
Lost Work Time	13%	20%	27%	33%	7%	100%
Fatality	27%	40%	7%	27%	0%	100%

Conclusion and Future Work

The increasing integration of drones in the construction industry has created new opportunities to improve operational efficiency and data collection. However, this technological shift also introduces new challenges, particularly concerning the safety and psychological well-being of construction professionals. Recognizing the potential impact of drones on those who will soon enter this field, this study aimed to understand the perceptions and reactions of construction students—future industry professionals—to drones in a simulated construction environment. In this study, an immersive virtual reality construction site was developed, enabling participants to interact with drones in a controlled yet realistic setting. Through a user-centered experiment, the study evaluated the cognitive load, attitudes, and perceived safety risks of these students when exposed to drone presence during typical construction tasks. The overall results show that when performing construction activities around drones on job sites, construction students did not perceive significantly high cognitive load or negative attitudes. They also expected only mild safety incidents while working in the presence of drones on site. However, it is worth noting that in qualitative feedback, some participants mentioned feeling uneasy and nervous when drones came close to them. Additionally, the lack of transparent information about the drone's job raised concerns about potential physical contact or other risks. Since the construction site environment and the drone tasks vary for different projects, these results can only provide insights into specific human-drone interactions on job sites. Our future study will focus on a wider array of construction contexts, including human-drone collaboration on the same target tasks. Furthermore, to address the safety concerns of construction students when drones approach them and they lack information about the flight status, innovative information exchange systems such as human-drone communication protocols are needed to enhance perceptions and improve the actual safety performance of construction practitioners working with drones on jobsite.

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References

Akalin, N., A. Kristoffersson, and A. Loutfi. 2022. "Do you feel safe with your robot? Factors influencing perceived safety in human-robot interaction based on subjective and objective measures." *International Journal of Human-Computer Studies*, 158: 102744. https://doi.org/10.1016/j.ijhcs.2021.102744.

Bonci, A., P. D. Cen Cheng, M. Indri, G. Nabissi, and F. Sibona. 2021. "Human-Robot Perception in Industrial Environments: A Survey." *Sensors*, 21 (5): 1571. Multidisciplinary Digital Publishing Institute. https://doi.org/10.3390/s21051571.

Brown, S., R. D. Brooks, and X. S. Dong. 2020. *New Trends of fatal falls in the construction industry*.

Bureau of Labor Statistics. 2022. *A look at falls, slips, and trips in the construction industry : The Economics Daily: U.S. Bureau of Labor Statistics*.

Calantropio, A. 2019. "The Use of UAVs for Performing Safety-Related Tasks at Post-Disaster and Non-Critical Construction Sites." *Safety*, 5 (4): 64. Multidisciplinary Digital Publishing Institute. https://doi.org/10.3390/safety5040064.

Chang, V., P. Chundury, and M. Chetty. 2017. "Spiders in the Sky: User Perceptions of Drones, Privacy, and Security." *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems*, CHI '17, 6765–6776. New York, NY, USA: Association for Computing Machinery.

DroneDeploy. 2021. *DroneDeploy State of the Drone Industry Report 2021*.

Eiris, R., G. Albeaino, M. Gheisari, W. Benda, and R. Faris. 2021. "InDrone: a 2D-based drone flight behavior visualization platform for indoor building inspection." *Smart and Sustainable Built Environment*, 10 (3): 438–456. https://doi.org/10.1108/SASBE-03-2021-0036.

Fortunato, B. R., M. R. Hallowell, M. Behm, and K. Dewlaney. 2012. "Identification of Safety Risks for High-Performance Sustainable Construction Projects." *Journal of Construction Engineering and Management*, 138 (4): 499–508. American Society of Civil Engineers. https://doi.org/10.1061/(ASCE)CO.1943-7862.0000446.

Hallowell, M. R., and J. A. Gambatese. 2009. "Activity-Based Safety Risk Quantification for Concrete Formwork Construction." *Journal of Construction Engineering and Management*, 135 (10): 990–998. American Society of Civil Engineers. https://doi.org/10.1061/(ASCE)CO.1943-7862.0000071.

Hanoch, Y., F. Arvizzigno, D. Hernandez García, S. Denham, T. Belpaeme, and M. Gummerum. 2021. "The Robot Made Me Do It: Human–Robot Interaction and Risk-Taking Behavior." *Cyberpsychology, Behavior, and Social Networking*, 24 (5): 337–342. Mary Ann Liebert, Inc., publishers. https://doi.org/10.1089/cyber.2020.0148.

Hart, S. G., and L. E. Staveland. 1988. "Development of NASA-TLX (Task Load Index): Results of Empirical and Theoretical Research." *Advances in Psychology*, Human Mental Workload, P. A. Hancock and N. Meshkati, eds., 139–183. North-Holland.

Irizarry, J., D. Costa, and A. Mendos. 2016. "Lessons learned from unmanned aerial system-based 3D mapping experiments."

Jeelani, I., and M. Gheisari. 2021. "Safety challenges of UAV integration in construction: Conceptual analysis and future research roadmap." *Safety Science*, 144: 105473. https://doi.org/10.1016/j.ssci.2021.105473.

Jeelani, I., and M. Gheisari. 2022. *Safety Challenges of UAV Integration in the Construction Industry: Focusing on Workers at Height*.

Kaufeld, M., and P. Nickel. 2019. "Level of Robot Autonomy and Information Aids in Human-Robot Interaction Affect Human Mental Workload – An Investigation in Virtual Reality." *Digital Human Modeling and Applications in Health, Safety, Ergonomics and Risk Management. Human Body and Motion*, Lecture Notes in Computer Science, V. G. Duffy, ed., 278–291. Cham: Springer International Publishing.

Li, Y., and C. Liu. 2019. "Applications of multirotor drone technologies in construction management." *International Journal of Construction Management*, 19 (5): 401–412. Taylor & Francis. https://doi.org/10.1080/15623599.2018.1452101.

Martinez, J., M. Gheisari, and L. Alarcon. 2020. "UAV Integration in Current Construction Safety Planning and Monitoring Processes: Case Study of a High-Rise Building Construction Project in Chile." *Journal of Management in Engineering*, 36: 1–15. https://doi.org/10.1061/(ASCE)ME.1943-5479.0000761.

Namian, M., A. Albert, and J. Feng. 2018. "Effect of Distraction on Hazard Recognition and Safety Risk Perception." *Journal of Construction Engineering and Management*, 144 (4): 04018008. American Society of Civil Engineers. https://doi.org/10.1061/(ASCE)CO.1943-7862.0001459.

Nenna, F., V. Orso, D. Zanardi, and L. Gamberini. 2023. "The virtualization of human–robot interactions: a user-centric workload assessment." *Virtual Reality*, 27 (2): 553–571. https://doi.org/10.1007/s10055-022-00667-x.

Nomura, T., T. Kanda, and T. Suzuki. 2006. "Experimental investigation into influence of negative attitudes toward robots on human–robot interaction." *AI & Soc*, 20 (2): 138–150. https://doi.org/10.1007/s00146-005-0012-7.

Pandit, B., A. Albert, Y. Patil, and A. J. Al-Bayati. 2019. "Impact of safety climate on hazard recognition and safety risk perception." *Safety Science*, 113: 44–53. https://doi.org/10.1016/j.ssci.2018.11.020.

Sabino, H., R. V. S. Almeida, L. B. de Moraes, W. P. da Silva, R. Guerra, C. Malcher, D. Passos, and F. G. O. Passos. 2022. "A systematic literature review on the main factors for public acceptance of drones." *Technology in Society*, 71: 102097. https://doi.org/10.1016/j.techsoc.2022.102097.

Umar, T. 2020. "Applications of drones for safety inspection in the Gulf Cooperation Council construction." *Engineering, Construction and Architectural Management*, 28 (9): 2337–2360. Emerald Publishing Limited. https://doi.org/10.1108/ECAM-05-2020-0369.

Xia, Y., and G. LeTendre. 2021. "Robots for Future Classrooms: A Cross-Cultural Validation Study of 'Negative Attitudes Toward Robots Scale' in the U.S. Context." *Int J of Soc Robotics*, 13 (4): 703–714. https://doi.org/10.1007/s12369-020-00669-2.

Zafari, S., and S. T. Koeszegi. 2021. "Attitudes Toward Attributed Agency: Role of Perceived Control." *Int J of Soc Robotics*, 13 (8): 2071–2080. https://doi.org/10.1007/s12369-020-00672-7.

Zhou, S., and M. Gheisari. 2018. "Unmanned aerial system applications in construction: a systematic review." *Construction Innovation*, 18 (4): 453–468. Emerald Publishing Limited. https://doi.org/10.1108/CI-02-2018-0010.

Zhu, Z., I. Jeelani, and M. Gheisari. 2023. "Physical risk assessment of drone integration in construction using 4D simulation." *Automation in Construction*, 156: 105099. https://doi.org/10.1016/j.autcon.2023.105099.