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Physical risk assessment of drone integration in construction using 4D simulation

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ABSTRACT

Drones are increasingly being used in construction for various applications. However, this integration has increased interactions between drones and workers, posing significant safety challenges for workers. This paper assessed the physical risks of drones on construction sites using VR-based 4D simulations. Roofs, ladders, and scaffolds were identified as the top high-risk environments where workers were at an increased risk of accidents when working around drones. A system-level virtual simulation environment was developed to run 2700 simulations per scenario with varying parameters, mimicking and visualizing potential interactions between workers, structures, equipment, and drones flying at different distances of workers: Near-Drone (<4 ft) and Distant-Drone (>4 ft). The results suggest that the Distant-Drone had a higher frequency of collision incidents with equipment and the ground, while the Near-Drone had a higher frequency of collision incidents with buildings and workers. This differential impact of flight parameters and interaction distance on drone collisions implied the need for targeted safety strategies for different working contexts.

1. Introduction

The two major challenges that the construction industry has incessantly been battling over the last few decades are the ever-dwindling supply of skilled labor and consistently high injury rates. To overcome these challenges, advancing the development and application of different technological solutions has been a major research and innovation endeavor in construction [1]. The investment in construction technology has more than doubled over the past decade with over $25 billion invested between 2014 and 19 [2]. With the rise in construction activities to satisfy our growing infrastructural needs, coupled with a dwindling supply of skilled labor, technology will greatly influence how construction activities are carried out in the future.

Various advanced sensing and information technologies have been developed and implemented in the construction sector to improve construction performance in terms of safety, quality, productivity, and cost [3]. One such technological brilliance are drones, also known as unmanned aerial vehicles (UAVs), which have become increasingly popular in construction projects due to their numerous advantages. In fact, construction is the top adopter of drone technology among all industries [4]. Compared to the previous year, the use of drones in construction increased by >200% in 2018 [4] and the trend continues based on statistics from 180 countries. Despite the worldwide economic impact of the pandemic, 88% of worldwide drone users in the construction industry intend to grow or maintain investment in drone technology in 2021 [5]. Drones can accomplish data collection and inspection tasks more effectively and at a lower cost on construction sites [6]. More importantly, drones can also perform different activities in risky or inaccessible areas eliminating the need for workers to go in such areas [7]. Finally, drones can be integrated with other emerging technologies like BIM (Building Information Modeling) and the Internet of Things (IoT) and equipped with various sensors that to automate the collection and analysis of necessary data needed for documentation and inspection [8,9]. As such, drones are being used for numerous applications in construction, including building inspection [10–12], damage assessment [13,14], site surveying and mapping [15–17], progress monitoring [18–21], and safety inspection [22]. This significant increase in drone usage on construction jobsites is expected to continue. The worldwide market for construction drones is projected to increase with a compound annual growth rate (CAGR) of 15.4% from 2020 to 2027 [23]. The U.S. Army Corps of Engineers also emphasizes that “UAS technology will not be stopped or slowed, so it is critical that the Corps of Engineers Civil Works tackles this technology quickly and strongly.” [24].

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As all trends indicate, the adoption of drones in the construction industry is growing, leading to increased collaboration and interaction between human workers and drones on job sites. In the near future, we anticipate the emergence of drone-dominant construction sites, where drones with different responsibilities will work collaboratively with human workers to perform a broader range of construction-related tasks. Since construction remains a human-centric industry, these drones must work side by side with humans. This includes the drone operators and other workers on-site who may be uninvolved with drone operations. As a result, a considerable rise in the risk of unintended contact between drones and human employees should be expected. Construction is already one of the most dangerous industries, which has resulted in >5000 fatal work injuries in the US in the past five years [25]. With the increase of drone integration in construction, additional safety challenges can make construction job sites even more dangerous than before, especially for construction workers who work in hazardous work conditions (on heights, use dangerous tools, work near heavy equipment). Jeelani and Gheisari [26] categorized the safety challenges of drones in construction as physical risks, attentional costs, and psychological impacts. Being physical entities sharing their work environment with workers, there is always the chance of physical contact with drones and other nearby humans and objects, (categorized as physical risks). Drones, that share the work environment with human workers, can collide with workers (struck-by incidents) resulting in direct injuries or cause loss of balance for those working on heights, which can cause more serious injuries. Drones can also collide with other physical entities on site (scaffolding, ladders, buildings) and result in subsequent accidents. With drones flying over the work-zone, there is always a risk of it (or its payload) falling on the workers below due to some technical issue (e.g., loss of power), human error (e.g., poor teleoperation), or environmental condition (e.g., high winds). As such drones not only pose safety risks to workers who operate the drones or work directly with them but also to workers who just happen to be working in the same job site. Workers who interact with drones or work in close proximity to them are more likely to be struck by drones and also face additional risks of their body parts getting caught in the moving parts of drones. Drones can also cause distraction among workers, which can result in unsafe behavior resulting in serious injuries [27]. Research has also demonstrated that working with robotic machines (such as drones) especially those equipped with recording devices can be stressful for workers and instill negative emotional states [28], which in addition to affecting the long term mental health of workers, can also lead to poor performance and unsafe behavior. While attentional and psychological impacts of working with or near drones are important and worthy of investigation, the most crucial and direct safety challenges of drones are the physical risks that these flying machines pose on workers. Therefore, this study focuses on the physical risks posed by drones for workers on a construction site.

While there is substantial research about drone development and applications in construction, limited research has been conducted to identify and analyze the safety challenges of drones on construction sites. For example, Xu et al. [29], Jeelani & Gheisari [26], and Khalid et al. [30] conducted preliminary studies and categorized the safety concerns related to drone applications in construction. Yildiz [31] provided a narrative review of non-technical aspects of safety challenges of using a drones on construction site. Namian et al. [32] recorded from and analyzed construction experts' perspectives on drone use in construction to identify drone-associated risks in construction. These preliminary studies have laid the foundations for the empirical research that is needed to investigate different health and safety challenges associated with integration of drones on construction job sites.

There is a critical need to evaluate drones in varying operating conditions on construction job sites and identify the specific safety challenges that drones pose not only for workers who work with them but also for workers who happen to work in the same environment. Therefore, this study aims at identifying and evaluating the physical risks associated with the operation of drones in construction sites under different operating conditions. Since it is almost impossible conduct such an investigation in real-world without putting the workers in actual risk, this study uses 4D VR simulations to simulate different work scenarios and operating conditions for risk assessment. The VR simulations help in replicating real-world characteristics in terms of time, physical space, and material properties while surpassing the physical limits of real-world. As such, several studies have used 4D simulations to develop drone flight control systems [33], optimize drone flight path [34], and build training system for drone inspectors [35], through an interactive and dynamic environment.

To achieve the objectives of this study, this study developed a virtual 4D simulation environment to mimic and visualize potential interactions between drones and workers, structures, equipment, and other construction entities to obtain a causal perspective of different incidents that can potentially occur on construction sites. This study is the first effort to identify and assess specific physical risks resulting from drone integration under varied working conditions at construction sites. The study can provide insights and suggestions for researchers and practitioners about mitigating drone-related safety risks on job sites especially when the number of drones are increasing rapidly on construction sites. Identifying and assessing specific safety risks can provide critical information needed for drone flight regulations and system designs for construction applications. This study also provides a fundamental framework for evaluating the impact of other robots and autonomous agents in construction under different scenarios and operating conditions using 4D VR simulations.

2. Theoretical underpinning

Safety systems theory provided the theoretical foundation for systems engineering, which views each system as an integrated whole even though it is composed of diverse, specialized components [36]. Under the framework of system safety theory, a construction job site is an integrated system where various components interact. Safe drone integration is an emergent property under system safety theory, arising from interactions among human workers, drone operation, and work procedures. Accidents happen when the control system fails to handle component failures, external disturbances, or dysfunctional interactions. Furthermore, a basic assumption of the safety system theory is that optimizing individual components of an entire system will not always lead to a system optimum. The properties and behaviors of a system are determined by the interactions between its components, not by the nature of the components themselves [37]. Therefore, to identify safety risks of drone integration in construction sites, scenario contexts, including different entities within those scenarios, and their dynamic interactions need to be considered rather than solely focusing on drone characteristics. In this study, a systems level 4D simulation model was built to represent and assess the interactions between drones and other entities in dynamic construction sites and help to identify safety risks under various conditions. This virtual site can represent accident causal factors and conditions at a system level with the time dimension. The study of evaluating the physical risks of drones in construction environments can also be explored through the lens of the determinant variable theory [38], providing a framework to examine the relationships between variables that determine the cause and effect of a particular phenomenon. When applied to the study of drone-related physical risks in construction, by examining the relationships between the dependent variable (drone-related physical risks) and the independent variables (drone operational factors), the determinant variable theory can provide valuable insights into the underlying factors that contribute to drone-related risks in construction environments. This approach can complement the System Safety Theory by identifying the specific design and operational factors that have a significant impact on the overall safety performance of the integrated system, which includes human workers, drones, equipment, and management.

3. Study background

3.1. Safety challenges of drones in construction domain

Drones can be defined as unmanned aerial vehicles operated remotely without a pilot [39]. Drones are increasingly being used in the construction sector to assist with structural inspection, mapping and surveying, 3D modeling, progress monitoring, material delivery, and safety inspection [40]. Drones can undeniably provide a more efficient and economical way to perform construction practices. [41]. They can reach high elevations and dangerous zones, that are inaccessible to human workers and provide substantial information of construction projects through precise sensors and processors. Specifically, rotary-wing drones can take off and land vertically, which make them have the advantage of carrying various sensor devices and the potential to hover for long time [42]. Furthermore, Rotary-wing drones have strong robustness, high maneuverability, and low purchase and maintenance costs [13], which also make them suitable and popular for construction applications. However, drones might also create unsafe conditions especially with more drones integrated in construction sites, due to limited piloting skills, drone technical limitations, challenging environmental conditions, and jobsite obstacles [26]. These unsafe conditions may result in different risks to human workers sharing their work environment with drones. Physical contact risks are the most basic and essential safety challenge of drone integration in construction. Drones are physical entities that share a workspace with humans, equipment, structures, and other objects on construction sites. With increased drone use on construction sites, the interactions *(intended and unintended) between drones and human workers or other entities (e.g., structures, equipment, materials) will rise drastically. These interactions may expose workers who already work in hazardous construction environment to more risks. According to CPWR (Center for Construction Research and Training) statistics, falling and contact with objects and equipment are the top two reasons resulting occupational fatal injuries in construction [43]. Drones integrated into construction sites will raise the probability of such contact and fall hazards. Direct accidents involving drones include being struck by flying drones, being hit by falling drones, and becoming entangled in moving elements of drones. Indirect accidents involving drones include continuous collisions caused by drones colliding with other objects, as well as dust and particle emissions created by the drones [26].

3.2. Simulation for drone operation

As it is highly dangerous and practically impossible to conduct studies exploring safety risks of drones under varying conditions in real environment, this study leverages the power of virtual simulations. Simulation can be defined as the art and science of creating a representation of a process or system for experimentation and evaluation [44]. A simulation model consists of a collection of variables and a mechanism to dynamically characterize those variables over time [45]. At a systems level, the simulation model can aid in representing the interactions between different modules, components or objects that constitute an entire system. In construction, simulation can be viewed as the science of developing and experimenting with computer-based representative models, which can help to understand their underlying behavior under construction systems [46]. Simulation techniques are useful to imitate reality and process information iteratively on construction practices since construction activities are dynamic and feature complex behavior, uncertainties, and dependencies [47]. Simulation in construction can also help in quantitative operations and processes involving significant uncertainties and logical complexity [48]. A four-dimensional (4D) simulation can include a time element to connect a three-dimensional (3D) model of the structure to dynamic construction operations, allowing the construction process to be viewed throughout time [49]. Construction 4D simulation have been widely implemented because of their efficient application in visualization of construction sites and documents, identification of potential conflicts and safety issues, and other potential challenges [50]. 4D simulation approach can be employed to optimize the planning and design of a construction project, by it providing an interactive environment for simulating the relationship between construction space, resources and time [51].

Specifically, one of most critical purposes of simulation is to observe processes, interactions, and the effects of those interactions within multiple contexts to better understand the situation being investigated [52]. Therefore, to get a better understanding of drone-integrated construction sites, a simulation approach can be adopted to investigate the interactions and potential safety risks of drones. There are some research studies about developing drone simulation systems in different fields. For example, an interactive drone flight control system for agriculture sowing is composed of virtual drone models and virtual scenes, and the motor speed was used to change drone altitude and position during simulation [33]. An application was developed that allows the drone generates collision-free flight paths based on Building Information Modeling (BIM) data in a realistic simulation environment [34]. The flight mission for inspection drone in simulation is structured by flight waypoints, drone attitude, camera attitude and shutter command. Parameters which including mass and load, speed, battery capacity, and movement patterns were implemented in a VR training system for bridge inspectors using a virtual assistance drone [35]. In a validation study of drone performance in the mapping of disaster-struck areas in the simulator, the drone flight design include flight path, flight speed, flight height and camera specifications [53]. A simulation platform which aims to simulate the localization, mapping, and path-planning kits of drones use position, velocity, and mass to generate dynamic drone model [54]. Al-Mousa has proposed a framework for drone traffic integration simulation, which included aircraft type, dimensions, weight, speed, position, battery charge, and sensor range [55].

In this study, a game engine (Unity3D®) is used to enable simulating building sites populated by drones while keeping the physical, dynamic, and organizational features. Unity3D® is a powerful game engine with flexible interactivity and outstanding rendering capabilities, making it a convenient platform for dynamic visualization and simulation processing [56]. A virtual environment can be created in Unity3D® to imitate a construction site with virtual construction workers, structures, equipment, and other construction entities which interacting with each other [57].

4. Research methodology

This research was aimed to identify and evaluate the physical risks associated with use of drones in construction under various operating conditions. Virtual simulation environments, while unable to replicate every nuance of real-world construction sites, offer substantial advantages for research in this context. The use of live testing to evaluate the physical risks connected with drone operations within active construction sites is not feasible due to the inherent safety risks and potential ethical concerns it would present. Construction sites are dynamic, complex, and unpredictable environments filled with hazards, making them ill-suited for controlled and potentially dangerous testing. Moreover, attempting to explore all permutations of parameters that influence human-drone interactions in these conditions is virtually impossible. In contrast, virtual simulations, provide a controlled and safe setting to thoroughly investigate potential risks, without the possibility of causing real harm. These simulations enable the testing of numerous ‘what if’ scenarios without direct experimentation on the actual system, allowing for a comprehensive exploration of a vast array of conditions. This method ensures safety for workers while still enabling a rigorous examination of potential risks associated with drone operations on construction sites. Therefore, in this study a virtual simulation environment was developed to mimic and visualize potential interactions between workers, structures, equipment, and drones. The research was conducted in three phases of (1) Scenario Design, in which OSHA reports were analyzed to identify high-risk environments that would potentially become more dangerous due to drone integration. These scenarios were conceptualized, which included the overall scenario design, job responsibilities of workers, and different drone interactions; (2) Simulation Development, which involved the technical development of 4D VR simulation using the Unity3D® game engine. Different flight parameters and their ranges were also selected as varying parameters to mimic different flight conditions of drones in the 4D simulation; (3) Human-Drone Collision Assessment, which focused on the identification of contact risks by running the simulation 2700 times per scenario with randomly varying parameters and analyzing the number and frequency of different collisions. To assess the effects of flight parameters, the Kruskal-Wallis test was employed. The research approach diagram is presented in Fig. 1. This section will further discuss the three phases of this study.

4.1. Scenario design

In this phase, different high-risk scenarios where drones and human work in the same environment in construction were designed. The goal was to design dynamic virtual scenarios to realistically simulate construction settings that (a) are already hazardous for workers and (b) could pose additional risks to workers after the introduction of drones. The scenario development included two steps:

4.1.1. Identification of simulation scenario characteristics

The objective of this step was to identify the detailed static and dynamic characteristics of scenarios that are likely to expose construction workers to significant risks if drones are introduced. Review of accident statistics reveal that falls to a lower level have remained the leading cause of construction fatalities over time. Among the 1034 fatal injuries in the construction industry in 2020, 46.1% were due to falls, slips, and trips [25]. According to the Center for Construction Research and Training (CPWR), more than one-third of construction worker fatalities are due to falling accidents [43]. Examining the fall accidents in more detail reveal that roofs, ladders, and scaffoldings are the three top places of work that resulted in fatal falls in construction [58], accounting for about 75% of fall fatalities [59]. Coincidentally, these high-risk, at-height locations (i.e., roofs, ladders, and scaffolding) are also the areas where workers are most exposed to drones and the risks posed by them. Drones can exacerbate the risk of falls from these high-risk locations resulting in severe injuries and even death. Therefore, "*roof*", "*ladder*" and "*scaffolding*" were selected as the work environments for the three 4D simulation scenarios.

In each scenario, the static and dynamic elements such as construction tasks being performed, work height, other physical entities on the scene, were identified to design the dynamic scenario content for 4D simulation. Construction incident data were accessed from specific US sources to represent the recent trend and general characteristics of safety incidents worldwide. The CPWR's fatality maps [43] and OSHA's Integrated Management Information System (IMIS) database [60] were explored to analyze accidents related to "*roof*", "*ladder*" and "*scaffolding*" in the last 5 years. 337 fatal incidents related to "*roof*", 179 incidents related to "*ladder*", and 134 incidents related to "*scaffolding*" were analyzed. The details of narrative descriptions were used to identify the key characteristics that led to accidents in each scenario. Table 1 summarizes the key finds of content analysis.

4.1.2. Scenario conceptualization

The focus of this step was on designing three dynamic simulation scenarios that would mimic work high-risk environments involving scaffoldings, ladders, and roofs. Virtual drone missions and flight paths were then incorporated into each scenario to identify the potential risks associated with the use of drones in these high-risk environments. The safety risks posed by drones are largely affected by the interaction distance between the drone and human workers. Edward Hall defined four distance zones for human-human interaction as intimate (0–1.5 ft), personal (1.5–4 ft), social (4–12 ft), and public (>12 ft) [61]. This distance can be applied to define distance of human-drone interactions in construction site. To accurately mimic realistic drone applications in construction and account for different possibilities of interaction, two drones were included in each simulation scenario:

- Near-Drone: performing tasks that required close interaction with human workers (< 4 ft), such as aerial construction and material delivery.
- Distant-Drone: performing tasks that required a greater distance from workers (> 4 ft)., such as monitoring, mapping, and inspection,

To create a realistic simulation of construction work, a range of static

Table 1
Frequent words analysis result for fatal falling incidents.

Environment	*Most Common Construction Tasks that resulted in falls*	*Most Common Falling Height*
Roof	Installing Panels / Installing Trusses	20 Feet
Ladder	Painting / Installing Gutters	10 Feet
Scaffolding	Installing Panels	20 Feet

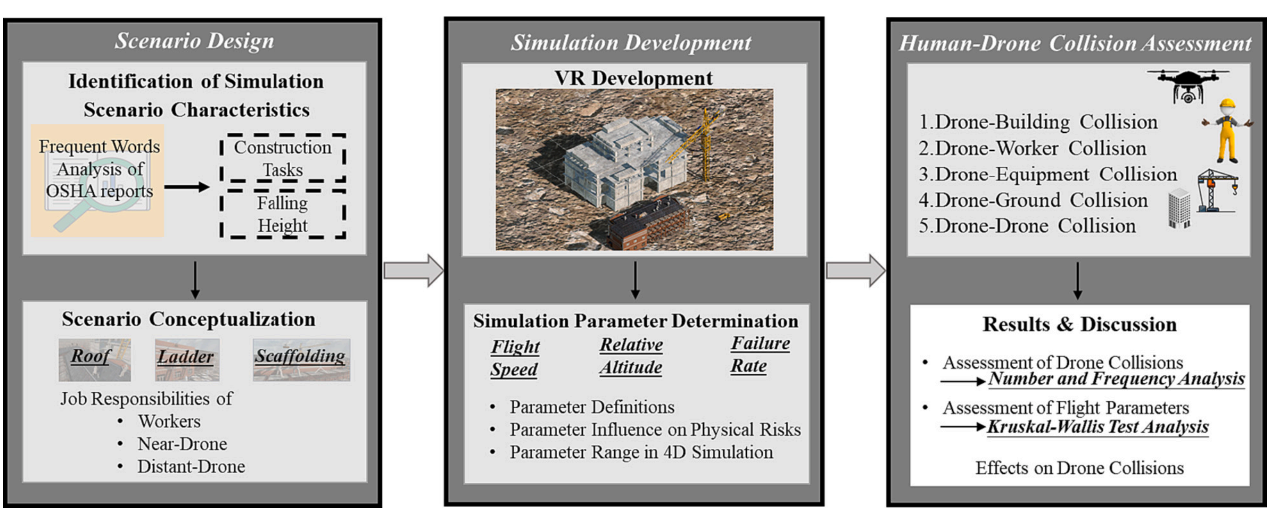

Fig. 1. Research approach diagram.

and dynamic construction elements were incorporated into the virtual scenarios. These include under construction buildings, temporary structures, virtual construction crews, construction equipment such as cranes, dump trucks, lighting. In each 4D simulation scenario, the human workers represented the general working crews not involved in drone operation but exposed to safety risks associated with drones while working in the hazardous site environment. As such, the workers in the simulations had no control over drone flight. The designated tasks for the virtual crews were based on the tasks and falling heights identified in previous step. Virtual workers were programmed to move dynamically within their working area as they would in real construction site while performing their designated tasks. In each scenario, a near-drone was programmed to fly from material yard to the work location and fly close to workers to deliver different material. A distant-drone was programmed to repeatedly fly along a polyline flight path over the targeted area mimicking the inspection or monitoring task. The initial conditions of the simulation were based on realistic construction site setups and the typical behaviors of workers, equipment, and drones in such environments, representing the most typical states from which the system could evolve. For instance, the positions of workers and equipment were determined considering the spatial layout of a typical construction site and the nature of the tasks being performed. Similarly, the drones' initial positions and trajectories were designed to reflect standard operating procedures in drone-based construction activities.

The detailed responsibilities of workers and drones in each scenario are summarized in Table 2.

4.2. Simulation development

In this phase, 4D VR simulation was built using the Unity3D® game engine and following the scenario characteristics and conceptualization described in previous phase. This phase was completed in two concurrent steps of (1) VR Development and (2) Simulation Parameter Determination.

4.2.1. VR development

The Unity3D® game engine was used to develop the VR environment. Three-dimensional (3D) models of different construction components and temporary structures typically present on construction jobsites were obtained and converted to film box format (.FBX) before importing them into Unity® (Fig. 2.). These 3D models include drones, structures, equipment, and vehicles. Specifically, 3D models of quadcopter drones, equipped with easily accessible cameras that can accommodate different types of popular sensors in construction, such as LiDAR and laser scanning devices [40] were used in the simulation. These specific models were selected because they are the most popular and widely used drones in the construction industry [62]. They also offer

Table 2
Job Responsibilities of Human Crews and Drones in 4D simulation Scenario.

Scenarios	Responsibilities	
	Workers	Drones
Roof	• Eight workers on a roof at 20-ft above the ground • One worker carrying materials. • Others installing metal panels.	• Near-drone delivering materials from the ground to the roof. • Distant-drone inspecting roof installation progress.
Ladder	• Two workers on two sperate ladders at 10-ft above the ground. • Workers painting the window frames.	• Near-drone delivering materials from the ground to ladder. • Distant-drone inspecting site traffic flow.
Scaffolding	• Three workers on a scaffolding at 20-ft above the ground. • Two worker installing panels • One worker extending the existing scaffolding.	• Near-drone delivering materials from the ground to scaffolding. • Distant-drone monitoring site safety around the scaffolding.

the advantage of vertical takeoff and landing, enhancing operational flexibility [40,62]. Also, 3D models of construction workers were added to the scene and programmed to perform different tasks simulating the actions of actual workers on construction jobsites. Tasks included material delivery, panel installation, window frame painting, and scaffolding erection. These models were created using Daz 3D® [63]. The animations for the virtual workers to perform various activities were imported from Adobe® Mixamo [64]. Additional 3D models (e.g., work lights, barriers, and guard rails) were also added to simulate the surrounding construction environment.

The location and the size of each virtual instance was established to preserve the spatial accuracy of the simulated construction site for all three scenarios. The dynamic assets (crew, vehicles, cranes, and drones) were 4D programmed to carry out designed tasks and move with the predefined path (Fig. 2.). Different drone interactions were designed for specific tasks in each scenario (Fig. 2.). Near-drones flew along predetermined routes with waypoints to simulate material delivery [65], while distant-drones inspected or monitored the building surface area following a flight path parallel to the site surface to capture the images [66]. In each scenario, the virtual tower crane was set to rotate with a constant speed beside the structures and its path overlapped with part of the crew working area. Vehicles (e.g., dump truck) and workers performing delivery tasks were programmed as moving linearly at a constant speed in their predefined path. The area of each virtual construction site was approximately 3000 square meters (32,000 square feet).

4.2.2. Simulation parameter determination

The objective of this step was to identify different simulation parameters, which can mimic different flight conditions that can potentially influence the physical risks posed by drones. Although drones were set to fly along a predefined route, different flight parameters can affect the likelihood of collisions with workers or other objects.

Previous literature [33–35,53–55] suggested the following three critical drone flight parameters can properly determine different flight conditions and therefore, were used in this simulation:

- *Flight Speed*: refers to the speed at which a drone moves through the air. It affects the position of drones in real-time, collision energy, interactions, fall trajectory in case of failure, and human reaction time to avoid safety incidents.
- *Relative Altitude*: refers to vertical distance between the drone and the targeted. It affects the distance to other entities/humans, gravitational potential energy, projection area in case of failure or collision, and human reaction time to avoid safety incidents.
- *Failure Rate*: refers to a combined parameter that accounts for failures caused by the elements that have the greatest impact on how the drone functions, such as bird strikes [67], bad weather [68], and operational [69,70] and system faults (including failures in the control system, navigation system, power system, etc.) [71]. To simulate the unpredictable nature of real-world drone failures, randomness was incorporated into the timing of drone failure within the simulation. The drone failure event was designed to occur at an arbitrary point during the simulation run, mimicking situations where drones could suddenly fail due to factors such as component failures, external interference, or dysfunctional interactions between system components. The higher failure rate was programmed to increase the likelihood of drone failure and the potential (but not necessarily happened) subsequent collision incidents, similar to those in the real world. This approach facilitated the replication of the inherent randomness and uncertainty often associated with drone failures in actual construction environments.

Related regulations (e.g., [72] [73]) and literature were also reviewed to define a range for each of those flight parameters in 4D simulation scenarios. The selected range of those parameters are

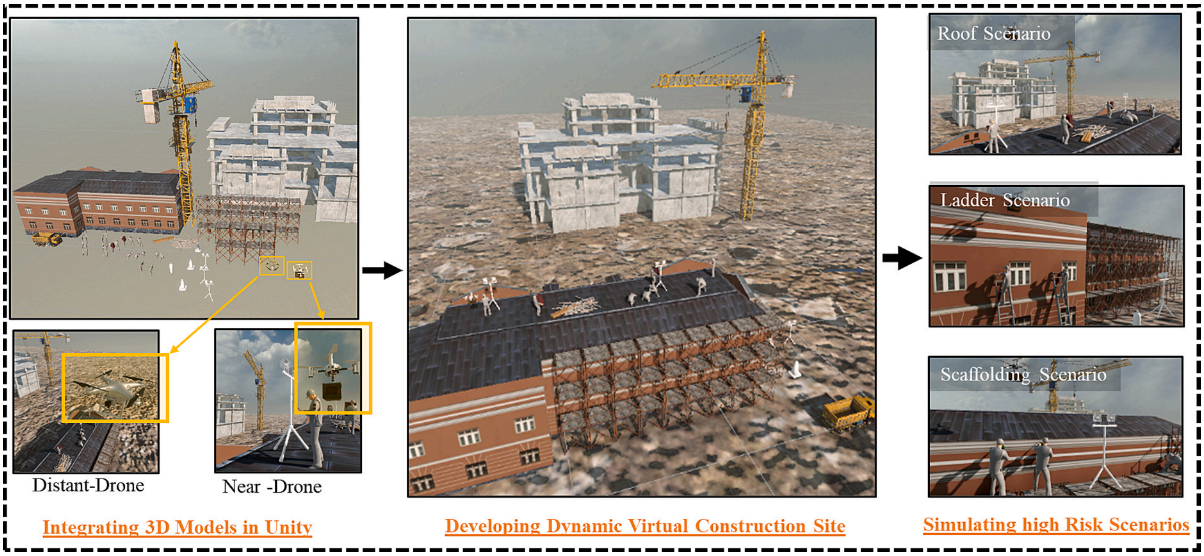

Fig. 2. VR development workflow.

illustrated in Table 3. In each simulation, parameters were randomly assigned a value from the selected range (Table 3), to reflect real-world uncertainty and variability in drone operations on construction sites To generate these random flight parameters, Unity 3D's built-in random number generator, adopting the Xorshift 128 algorithm [74], was employed to ensure a diverse array of potential drone operation scenarios.

4.3. Drone collision assessment

A total of 2700 simulation (27 combinations of three parameters, with three levels each. Each combination simulated 100 times) were run under each of the three scenarios (i.e., roof, ladder, scaffolding) to **first assess drone collisions and then study flight parameters' effects on those collisions**. In 4D simulation, five categories of drone collision were identified as:

- *Drone-Building Collision:* drone colliding with building on the site
- *Drone-Worker Collision:* drone colliding with human workers on site
- *Drone-Equipment Collision:* drone colliding with equipment on site including vehicles
- *Drone-Ground Collision:* drone colliding with the ground
- *Drone-Drone Collision:* drone colliding with another drone on site during flight

Drone collisions were identified using the Rigidbody and Collider Components of the physics engine in Unity3D® [84] [85]. The number and types of drone collisions were computed for both near and distant drones to evaluate different types of collisions and their frequency at different interaction distances. Subsequently, the impact of flight parameters on drone collisions at both near-drone and distant-drone interaction distances was analyzed using the Kruskal-Wallis test, which is a nonparametric equivalent of one-way ANOVA used for testing whether samples originated from anon-normal distribution.

Table 3
Flight parameter range selected for 4D simulation.

Flight Parameter (Unit)	Selected Range	Supporting Literature
Flight Speed (Meter/Second)	2–6 m/s	[15,18,19,75–77]
Relative Altitude (Meter)	5–25 m	[12,78–80]
Failure Rate (%)	0–6%	[81–83]

5. Results

For each scenario, the frequency of different types of drone collisions were analyzed, followed by a series of statistical analyses to evaluate the relationship between collision types and flight parameters. The following subsections discuss the results for each scenario in detail.

5.1. Roof scenario

5.1.1. Drone collisions in roof scenario

In the roofing scenario, a total of 2700 simulation runs were conducted, and the Near-Drone experienced 95 collision incidents (3.52% incident rate) with 196 total collisions, while the Distant-Drone had 180 incidents (3.52% incident rate) with 302 collisions, as shown in Table 4. The number of collisions is higher because many collision incidents involved several subsequent collisions after the first contact. The two drones in the scenario had 80 collision incidents with buildings (2.96% incident rate), 174 collision incidents with equipment (6.44% incident rate), 198 collision incidents with ground (7.33% incident rate), and 40 collision incidents with workers (1.48% incident rate). The higher number of drone-ground collisions of Distant-Drone was attributed to the fact that most drone failures result in the drone ultimately falling to the ground. The results further revealed that the Distant-Drone had a higher incidence of collisions with equipment (64% of all drone-building collisions) and ground (87% of all drone-ground collisions), while the Near-Drone had more collisions with the building (81% of all drone-building collisions) and workers (97.5% of all drone-worker collisions).

Table 4
Results for Drone Collision Incident in Roof Scenario.

Type of Collision Incident	Near-Drone: Drone in close interaction distance with humans (< 4 ft)	Distance-Drone: Drone in distant interaction distance with humans (>4 ft)
Drone-Drone	0	0
Drone-Ground	29	172
Drone-Equipment	63	114
Drone-Building	65	15
Drone-Worker	39	1
Total Collisions	95	180

5.1.2. Effects of flight parameters on drone collisions in roof scenario

The collision results in the 4D simulation indicated that all the collision incidence rates are <10%, which means the data of collision numbers is right skewed. Additionally, the Shapiro-Wilk normality test showed that the data was not normally distributed. The resulting p-value was <0.001 for all types of collision in three scenarios. Therefore, the Kruskal–Wallis test was employed to test whether the overall contact risks or specific types of risks are affected by different flight parameters. The significance level of $p < 0.05$ was chosen for this study. As presented in Table 5., the Kruskal–Wallis test result shows that the failure rate for Near Drone significantly affects the overall drone collisions and specifically the drone collisions with buildings. For Distant Drone, relative altitude significantly affects the overall drone collisions and specifically with the ground and equipment. In addition, the failure rate also significantly affects drone collisions with the ground, building, and also the total collisions.

5.2. Ladder scenario

5.2.1. Drone collisions in ladder scenario

In Ladder Scenario, the Near-Drone had 109 collision incidents with a total of 224 collisions in 2700 simulation runs (4.04% incident rate), and the Distant-Drone had 127 collision incidents with a total of 196 collisions in 2700 simulation runs (4.70% incident rate), as presented in Table 6. The two drones had 35 collision incidents with buildings (1.30% incident rate), 141 collision incidents with equipment (5.22% incident rate), 203 collision incidents with the ground (7.52% incident rate), and 34 collision incidents with workers (1.26% incident rate). The Near-Drone had more collisions with the building (82.86% of all drone-building collisions), equipment (54.17% of all drone-equipment collisions), and the workers (97.06% of all drone-worker collisions).

Table 6
Results for Drone collision incident in ladder scenario.

Type of Collision Incident	Near-Drone: Drone in close interaction distance with humans (< 4 ft)	Distance-Drone: Drone in distant interaction distance with humans (>4 ft)
Drone-Drone	1	1
Drone-Ground	83	122
Drone-Equipment	78	66
Drone-Building	29	6
Drone-Worker	33	1
Total Collisions	109	127

5.2.2. Flight parameters effects on drone collisions in ladder scenario

The Kruskal–Wallis test was also performed for the right-skewed collision results in Ladder Scenario. As presented in Table 7., The Kruskal–Wallis test result shows that the failure rate significantly affects the total drone collisions for both drones and specifically their collisions with the ground and the equipment. In addition, relative altitude significantly affects drone collisions with the ground, equipment, and total collisions for distant drone.

5.3. Scaffolding scenario

5.3.1. Drone collisions in scaffolding scenario

Table 8. shows the collision incidents in the Scaffolding Scenario, where Near-Drone had 118 collision incidents (215 collisions) in 2700 simulation runs (4.37% incident rate), and Distant-Drone had 123 collisions incidents (192 collisions) in 2700 simulation runs (4.56% incident rate). The analysis revealed that the two drones had 66 collision incidents with buildings (2.44% incident rate), 158 collision incidents with equipment (5.85% incident rate), 158 collision incidents with the ground (5.85% incident rate), and 25 collision incidents with workers (0.93% incident rate). The Near-Drone had a higher percentage of collisions with buildings (80.30% of all drone-building collisions), equipment (59.49% of all drone-equipment collisions), and workers (100% of all drone-worker collisions), and a lower percentage of collisions with the ground (27.22%). In the ladder scenario, only one collision was recorded between the two types of drones representing a low probability event with a 0.03% incident rate.

5.3.2. Flight parameters effects on drone collisions in scaffolding scenario

To analyze the collision results of the Scaffolding Scenario, the Kruskal-Wallis test was utilized since the data was right-skewed and not normally distributed, as indicated by the Shapiro-Wilk normality test. Table 9. presents the results of the Kruskal-Wallis test, which shows that for the Near-Drone, the flight speed has a significant impact on drone collisions with the ground, while the relative altitude significantly affects drone collisions with buildings. Furthermore, the failure rate significantly affects drone collisions with the ground, equipment, workers, and overall collisions. On the other hand, for the Distant-Drone, the relative altitude significantly affects drone collisions with the ground, equipment, and overall collisions, while the failure rate level significantly affects drone collisions with the ground and overall collisions.

6. Discussion

6.1. Key insights from collision numbers in three scenarios

In each of the three scenarios, the Distant Drone had a higher frequency of collision incidents with equipment and ground, while the Near Drone had a higher frequency of collision incidents with buildings and workers. This finding indicates that the drone's mission and interaction distance can impact the types of collision incidents that are more likely to occur, which is in line with the System Safety Theory that postulates that the safety performance of the integrated system, including drones, workers, equipment, and management, is affected by the interactions among its components. Also, in line with the

Table 5
Kruskal–Wallis Test P-value Results for Flight Parameters Effects on Drone Collisions in Roof Scenario.

Type of Collision Incident	Near-Drone: Drone in close interaction distance with humans (< 4 ft)			Distance-Drone: Drone in distant interaction distance with humans (>4 ft)		
	Flight Speed	Relative Altitude	Failure Rate	Flight Speed	Relative Altitude	Failure Rate
Drone-Drone	NA	NA	NA	NA	NA	NA
Drone-Ground	0.08	0.64	0.06	0.91	0.00*	0.00*
Drone-Equipment	0.06	0.53	0.12	0.46	0.00*	0.19
Drone-Building	0.56	0.32	0.01*	0.24	0.45	0.00*
Drone-Worker	1	0.36	0.14	0.37	0.37	0.37
Total Collisions	**0.45**	**0.82**	**0.00***	**0.75**	**0.00***	**0.00***

* *p value < 0.05.*

Table 7
Kruskal–Wallis test *P*-value results for flight parameters effects on Drone collisions in ladder scenario.

Type of Collision Incident	Near-Drone: Drone in close interaction distance with humans (< 4 ft)			Distance-Drone: Drone in distant interaction distance with humans (>4 ft)		
	Flight Speed	Relative Altitude	Failure Rate	Flight Speed	Relative Altitude	Failure Rate
Drone-Drone	0.37	0.37	0.37	0.37	0.37	0.37
Drone-Ground	0.44	0.92	0.00*	0.12	0.00*	0.00*
Drone-Equipment	0.53	0.34	0.00*	0.05	0.00*	0.01*
Drone-Building	0.64	0.78	0.28	0.61	0.13	0.13
Drone-Worker	0.44	0.69	0.30	0.37	0.37	0.37
Total Collisions	**0.40**	**0.94**	**0.00***	**0.10**	**0.00***	**0.04***

* *p value < 0.05.*

Table 8
Results for Drone collision incident in scaffolding scenario.

Type of Collision Incident	Near-Drone: Drone in close interaction distance with humans (< 4 ft)	Distance-Drone: Drone in distant interaction distance with humans (>4 ft)
Drone-Drone	0	0
Drone-Ground	43	115
Drone-Equipment	94	64
Drone-Building	53	13
Drone-Worker	25	0
Total Collisions	118	123

determinant variable theory, the drone's mission and interaction distance emerge as determinant variables that influence the drone-related physical risks in construction sites.

Distant Drones cover a larger area while inspecting or monitoring a work site and, as such, have more encounters with the equipment on site. Since these drones operate at some distance from workers and buildings, they tend to fall on the ground in case of a failure, posing risks to the unsuspecting workers on the ground. On the other hand, drones that interact closely with workers and operate within a smaller work zone requiring tighter maneuvers are more likely to collide with workers and building elements. These drones pose more risk, such as struck-by and caught-in or between incidents, to the workers who work directly with them or around them.

Barring the ground collisions (which were due to drones ultimately falling on the ground after an incident), the number of collision incidents with equipment was higher than other collision types for both drones. This highlights the importance of considering the potential risks of drones colliding with construction equipment during aerial operations. It's also interesting to note that the number of collision incidents with workers for the Near Drone was relatively low, but the frequency of these incidents was high. This could indicate that collisions with workers are less frequent overall, but when they do occur, they are more likely to involve drones that require close interaction with workers. This observation further supports the determinant variable theory, as it shows the influence of drone interaction distance on the likelihood and types of drone-related incidents.

6.2. Flight parameters and drone collisions

The study's examination of the effects of flight parameters, such as failure rate, relative altitude, and flight speed, on drone collisions provided valuable insights into the factors that influence collision risks in construction environments. This analysis aligns with the determinant variable theory, which posits that these flight parameters can be considered independent variables that determine the drone-related physical risks (dependent variable) in construction sites. In all three scenarios, the failure rate was found to significantly affect overall drone collisions and specific types of collisions for both Distant and Near Drones. This finding highlights the importance of maintaining drone systems in good working condition and investing in reliable drone technologies to minimize the risks associated with failures, which is consistent with the System Safety Theory's emphasis on the interactions between components within an integrated system. Regular maintenance, inspections, and use of robust drone systems can help reduce the likelihood of drone failures and, in turn, lower the overall collision risks. Additionally, implementing fail-safe features, such as obstacle detection and avoidance systems, can further enhance the safety and reliability of drone operations in construction environments, addressing the systemic nature of safety risks.

For Distant Drones, relative altitude had a significant impact on the likelihood of colliding with equipment and the ground, as well as the total collisions in all three scenarios. A possible technical explanation for this result is that as the drone operates at an altitude closer to the equipment (e.g., the rotating crane in this simulation environment), it may experience aerodynamic disturbances caused by the airflow around the equipment, increasing the chances of collisions. Furthermore, the limited visibility and situational awareness of the drone operator when operating at the same altitude as the equipment could contribute to the

Table 9
Kruskal–Wallis test *P*-value results for flight parameters effects on Drone collisions in scaffolding scenario.

Type of Collision Incident	Near-Drone: Drone in close interaction distance with humans (< 4 ft)			Distance-Drone: Drone in distant interaction distance with humans (>4 ft)		
	Flight Speed	Relative Altitude	Failure Rate	Flight Speed	Relative Altitude	Failure Rate
Drone-Drone	NA	NA	NA	NA	NA	NA
Drone-Ground	0.03*	0.24	0.00*	0.17	0.00*	0.03*
Drone-Equipment	0.67	0.19	0.00*	0.06	0.00*	0.34
Drone-Building	0.55	0.04*	0.05	0.58	0.93	0.37
Drone-Worker	0.08	0.46	0.02*	NA	NA	NA
Total Collisions	**0.12**	**0.13**	**0.00***	**0.08**	**0.00***	**0.04***

* *p value < 0.05.*

increased collision risks. Avoiding the altitude that approaches other moving equipment can help reduce the contact risks of distant interaction drones. For Near Drones, the failure rate significantly impacted the total collisions in all three scenarios. A low level of failure rate can significantly reduce overall contact risks for close interaction drones. The study's results suggest that close interaction drones might require more precise control and a higher level of situational awareness to prevent collisions with workers, equipment, and building elements. This observation aligns with the determinant variable theory, which emphasizes the relationships between independent variables (drone operational factors) and the dependent variable (drone-related physical risks).

Incorporating advanced sensor systems, such as LIDAR or computer vision, could improve the drone's ability to navigate safely in close proximity to these elements. Moreover, establishing safe operating zones, restricted access areas, and implementing strict communication protocols between drone operators and construction workers can minimize the risks associated with close interactions, addressing the System Safety Theory's focus on optimizing the interactions between components in an integrated system.

The differences in the impact of failure rates on the types of collisions in various scenarios can be attributed to the varying performing tasks and working zones of close interaction drones. In the Ladder and Scaffolding Scenarios, the close interaction drone passed more equipment and covered more site ground compared to the drone in the Roof Scenario. This could result in more complex flight paths and higher cognitive demands on the drone operator, increasing the chances of collisions. The flight path of close interaction drones in the Scaffolding Scenario also passed more workers than in the Roof and Ladder Scenarios, which might require stricter safety measures and closer collaboration between drone operators and construction workers. By understanding the impact of flight parameters on drone collisions and their possible technical explanations, targeted strategies can be developed to mitigate these risks, such as adjusting flight parameters, implementing geofencing, providing specialized training for drone operators, and incorporating advanced sensor systems. These adjustments can help minimize collision risks and create a safer working environment for all site personnel, supporting the principles of both the System Safety Theory and the determinant variable theory.

7. Conclusions and future Work

This study identified and evaluated the physical risks associated with the operation of drones in construction sites under different operating conditions. Driven by the safety systems theory and the determinant variable theory, this study offers a system-level 4D simulation environment that can represent and assess the interactions between drones and other entities in dynamic construction sites. By conducting a frequency analysis of OSHA reports, the study first identified the characteristics of roofs, ladders, and scaffolds - the top three high-risk environments where workers would be at increased risk of accidents when working around drones. To replicate three dynamic scenarios featuring drones in virtual environments, the conceptualized content of scaffolding, ladder, and roof scenarios was developed. Each scenario included the job responsibilities of human crews and incorporated two different types of drone interactions: Near Drone and Distant Drone. These interactions were designed to simulate the potential risks that could arise from the presence of drones in hazardous environments. The 4D VR simulation was built using the Unity3D® game engine, and flight speed, relative altitude, and failure rate were selected as varying parameters to mimic different flight conditions of drones in the 4D simulation, based on previous literature. The identification of contact risks phase involved running the simulation 2700 times per scenario with randomly varying parameters. The physics engine of Unity3D® was used to detect collisions between each type of drone and workers or other objects such as buildings, elements, and equipment. To assess the effects of flight, the Kruskal-Wallis test was employed to test whether the overall contact risks or specific types of risks are significantly different under the influence of parameters.

The results indicated that, across all three scenarios, the Distant Drone had a higher frequency of collision incidents with equipment and the ground, while the Near Drone had a higher frequency of collision incidents with buildings and workers. The failure rate was found to significantly influence both overall drone collisions and specific types of collisions for both the Distant and Near Drones in all three scenarios. Specifically, for Distant Drones, the relative altitude significantly impacted the likelihood of colliding with equipment and the ground, as well as the total collisions in all three scenarios. For Near Drones, only the failure rate significantly impacted the total collisions in all three scenarios. The differential impact of flight parameters on drone collisions suggests that targeted strategies can be developed to mitigate safety risks for different drone working contexts, thereby creating a safer working environment on construction sites.

7.1. Contributions

This study presents a novel system-level approach for evaluating the physical risks associated with drone operation in construction sites. The study provided valuable insights into the physical risks associated with drone operations in various scenarios and the impact different operational parameters on those risks. As drone technology continues to evolve and its adoption within construction sites increases, the risks highlighted in our study may become more prevalent. Hence, understanding these risks now allows industry stakeholders to implement preventative strategies and policies, and to develop drone technology that addresses these risks, leading to safer and more effective drone integration in the future. The developed 4D simulation environment can serve as a valuable tool for informing risk management strategies and improving safety practices in the industry. It can also serve as a training tool for construction workers, enhancing their understanding of potential risks and how to mitigate them when working in drone-integrated environments. Additionally, the study introduces the first 4D simulation framework for drone integration in construction, which can serve as a fundamental methodology for future research on human-drone interactions in construction by allowing adjustment of scenario content and simulation parameters to achieve desired simulation designs. Furthermore, this study provides a methodology for developing simulation content, parameters, and analysis design for other robotic integrations in construction sites, which is important for assessing the safety challenges of human-robot interaction. By enabling the evaluation of potential risks and identifying areas for improvement, this approach has the potential to enhance worker safety and improve the efficiency of construction tasks.

7.2. Limitations & future work

Given that the interactions between drones and dynamic construction operations are highly dependent on the scenario content, the quantitative results from this study can only offer insights into a specific type of drone-integrated construction scenario rather than serve as a generalized tool that can be applied to all types of construction sites. For instance, in a 4D simulation environment where the distribution density of workers and equipment may vary, there could be a higher number of safety risks and drone-related accidents. This is because the environment may involve more complex movement paths and dynamic interactions, making it more challenging for drones to navigate safely. While quantitative results directly apply to specific scenarios and similar environments, the insights gained from this study, especially regarding the effects of different flight parameters on drone collisions, are significant for developing targeted strategies to mitigate collision risks. These insights can be generalized to other scenarios despite the scenario-specific nature of the quantitative results. Additionally, the qualitative insights on potential risks and risk mitigation strategies are broadly applicable, as the established 4D simulation framework can be adapted to various construction scenarios, adjusting content and simulation parameters to match the unique conditions and variables of different sites.

Although the study incorporated several factors affecting drone collision, it acknowledges the absence of certain random variables such as sudden changes in environmental conditions like wind speed, or varying worker response times to potential hazards. These are indeed crucial parameters that can influence drone operations and worker safety. The current simulation does not incorporate these variables primarily due to their complex and stochastic nature. In future research, these elements could be integrated into the simulation to provide a more comprehensive understanding of the risks associated with drone operations on construction sites. For instance, a wind module could be incorporated into the simulation environment to model the impact of sudden wind gusts on drone stability and control. Similarly, a behavioral model representing the diversity in worker response times could be developed to understand how human factors contribute to the risks. Additionally, although the failure rate parameter includes a variety of system failures including power failures related to battery performance, specific battery life considerations, such as battery drain due to flight speed, load, or environmental conditions, were not explicitly modeled in the simulation. While incorporating a specific power failure event into the failure rate parameter allows for the simulation of sudden and unexpected battery failures, it may not fully capture the complexity of battery performance and its impact on drone operation. Future iterations of our simulation framework could incorporate battery performance, especially in scenarios where drones are expected to perform prolonged tasks, carry heavy loads, or operate under demanding environmental conditions. Including such factors in the model could help create a more comprehensive and realistic picture of the operational challenges and potential risks associated with drone usage on construction sites.

Moreover, although the scenario content used in the study was realistic, it was still relatively simplistic. The study selected roofs, ladders, and scaffolding scenarios based on the frequency analysis of OSHA reports which identified these as high-risk environments in construction. While these high-risk areas provided valuable insights that may apply to other areas of a construction site, future studies could expand the scope to other elements of construction sites or incorporate more site-specific details to further enhance the simulation's applicability to diverse real-world contexts. Additionally, the real-world validation of these simulation results would further strengthen the findings. Furthermore, future research should aim to incorporate more complex object movements and interactions to make the simulation more realistic and representative of real-world construction sites. For example, workers may move around the working area in a more random pattern, communicate with each other, and exchange positions. Equipment may operate according to their assigned tasks rather than simply moving linearly, and workers may perform more complicated tasks that require collaboration with different types of drones. To create a comprehensive drone simulation, it's essential to design detailed and nuanced flight paths that are tailored to specific tasks and scenarios. These flight paths should also be combined with drone safety functions such as object detection and avoidance. Additionally, given the inherent unpredictability and variability in real-world construction environments, the initial conditions in this study are approximations and are subject to change in different scenarios. Future research could consider developing more sophisticated models for determining initial conditions, perhaps based on machine learning techniques or using real-time data from actual construction sites. By integrating these characteristics into a 4D simulation framework, a universal template can be created that applies to any construction scenario design. This 4D simulation scenario can provide valuable insights into the risk of contact with drones, enabling the development of safety recommendations for construction sites. Further investigation might also include specific situations, such as drone flights in restricted areas like no-fly zones. While this study focused only on the safety implications, future studies can also evaluate the impact of different flight parameters on other aspects of drone missions, such as quality, accuracy, reliability of monitoring, and data collection. Furthermore, this study focuses on human workers who work in close proximity to drones but do not perform related construction tasks with them. These workers coexist with drones in the same physical environment but do not have direct interaction with them. Future studies should expand the scope of different human-drone interaction levels on construction sites. Using different levels of interaction can help address a broader range of situations that pose safety risks and simulate the likelihood of collision accidents. This can provide comprehensive guidelines for future construction sites where drones are commonly used, helping to improve safety and reduce the potential for accidents. In addition, future case studies should be conducted to validate simulation results by utilizing available drone incident reports from construction sites. Comparing the findings from 4D simulations with real-world incidents can assist in calibrating simulation scenarios and parameter settings. This alignment with realistic construction site conditions will enable the simulation to provide more comprehensive safety guidelines.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

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Data availability

Data will be made available on request.

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