Working with Drones: Design and Development of a Virtual Reality Safety Training Environment for Construction Workers

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ABSTRACT

The use of drones in construction grew exponentially over the last few years, making the construction industry one of the fastest commercial adopters of this technology. Drones are widely used in the construction industry for a wide variety of applications (e.g., site surveying/mapping, earthwork volumetrics, safety inspection, progress monitoring). Nevertheless, the integration of drones in construction raises novel occupational safety and health issues for onsite construction workers. This study presents the technical design and development of DroneSim, a virtual reality (VR) safety training environment for human-drone interaction on construction jobsites. Specifically, DroneSim aims at training construction workers on how to safely collaborate and work with drones on jobsites. The paper discusses the complete workflow involved in designing and developing the VR environment, which consisted of (1) identifying current and future drone-mediated construction applications; (2) identifying the technical and functional requirements pertaining to each of the applications; (3) proposing different drone types based on the identified applications; and (4) developing the VR-based environment, which included the incorporation of static objects, sound effects, animations, text-to-speech, as well as audio, lip-sync, and gesture synchronization.

INTRODUCTION

The dynamic and complex jobsite conditions make construction one of the most hazardous industries to work for, accounting for more than 20% of occupational fatalities in the 2019 US private sector (US Bureau of Labor Statistics 2019). In construction, around 200,000 worker-related occupational injuries are reported yearly, and more than 28,000 fatalities occurred since 2000 (US Bureau of Labor Statistics 2019). In addition to the life-threatening nature of workplace injuries and fatalities, the financial implications of jobsite-related incidents go beyond lost time and productivity. In fact, the average healthcare-related expenses associated with a fatality are estimated at around $1 Million (National Safety Council 2014).

To cope with the declining growth in efficiency, productivity, and labor availability, construction has recently started to integrate automated and robotic processes into existing practices. In particular, drones, also known as Unmanned Aerial Systems (UASs) or Unmanned Aerial Vehicles (UAVs), emerged as one of the top technologies adopted on jobsites. The aerial platforms' abilities to safely, efficiently, and cost-effectively accomplish tasks enabled them to be integrated in a variety of applications across different phases of construction projects (González-deSantos et al. 2020; Jiang et al. 2020; Mutis and Romero 2019). In the future, drone presence is expected to increase even more, and these platforms are anticipated to become ubiquitous and populate jobsites. In fact, there is an ongoing paradigm shift in the roles of these aerial platforms in construction: drones have recently started to be regarded as active collaborators that interact and collaborate with jobsite personnel and ground robots (i.e., autonomous and self-driving construction machinery), rather than passive followers, simply following humans' navigation commands. For example, these aerial platforms are envisioned to assist construction workers at heights in painting and constructing facades, delivering construction tools and materials, as well as communicating with personnel from farther distances (Albeaino and Gheisari 2021). With the recent developments in artificial intelligence, machine learning, robotics, and engineering, drone technology integration in construction is expected to increase even more and become commonplace in such environments.

There is a need to explore drone technology more from the context of human-robot interaction to understand their impact holistically, especially as it relates to the health and safety of workers. This is particularly important in order to cope with: (1) rapid and sudden changes that the construction domain is witnessing in terms of robot integration; (2) projected growth in drone adoption and human-drone interaction on construction jobsites; and (3) ill-preparedness or unreadiness of the workforce for such rapid changes in current construction processes. While it is important to conduct studies in realistic environments to investigate human-drone interaction at different interfaces and observe worker behavior around the aerial vehicles, such studies are somehow futuristic and unsafe to be conducted in real-world jobsites, justifying the need for virtual types of environments. In this study, the technical design and development of DroneSim, a Virtual Reality (VR) safety training environment aiming at simulating future construction workplaces with different autonomous agents such as drones will be presented. This will ultimately help in better understanding the interaction between human workers and autonomous agents on jobsites.

BACKGROUND

Construction is one of the most hazardous industries in terms of occupational injuries and fatalities (Martinez et al. 2021). Causes behind these fatal and non-fatal injuries include the nature of the jobsite environment, which is characterized as loud, complex, dynamic, and challenging. Such characteristics, combined with the nature of tasks (e.g., working outdoors and at elevated areas and platforms) and other interrelated factors (e.g., risky activities, site conditions, organizational characteristics, and weather conditions), increase the chances of hazardous situations and render the identification of the main causal factors behind such situations challenging (Hu et al. 2011; Nadhim et al. 2016). For example, Hasanzadeh et al. (2019) associated the ability to identify and recognize onsite safety hazards with individual characteristics and personality traits. Haslam et al. (2005) indicated that jobsite conditions (e.g., site layout, housekeeping) account for around 50% of jobsite accidents. Organizational characteristics (e.g., company sizes, funding availability) could also play an important role in jobsite safety: smaller companies with limited funding do not have enough resources to train construction workers and provide them with the necessary personal protective equipment (PPE) and fall arrest systems, jeopardizing their safety performance (Nadhim et al. 2016). Project management is another factor affecting jobsite safety, especially since workers' jobsite attitudes and behaviors tend to change considerably should the projects fall behind schedule. Despite the adoption of multiple protection measures such as personal protective equipment and personal fall arrest systems to mitigate the safety risks, these attempts have not been enough to completely eliminate worker injuries and fatalities on jobsites. This encouraged construction personnel to shift focus towards training construction workers as to the safest and most efficient construction practices.

Drones are one type of robots that are being increasingly integrated in the construction domain. These aerial platforms' abilities to complete construction tasks safely, and in less time and cost, allow them to become efficient alternatives to traditional robot-less construction procedures. If mounted with onboard cameras and other sensors, these devices are capable of providing a bird's eye-view of the jobsite conditions, enabling them to capture different jobsite visualizations throughout the entire construction lifecycle. In the pre-construction stage, drones are used to conduct site feasibility studies and site activity planning (Jiang et al. 2020). In the construction stage, they are being deployed for a wide variety of tasks, mainly for inspecting structures and infrastructures, monitoring jobsite and worker compliance with safety standards, and monitoring construction activity progress over time (Eiris et al. 2020; González-deSantos et al. 2020; Park et al. 2018). Applications in the post-construction phase of a project include maintenance of facilities (e.g., damage quantification and identification, thermal leak detection), and assessment of buildings in the post-disaster setting (Mutis and Romero 2019). In the future, drones are expected to become more ubiquitous and populate construction jobsites. For example, drones are envisioned to assist in security surveillance (i.e., monitoring jobsite against trespassing and thieving activities), aerial construction (i.e., helping construction workers in bricklaying and painting tasks), material handling (i.e., transporting construction tools and materials on jobsites), and site communication (i.e., communicating with jobsite personnel) (Albeaino and Gheisari 2021). This shows that aerial vehicles are becoming more involved in construction processes, shifting roles from simply following human-inputted control commands to collaborating and assisting in different jobsite activities. With the developments in different technologies (e.g., artificial intelligence, photogrammetry, machine learning, robotics), drone-mediated construction applications and interaction with humans will expand even more on jobsites. Given that workers are not yet prepared for such rapid drone integration, training them about the safest interaction practices between them and aerial vehicles is a necessity. However, this type of training type often needs to be conducted in VR-based environments, especially since most of these scenarios are futuristic (difficult to observe in real world) and more importantly, not safe to be conducted in the real world.

Multiple studies have explored using VR-based environments for training and safety performance evaluation in construction. As an example, Kisker et al. (2021) asked subjects to virtually walk along an overhanging steel structure at height, measured their resulting psychophysiological (i.e., heart rate) effects during the experiment, and showed that they had experienced a "presence" feeling while being exposed to heights in the VR environment. In addition, Sakib et al. (2020) exposed drone pilots to real-world and VR-based training conditions while analyzing their mental workload, stress, and performance using wearable technology. The collected user physiological data showed that VR-mediated training is an efficient drone training option when compared with real-world applications. Advantages of VR include the ability to: (1)

replicate real-world scenarios and environments and perform data collection that could otherwise be too difficult or hazardous to be conducted on real construction jobsites; (2) perform studies in a repeatable, safe, and controlled environment while maintaining the spatiotemporal context of actual jobsites; and (3) simulate futuristic construction environments to study the potential effects of new or upcoming technology implementation on construction workers (Kisker et al. 2021). By identifying how drones are being deployed and how they will in the future be utilized on construction jobsites, VR experiments can be developed, and the training of workers can be safely and repeatably be conducted and evaluated.

DEVELOPMENT OF DRONESIM

Identifying and Designing Human-Drone Interaction Applications. The aim of this study is to design and develop DroneSim, a VR safety training for human-drone interaction on construction jobsites. For this reason, the construction literature was queried, and studies were analyzed to identify current and future potential human-drone interaction applications on jobsites. Table 1 summarizes the current and future drone applications that were chosen to be simulated in VR based on the literature search (Albeaino et al. 2019; Albeaino and Gheisari 2021). The next step after identifying the scenarios was to identify the technical and functional requirements pertaining to each of the scenarios prior to visualizing and prototyping the experiences in VR. For this reason, storyboarding was adopted to plan and contextualize the VR training environment. Multiple drones – Inspector-Drone, Builder-Drone, Safety-Drone, and Delivery-Drone – specifically intended to accomplish construction tasks near workers were also selected for each of the identified construction applications (See Table 1). The training environment design was an iterative process and regularly subjected to modification based on the feedback and discussions between the research team and different construction and safety experts.

Table 1. Selected current and future drone-mediated construction applications in DroneSim

Applications	Description	Proposed Drone Types
Progress Monitoring	Collecting imagery throughout different stages of construction projects to track project progress.	Inspector-Drone
Building Inspection and Maintenance	Inspecting building for structural integrity assessment and damage identification and quantification.	Inspector-Drone
Earthwork Operations	Assisting in earthmoving calculations.	Inspector-Drone
Aerial Construction	Assisting in the aerial construction of buildings (e.g., painting, bricklaying).	Builder-Drone
Site Communication	Communicating using drones with jobsite personnel from farther distances.	Builder-Drone
Safety Management	Monitoring and inspecting workers' safety performance and jobsite standards.	Safety-Drone
Security Surveillance	Monitoring against thieving and trespassing activities.	Safety-Drone
Material Handling	Delivering construction tools and material on jobsites.	Delivery-Drone

DroneSim Technical Development. The technical development of the VR safety training environment adopted in this study was performed by obtaining 3D computer-aided design (CAD) models of different components and temporary structures typically present on construction jobsites. These 3D models include construction buildings, drones, cranes, forklifts, excavators, earthmovers, concrete machines, among others. All these 3D models were then converted into film box format (.FBX) and imported into Unity® to recreate a jobsite environment in VR (Figure 1). The workstation used to develop DroneSim is a high-performance computer with an Intel® Core™ i7-9700 CPU at 3.60 GHz processor, 64 GB of RAM, and an Nvidia® GeForce RTX 2070 GPU. All the models were rendered using High Definition Rendered Pipeline (HDRP), which is used for advanced graphic visualization. Sound effects for drones, cranes, and excavators were produced in Fruity Loops, which is a Digital Audio Workstation. Animations pertaining to the movement of cranes, excavators, drones, and various other machinery within the construction site and visual effects for dust and vehicle tire tracks were created. Different scripts were written in C# language for the different drone types (shown in Table 1) to perform their respective functions.

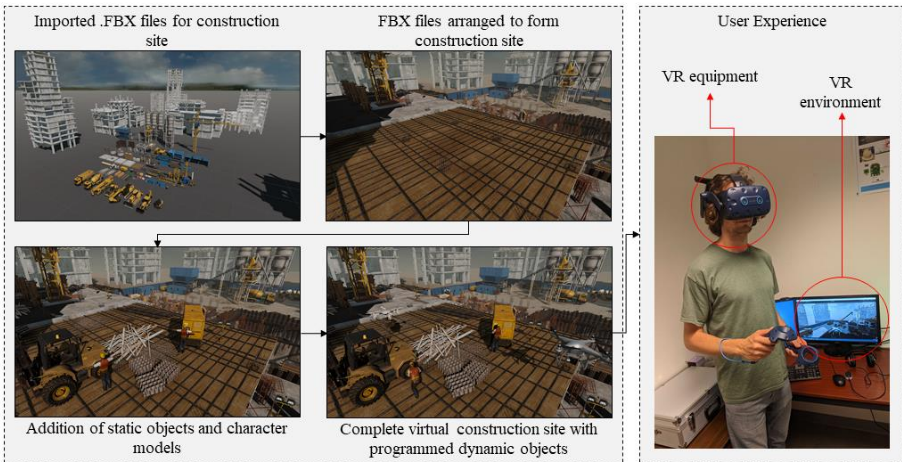


Figure 1. Workflow for the development of VR construction jobsite environment.

The development also consisted of importing construction-worker 3D models that replicate the actions performed by actual workers on construction jobsites. These 3D character models were created using Daz® 3D. In addition, text-to-speech software was utilized to produce audio dialogues for these 3D character models. The animations that have been used by these character models to perform various activities in the virtual construction site have been imported from Adobe®'s Mixamo. Scripts in C# language were also developed to synchronize the audio, lip-sync animations, and gesture animations to bring these 3D character models to life. Figure 2 shows the completed version of the VR-based construction environment along with static and dynamic objects (e.g., virtual agents, drones, equipment).

The elements used in the DroneSim design and development phase (i.e., virtual construction site, agents, and equipment) serve as a repository of interactive characters that can be relied upon to recreate any drone-mediated construction scenario. More specifically, each of the construction applications identified from the literature could be replicated using a scenario in DroneSim. Table 2 shows the different drone-mediated applications identified from the literature, corresponding example scenarios, and their visualizations in the DroneSim VR safety training environment. The VR-based visualizations also show the different drones that were modeled based on the identified applications and scenario examples. For example, the delivery drone was modeled and programmed so that it is capable of carrying payloads and delivering materials on jobsites; a builder drone was modeled to accomplish different aerial construction tasks, including carrying materials such as bricks as payloads to construct facades or to assist in painting work.

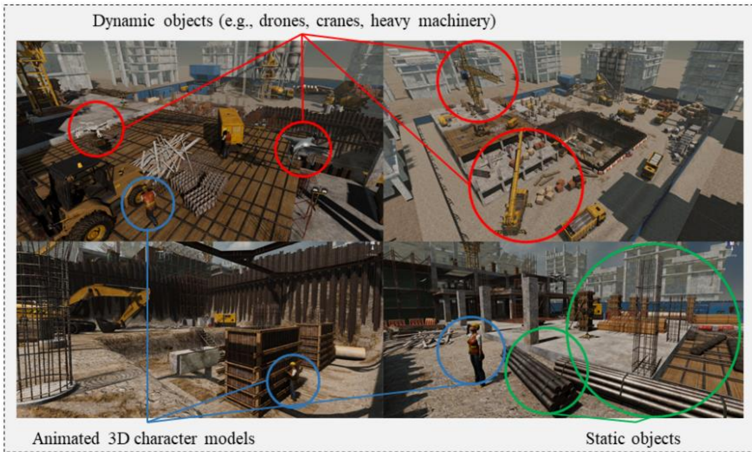
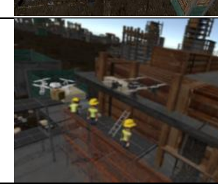


Figure 2. Overall visualizations of the VR construction environment.

Table 2. Drone-mediated applications and corresponding example scenarios.

Applications	Scenario Example	VR Environment Visualization
Progress Monitoring	The inspector-drone that is equipped with high-resolution cameras, GPS, and other localization systems inspecting the exterior wall brickwork to determine work progress and identify quality and/or structural issues.	
Building Inspection and Maintenance		
Earthwork Operations	The Inspector-Drone acquiring visuals during excavation work.	
Aerial Construction	A builder-drone is connected to a paint reservoir, an onboard compression pump, and a flexible hose with at least 2 degrees of motion to perform a painting job where workers prepare the surface and drones spray paint on a prepared surface of a high-rise building project. The builder-drone is also used as means of communication between construction workers and supervisors.	
Site Communication		
Safety Management	A safety-drone with visual and motion detection sensors, assists the crane operator and spotter who are moving a heavy structural steel beam by monitoring the blind spots of the crane operator.	
Security Surveillance	The safety-drone is monitoring the jobsite exit and entrance against any trespassing or thieving activities.	
Material Handling	A delivery-drone with a sturdy frame and high-performance rotors to carry tools and small material (e.g., wire and electrode feeds, fasteners, pipe fittings) to welders, roofers, or plumbers working on heights.	

CONCLUSION

This study aims at presenting the technical design and development of DroneSim, a VR-based safety training environment specifically developed for human-drone interaction on construction jobsites. DroneSim was designed based on current and future drone construction applications that were identified from the literature. The technical development of DroneSim, which included static objects, sound effects, animations, text-to-speech, and synchronizations, consisted of proposing different drone types and exploring the technical and functional requirements for each of the identified construction applications. Using DroneSim, different drone-mediated construction scenarios were presented for various types of drone-mediated applications. The ultimate goal of DroneSim is to assist in training the construction workforce in a realistic, repeatable, and safe environment, on how to operate, interact, and collaborate with drones on jobsites, paving the way for safe worker-drone interaction and collaboration on jobsites. Future work consists of ensuring that Occupational Safety and Health Administration (OSHA) safety guidelines commonly established on real-world jobsites are properly followed in DroneSim. Through the inclusion of different metrics and performance measurements, future studies should also evaluate the usability and effectiveness of DroneSim as a real-world training alternative using repeated-measures experiments involving construction workers. Such experiments are particularly important to: evaluate the differences between DroneSim and real-world jobsite environments; verify whether DroneSim can serve as a training platform to practice safe human-drone interaction; and prepare workers to safely use these aerial platforms on jobsites.

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