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Worker-Drone Communication in Construction: Perspectives from Safety Experts

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Drones are increasingly utilized in the construction industry, raising novel safety concerns for workers who share the same environment. We developed a drone communication protocol in Virtual Reality (VR), which enabled safe worker drone interaction through various natural communication modalities. To further develop this communication protocol in real drones and apply it to future construction sites, it is necessary to investigate its feasibility and implementation requirements. Therefore, we adopted a two-phase participatory design approach involving safety experts in the early design phases to inform future research efforts. In the first phase, safety experts were presented with the communication protocols in immersive VR and could utilize them in a virtual construction site scenario. In the second phase, we gathered their feedback through semi-structured interviews based on a social robot participatory design framework, considering both modalities and interactions. The checklist generated from the interview results was subsequently sent back to the safety experts for validation, resulting in final challenges and recommendations that emphasized augmenting and tailoring communication modalities to specific site environments and work contexts. As the first participatory design effort involving safety experts in human-drone interactions within construction, this study provides valuable insights for future advancements to enhance site safety.

Keywords: Human-Drone Interaction, Construction Safety, Participatory Design, Virtual Reality

Introduction

Drones have become increasingly popular in the construction industry, resulting in the industry ranking second highest in drone adoption among all sectors (Alvarado 2024). According to user analysis, over 80% of current construction drone users intend to expand or maintain their investment in drones (DroneDeploy 2021). The construction industry has high-risk working environments, resulting in more than 1,000 fatal work accidents in the U.S. every year (Bureau of Labor Statistics 2022). It is also a traditional industry highly reliant on human labor. Given these two inherent characteristics of the construction industry, as drones become more prevalent in the near future, interactions between human workers and drones will increase. This shared work environment in dynamic and complex site contexts is expected to raise novel safety concerns related to drones, including physical contact risks, psychological burdens, and negative impacts on technology perceptions (Aghimien et al. 2023; Namian et al. 2021; Szóstak et al. 2023; Xu et al. 2020). Existing studies indicate that effective communication between humans and robots facilitates the establishment of good relationships, enhances team performance, and improves safety (Inkulu et al. 2022). Natural communication modalities such as gesture and speech have been proven to help workers improve balance performance and reduce safety incidents during worker-drone interactions on construction sites (Hu et al. 2024; Zhu et al. 2024). Lights, audio, and path patterns have also proven intuitive and effective for communicating necessary information to facilitate interactions between humans and drones (Duncan et al. 2018; Inkulu et al. 2022; Mirri et al. 2019). Our preliminary study (Hu et al. 2024; Zhu et al. 2024; Zhu et al., *under review*) has established a bi-directional communication protocol in VR, integrating multiple natural modalities such as gesture, speech, light, sound, and flight paths (Agrawal 2022; Duncan et al. 2018; Inkulu et al. 2022; Mirri et al. 2019; Vie et al. 2021) to facilitate safe interactions between general construction workers and drones on construction sites.

The protocol features both drone-to-human and human-to-drone communication functions. Users can actively utilize gesture-based and speech-based commands to maintain the drone at a safe or comfortable distance. Additionally, the system employs light and sound alerts to notify users when the drone is approaching on-site, while the spiral flight path indicates the drone's landing status. Users can interact with the virtual construction drones utilizing the communication protocol within an immersive virtual roof construction site. The specific communication protocol, which is facilitated in both directions through various modalities and incorporates a virtual construction environment, is presented in Figure 1.

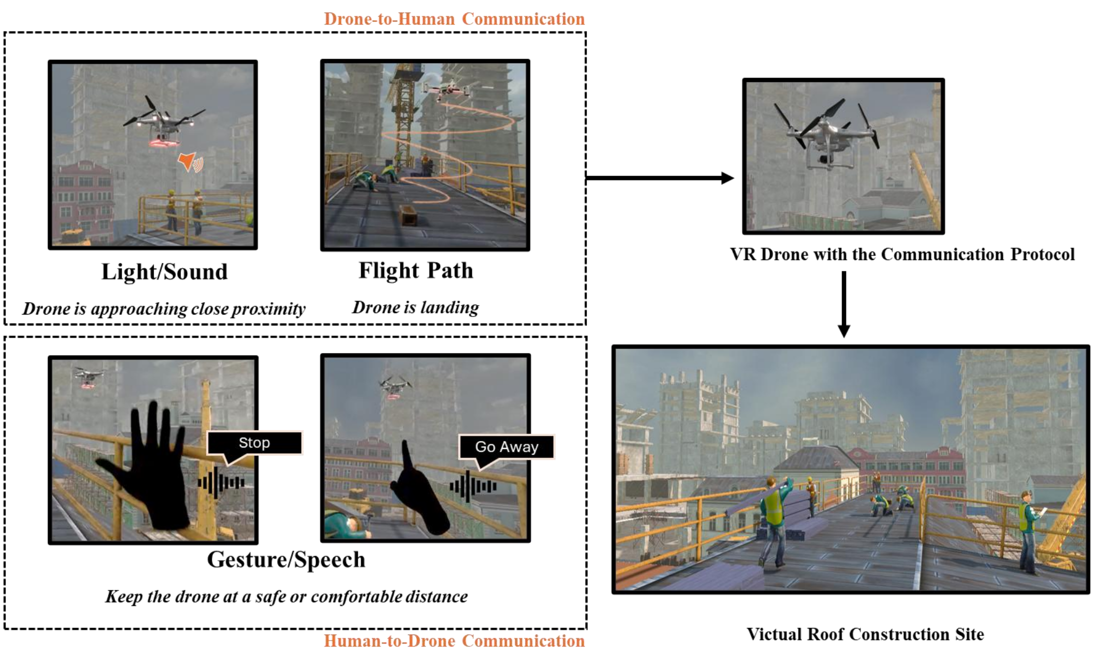

Figure 1. Bi-directional communication protocol for human-drone interaction in VR construction scenario

A user-centered study assessment in virtual environment revealed that workers using such a communication protocol could significantly enhance safety performance by reducing physical contact risks, lowering stress levels, and improving worker attitudes and perceptions of safety (Zhu et al., *under review*). The promising results from user-centered experiments to assess the proposed communication protocol in VR, which enabled safe communication with workers in virtual site scenarios, indicate significant potential. However, comprehensive safety considerations for implementing these communication functions on future construction sites remain unclear, including technical constraints, work procedures, application scenarios, and training requirements. Furthermore, although our preliminary design demonstrates strong capabilities and contributions to construction occupational safety interventions, there is room for improvement in specific functions. For example, augmenting communication modalities tailored to construction contexts while maintaining ease of understanding to convey safety intents on sites could enhance effectiveness and safety performance. These considerations should be thoroughly explored before applying these design resources to real drone prototypes and conducting field tests on construction sites.

Therefore, this study adopted a participatory design approach, involving safety experts to identify and incorporate the safety needs of construction sites into the early phases of the design process (Axelsson et al. 2021). As the first participatory design effort for human-drone interaction in construction, this approach provided insights into both challenges and recommendations for future improvements and further research on human-drone communication in construction environments, especially from safety perspectives.

Background

In this study, we adopt a participatory design approach to identify challenges and gather recommendations for our future design. The goal of the participatory design approach is to involve all stakeholders of new technology in the early design phase to create a better system and meet realistic user expectations (Bratteteig and Wagner 2016). Therefore, participatory design is widely applied in interactive systems design, involving designers, domain experts, and users at every stage—from early discussions aimed at understanding problems, concerns, and needs to brainstorm design possibilities, evaluating low-fidelity or early-phase prototypes and continually refining systems throughout subsequent iterations focusing on different aspects (Lazar et al. 2017). Participatory design is particularly beneficial in the early design process of robots applied in different social and industrial contexts (Björling and Rose 2019), and for systems development where a deep understanding of the application situation or context is required (Lazar et al. 2017). In our case, this study aims to find appropriate future research paths for implementing worker-drone communication in construction contexts and to provide guiding design principles based on our preliminary design and a VR prototype (Pnevmatikos et al. 2022).

Existing studies have used virtual prototypes as probes in participatory design research to collect information regarding application situations and user environments to inspire future design. Technology probes in workplace settings can help understand users' needs and desires in real-world settings, field-test new technology, and inspire users and researchers to think about new potentials (Madden et al. 2014). Virtual prototypes and simulations offer interactions identical to real application contexts and help test systems before robotic systems are implemented in the real world (Tian et al. 2021; Zamfirescu-Pereira et al. 2021).

Therefore, this study adopted the communication protocol we developed in VR as a probe for participatory design, featuring immersive construction site scenarios, and presented it to a panel of safety experts who could directly interact with it. Additionally, semi-structured interviews were conducted using a participatory design framework that focuses on social robot development (Axelsson et al. 2021). This framework examines how users interact with robots, including interaction modalities and interaction flow (Figure 2), which define how interactions occur and are planned within various contexts. The research methodology and selected participatory design techniques, including virtual reality demonstration and semi-structured interviews in this study, were discussed in detail in the following section.

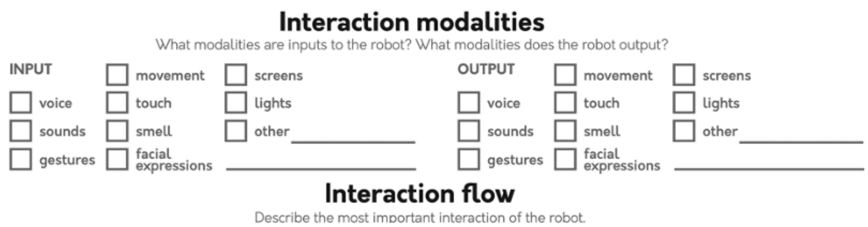

Figure 2. Participatory Design Framework for Social Robot Development (Axelsson et al. 2021)

Research Methodology

This paper presents a two-phase participatory design study aimed at exploring the future design and implementation of safe worker-drone communication on construction sites by leveraging the perspectives of safety experts (Figure 3). In the first phase, a bi-directional communication protocol in VR featuring immersive construction site scenarios was demonstrated to a panel of safety experts and served as probes, positioning the safety experts as future users interacting with drones using the proposed communication modalities on construction sites. In the second phase, semi-structured interviews were conducted to gather feedback from the safety expert panel. Additionally, a checklist offering insights into challenges and recommendations for future design and implementation to enhance safety on construction sites was sent back to the safety experts for validation.

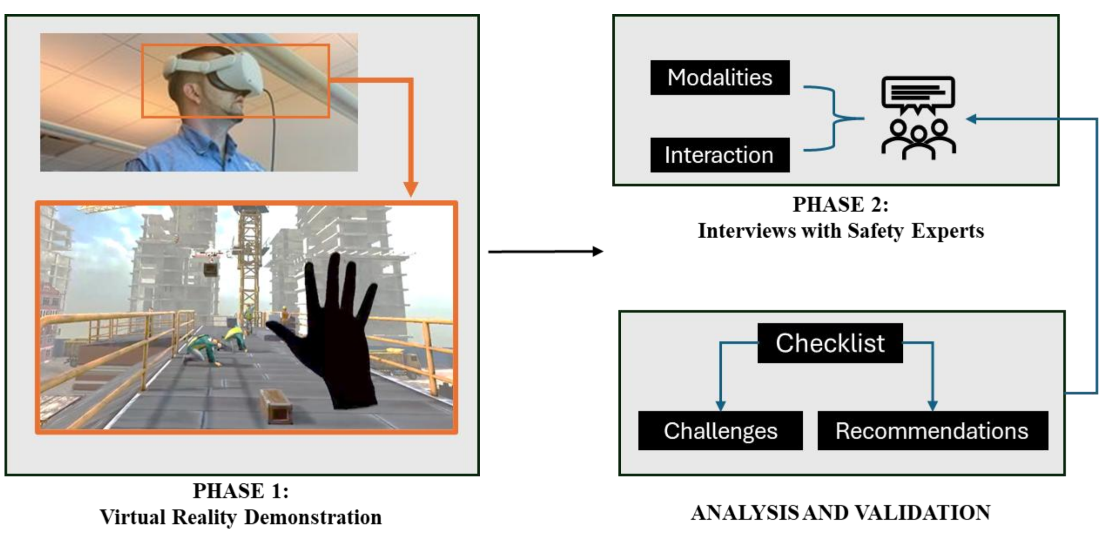

Figure 3. Research Methodology

Virtual Reality Demonstration

The participatory design study was approved by the University of Florida Institutional Review Board (IRB #ET00042493). Eight safety experts from a prestigious institution specializing in safety research, with a focus on safety engineering or occupational safety, volunteered to participate in the study. A summary of their demographics and experience is shown in Table 1.

Table 1. Demographic information of safety experts

Variable	**Category**	**Number (%)**
Gender	Male	7 (87.50%)
	Female	1 (12.50%)
Age	≤50	2 (25%)
	>50	6 (75%)
Educational Status	Bachelor's degree	1 (12.5%)
	Master's degree	1 (12.5%)
	Doctoral degree	6 (75%)
Work Experience	5 to 10 years	2 (25%)
	10 to 30 years	2 (25%)
	More than 30 years	4 (50%)

The average age of the safety experts is 53.23 years (SD = 8.60), and the average work experience is 22.50 years (SD = 12.50).

In the VR demonstration phase, the safety experts were first presented with an introductory video about the bi-directional communication protocol integrating multiple natural modalities we developed for safe worker-drone communication on construction sites. This video highlighted the critical information and the intent conveyed by each modality. Subsequently, the experts were immersed in a virtual roof construction site where they interacted with the virtual drone, utilizing communication protocol to experience specific utilization and potential implementation in future construction sites (Figure 1).

Interviews with Safety Experts

Since our proposed communication protocol for construction drones focuses on safe interactions and the social functionality of communication, the semi-structured interview questions were developed based on the participatory design framework focusing on social robot development (Axelsson et al., 2021). This framework examines the specific manner in which a user interacts with a robot, including two dimensions: modalities, which seek feedback for specific interaction methods such as gesture, speech, light, sound, and flight path in our study, and interaction flow, which defines how interactions occur and are planned within specific contexts. Based on this framework, the interview questions are listed in Table 2. Additionally, the researcher who conducted the interviews asked follow-up questions regarding the experts' feedback to seek more detailed recommendations.

Table 2. Semi-structured Interview Questions

Dimension	**Question**
Modalities	Q1. Do you have any suggestions for improving communication modalities for safe worker-drone interaction?
	Q2. Do you have any concerns or specific requirements related to these communication modalities?

Interaction	Q3. What strategies would you suggest for implementing communication systems between workers and drones to ensure safe and effective interactions on construction sites?

Results Analysis and Validation

A checklist was generated based on the content analysis of the interview results. It includes both challenges and recommendations regarding the implementation of different communication modalities at future construction sites to enhance safe interactions between drones and workers. The code structure is based on the experts' responses for both modalities and interactions, and it is classified into challenges and recommendations across different dimensions. Table 3 shows the frequencies of how many experts mentioned each item in their statements.

Table 3. Code Structure and Statement Frequencies

Code Level 1	**Code Level 2**	**Frequencies (out of 8)**
Challenges	Modality Limitations	7
Recommendations	Modality Augmentation	4
	Implementation Measures	6
	Team Responsibilities	5
	Training Requirements	8

A mini-Delphi approach (Pan et al. 1996) was applied in the second review round to confirm the reliability of the first round's expert interview results. The checklist was emailed back to each safety expert who conducted the VR demonstration and interviews, allowing them to add comments or raise any additional points. All eight experts confirmed their agreement with the checklist and offered no further comments on the challenges or recommendations. The checklist was thus considered validated, and the detailed results and insights are discussed in the following sections.

Results and Discussion

The validated checklist highlights challenges identified by safety experts, noting that communication modalities could be primarily compromised by technical constraints and environmental disturbances. The checklist also includes actionable recommendations, such as modality augmentation, implementation measures, team responsibilities, and training requirements. These detailed insights are discussed below.

Challenges

Modality Limitations: The major challenges in implementing different communication modalities stem from technical constraints that are exacerbated by environmental disturbances. These issues arise from both natural external conditions and the specific settings of construction sites. According to the validated checklist from safety experts, speech commands can be affected by noise disturbances, detection latency, and misinterpretation of commands during workers' daily tasks. Furthermore, gesture commands may not be suitable for workers holding tools or equipment and can also result in misinterpreted commands arising from routine activities. Overall, communication methods based on gestures or speech may be difficult for workers in confined spaces, especially when they need to communicate with both operating machines and drones. Additionally, in outdoor construction site environments, wind variations can disrupt the drone's flight path and its ability to convey information.

Recommendations

Modality Augmentation: Beyond the limitations of current communication modalities, safety experts suggested additional measures to enhance their safety performance, particularly those enabling drone-to-human communication. These augmentation measures are also utilized in other equipment and automation within industrial settings. For instance, augmenting auditory alarms could attract attention when the drone is out of the worker's sight. Additionally, enhancing visual indicators with cone-shaped light projections can clearly signal the drone's approaching path and increase its visibility.

Implementation Measures: Safety experts provided several recommendations to enhance overall safety. First, the system should incorporate effective proximity sensors to reduce potential injuries and include an emergency stop feature to override the entire system and prevent detection failures. These measures could minimize potential incidents and injuries, especially in the case of system failures. Furthermore, when implementing communication functions, the drone should slow down when it is within a certain distance to ensure safer and clearer communication. Additionally, setting a specific control distance can limit the number of workers who can control the drone, thus preventing conflicting commands.

Team Responsibilities: The critical concept of on-site safety is to prioritize worker well-being and ensure that workers know they can use communication to control drones and prevent safety issues. Furthermore, it is important to prioritize the pilot's authority to take control of the drone, especially during task-related operations and emergency situations. Critical decisions should be made by the on-site team, not just automated systems.

Training Requirements: To effectively incorporate the communication systems and enhance their safety performance, implement video instructions and VR training to familiarize workers with operating around drones and utilizing the communication protocols. Additionally, address the potential for drones to misinterpret random gestures as commands during training to prevent unintended actions. Furthermore, develop comprehensive training programs for drone pilots on construction sites and certify trainers in worker-drone communication.

Future Work

Based on the challenges and recommendations identified in the validated checklist from our participatory design study, several dimensions emerge for future research to explore:

Technical requirements: The most significant concerns for implementing different communication modalities stem from technical constraints and environmental disturbances arising from both natural conditions and the inherent characteristics of construction sites. Future studies should involve additional iterations of participatory design with robotics experts to address these technical challenges. User studies are also needed to refine clear technical system requirements based on workers' preferences and how they utilize communication commands, such as preferred communication proximity with drones. Furthermore, case studies or field tests to investigate the feasibility and reliability of detection systems during construction activities are crucial for ultimately improving system performance and ensuring safer communication between workers and drones.

Multi-agent interaction scenarios: Our current protocol focuses on communication between a single drone and a single worker on-site. However, construction sites often involve multiple workers and robotic agents, which can introduce conflicts in worker-drone communication. Future research should explore scenarios where two or more workers interact with a single drone or where multiple drones operate simultaneously. User studies should examine how observing others communicate with drones affects individual perception, overall performance, and the trust relationships among human workers and drone teams on-site. Additionally, understanding the impact of contradictory or overlapping communications from different workers is essential. It is also required to develop clear work procedures and define team responsibilities, which will be critical to managing these complex interactions effectively.

Training and Education: As we are devoted to developing innovative communication systems, it is essential to consider the training requirements for workers to become familiar with drone presence and the projected ubiquity on future construction sites. Future research should focus on designing effective training programs that educate users on how to interact safely and efficiently with drones and other robotic systems. Incorporating virtual reality simulations and interactive modules could especially enhance learning outcomes and promote widespread adoption of these technologies.

Conclusion

In this study, we adopted a participatory approach to involve safety experts in the early design process of proposed worker-drone communication functions on construction sites. Our aim was to gather safety insights, including challenges and recommendations for future implementation, to inform improvements and guide further research on our preliminary design. This design was presented as a communication protocol in VR integrating multiple communication modalities and incorporating a virtual construction site, allowing users to experience it in realistic contexts. First, we presented the protocol to a panel of safety experts through a VR demonstration, providing them with an experience and understanding of potential use scenarios. We then gathered their feedback through semi-structured interviews based on a social robot participatory design framework, considering both modalities and interactions. The checklist generated from the interview results was subsequently sent back to the safety experts for validation.

The validated results highlight challenges in applying different communication modalities due to external environmental variances and disturbances. They also emphasize the requirements for communication modality augmentations, emergency stop features for the communication system, and predefined communication responsibilities and situations. These findings inform the future path of human-drone communication on construction sites, including the safety needs for communication with other types of robots such as ground mobile robots. They underscore the importance of considering technical requirements for each communication modality tailored to the construction site environment and crew cooperation involving multiple worker agents in the communication loop. This study represents the first effort to use a participatory design approach that includes safety experts in the design stage when considering human-drone interaction in construction.

Compared to existing discussions of drone communication technologies, which include logistics applications in agricultural inputs and medical supplies as well as social uses in healthcare and companionship (Emimi et al. 2023; Herdel et al. 2022), this study focuses on safety-enhance communication designed for non-operator workers, especially in high-risk construction environments prone to fatal incidents. Based on the participatory design with safety experts, it sheds light on future study directions, including technical requirements, multi-agent interaction scenarios, and training and education. More iterations of participatory design with domain experts such as safety, drone, and construction experts, as well as end users like construction practitioners, are needed to refine the design and define an appropriate roadmap for transitioning from the VR protocol to real world prototypes and future implementation. The study and the participatory design approach also shed light on the co-design of other types of robots applied in various industrial contexts.

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