Safety Risk Assessment of Drones on Construction Sites using 4D Simulation

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Abstract –

The use of drones in the construction industry has been dramatically growing in different areas such as building inspection, site mapping, and safety monitoring. The increasing deployment of drones in construction leads to more collaboration and interaction between human workers and drones. This raises novel occupational safety issues, especially for those workers who already work in a hazardous environment. While there is significant research about the benefits of drones for specific construction applications, there is a knowledge gap about the safety risks of integrating such technology into construction sites. This study uses 4D simulation to mimic and visualize virtual construction sites populated with drones to detect safety risks of their presence under different working conditions. The validated 4D simulation can provide a valuable source for safety risk identification and assessment of drone integration on construction sites.

Keywords –

Drones; 4D Simulation; Safety; Risk Assessment; Construction Sites

1 Introduction

The application of drones or Unmanned Aerial Vehicles (UAVs) in the construction industry is continuously increasing in recent years. In 2018, the use of drones in construction rapidly increased by more than 200% compared to the previous year [1]. In 2021, despite the pandemic influence on the global economy, 88% of the present drone adopters in the construction industry were willing to increase or maintain their investment in drone technology [2]. Drones are popular in construction because they can perform tasks more efficiently with less cost, especially in dangerous or inaccessible spaces for human workers. Additionally, drones can carry different sensors, conveniently collecting data and providing comprehensive documentation for site records. Drones in construction have a wide range of application areas, including building inspection, damage assessment, site surveying and mapping, progress monitoring, and safety inspection [3]. As the application of drones expands in construction, a significant increase in interactions between drones and human workers is expected. Drones are flying robots that share a workspace with humans, equipment, structures, and other objects on construction sites [4]. Therefore, there is always a potential for collision incidents that pose serious safety risks to human workers collaborating with or working around drones. While there are substantial research studies about the application and benefits of drones in construction, limited research has been conducted to analyze the safety challenges of drones on construction sites. For example, Xu et al. [5], Jeelani & Gheisari [4], and Khalid et al. [6] conducted preliminary studies and categorized the safety concerns related to drone applications in construction. Despite these exploratory efforts, there is a dearth of research examining the specific safety risks resulting from varied working conditions based on different drone applications in construction.

2 Background & Motivation

2.1 Construction Safety

Construction is a massive, dynamic, and complicated industry that provides millions of job opportunities worldwide. At the same time, construction work comes with disproportionately higher safety risks and causes more fatal accidents than other sectors [7]. In 2019, there were 1,038 fatal occupational injuries in the construction industry in the United States, accounting for almost 20% of total incidents in all the sectors [8]. According to statistics data from CPWR (The Center for Construction Research and Training), 34.7% of fatal injuries were caused by falls and slips. 22.6% of fatal injuries were caused by contact with objects and equipment, 17.1% were transportation incidents, and 13.4% were caused by exposure to harmful substances or environments [9]. The statistics indicate that workers who work in dangerous locations (such as on heights) and are exposed to automation hazards, including equipment and transportation, are more likely to be exposed to safety risks. Besides fatal injuries, the rate of non-fatal injuries in the construction industry also remained consistently high. There are over 200,000 injuries reported from construction [4]. Non-fatal injuries can result in severe disabilities, income loss, chronic pain, and ongoing medical expenses, resulting in lower quality of life for the workers. Even less-serious injuries can lead to work time lost, productivity reduction, and increased medical costs [10].

2.2 Drone Application and Safety Challenges in Construction

Drones are unmanned aerial vehicles operated under remote control without a pilot [11]. The increasing uses of drones in the construction industry include aiding with construction structure inspection, mapping and surveying, 3D modeling, progress monitoring, material delivery, and safety inspection [12]. Undoubtedly, drones can provide a more efficient way to perform construction tasks at a lower cost [13]. They can access high-attitude and dangerous working zones, which are difficult to reach by human workers, and provide comprehensive data about construction sites through delicate sensors and processors. However, with more such aerial robots flying on construction sites, the interactions between drones and human workers or other objects (e.g., structures, equipment, materials, and vehicles) will dramatically increase. Furthermore, with the integration of drones in existing construction workplaces, more safety risks are expected for those who already work in high-risk environments. According to fatal injury reports, contact with objects and equipment is one of the top reasons that cause occupational injuries in construction [9]. Integrating drones in construction sites will increase the possibilities of such contact risks. Direct contact with drones includes being struck by flying drones, hit by falling drones, and caught in by drones' moving parts. Indirect accidents include continuous collisions caused by drones contacting other objects and dust and particulate emissions brought by the drones [4].

2.3 Simulation Approaches and Techniques

Simulation can be defined as the art and science of creating a representation of a process or system for experimentation and evaluation [14]. A simulation model is a set of variables and a mechanism for changing those variables dynamically over time [15]. At a systems level, this helps in stimulating the interactions between different modules or objects that constitute a system. As construction activities are dynamic and involve complicated behavior, uncertainties, and dependencies, simulation approaches are beneficial to replicate reality and process information iteratively on construction activities [16], and for quantitative analysis of operations and processes [17]. In construction, a 4D simulation can link a three-dimensional (3D) model of the building or facility to the dynamic construction activities, allowing the construction process to be visualized over time [18]. One of the goals of simulation approaches is the observation of processes, interactions, and outcomes of those interactions in varying conditions, which help in gaining a better understanding of the situation studied [19]. Drone simulation systems have been used 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 [20]. A VR training system for bridge inspectors with an assistant drone used parameters including mass and load, speed, battery capacity, and movement types [21]. Al-Mousa et al. brought up a framework for the drone traffic integration simulation, including aircraft type, dimensions, weight, speed, location, battery charge, and sensing range [22]. In construction, Gilles et al. used a VR-based flight training simulator for drone-mediated building inspections [23].

In this study, a game engine (Unity3D®) is employed to help this task by creating a replica of a scenario that mimics construction sites populated with drones while preserving the physical, dynamic, and organizational aspects. Unity3D® is a professional game engine with strong rendering capabilities and convenient interactivity, an attractive platform for dynamic visualization and simulations processing [24]. In Unity3D®, a virtual environment can be developed to simulate a construction site with virtual construction workers, structures, equipment, and other construction entities with their actions and interactions [25].

3 Research Objective

This study aims to develop a 4D simulation of a construction site populated with workers and drones performing different construction-related tasks. This immersive virtual environment will mimic and visualize interactions between drones, workers, and other construction entities and ultimately identify safety risks associated with drone integration in construction under different working conditions. Studying these interactions under varying conditions in the real world is not only dangerous but also impossible on a large scale. Using 4D simulations allowed us to vary multiple conditions and investigate the outcomes of critical situations without any risk.

4 Research Methodology

As illustrated in Figure 1, this study was completed in two phases: (1) ***Scenario Development***: (1-a) identification of simulation scenario characteristics and (1-b) simulation conceptualization. (2) ***Simulation Development***: (2-a) simulation parameter determination and (2-b) simulation demonstration and validation.

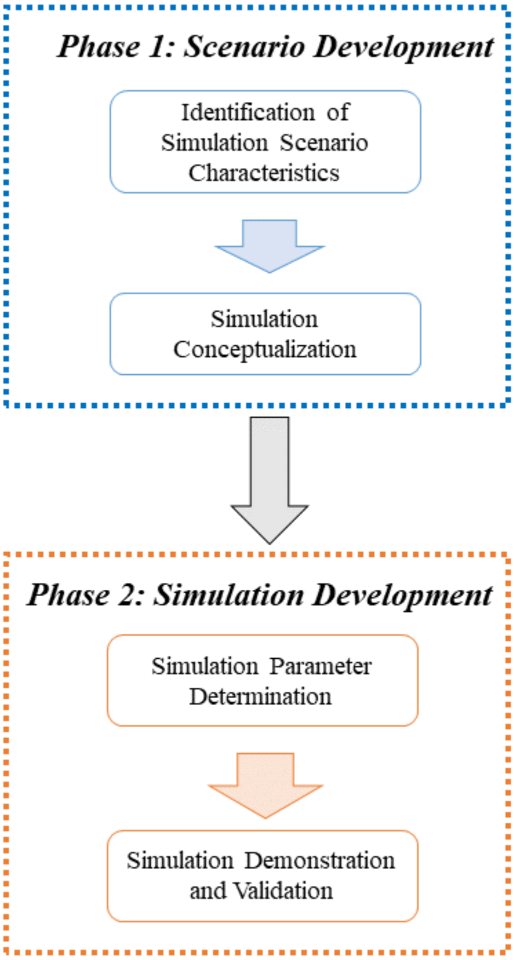


Figure 1. Research Methodology

5 Scenario Development

5.1 Identification of Simulation Scenario Characteristics

The objective of this step was to identify different physical and dynamic characteristics of high-risk scenarios that needed to be mimicked in the simulations. Working with drones is likely to introduce new risks for construction workers, especially those who work on heights. These workers are already at the highest risk of fatalities and are most likely to be affected by drones flying at heights. Therefore, past injury reports were thoroughly analyzed to find common characteristics that provided a base for defining the simulation scenario content.

The CPWR’s fatality maps [9] and OSHA’s Integrated Management Information System (IMIS) database [26] were explored to analyze the height-related accidents in the last 5 years to identify the frequent construction tasks that resulted in fatalities. The details provided in the investigation reports were used to identify the key characteristics associated with each accident. The analysis indicated that “roof” is one of the primary factors leading to fatal falls in construction. Further investigation of filtered reports of “falls from roof” accidents provided information about workers' tasks, working locations, and material or equipment. After filtering the data, 337 incidents involving falling or physical contact related to the keyword "roof" were analyzed. The most frequent words related to construction accidents and the most frequent falling height were identified by analyzing narrative descriptions in OSHA reports (Table 1.). In the filtered 337 “*roof*” incidents caused by falling or physical contact, the most frequent tasks for the workers who fall from the roof are installing panels or trusses, and the most frequent falling height is 20 feet.

Table 1. Injury Reports (2015-2018) Analysis Results [9]

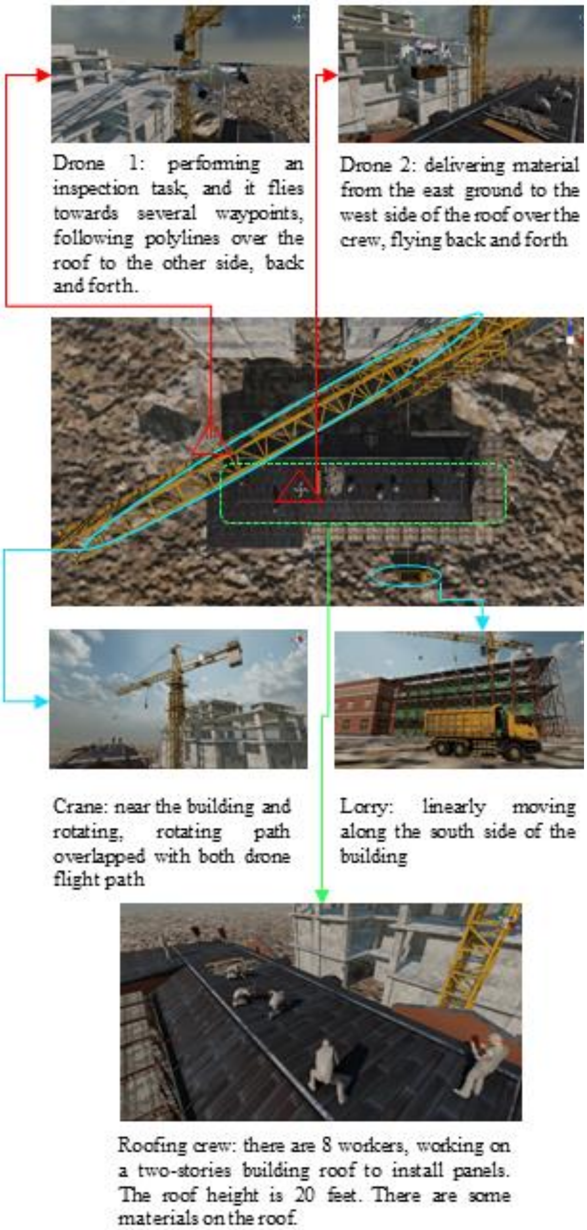
No.	Word related to “roof” accidents from injury reports	Count
1	roof	433
2	fell	414
3	concrete	66
4	floor	54
5	metal	44
6	Scaffold	36
7	installing	36
8	residential	33
9	ladder	29
10	skylight	25
11	struck	24
12	lift	22
13	platform	21
14	panels	21
15	trusses	20
	The most frequent fall height	
	20 ft	

Hence, the common characteristics obtained from this step were

(1) The working location should be on the roof.
(2) The building height needs to be 20 feet.
(3) The workers’ task should be installing panels.

5.2 Simulation Conceptualization

The objective of this step was to design dynamic simulation scenarios. This included (1) the design of static 3D virtual scenarios as the simulation environment and (2) the design of different virtual workers and drones performing their designated tasks within this environment. The common scenario characteristics identified in the previous step formed the basis for designing the 4D simulations in this step. Finally, the drone tasks and flight paths were also incorporated into the identified high-risk scenarios (Figure 2). The area of this virtual construction site is approximately 3,000 square meters (32,000 square feet).



Drone 1: performing an inspection task, and it flies towards several waypoints, following polylines over the roof to the other side, back and forth.

Drone 2: delivering material from the east ground to the west side of the roof over the crew, flying back and forth

Crane: near the building and rotating, rotating path overlapped with both drone flight path

Lorry: linearly moving along the south side of the building

Roofing crew: there are 8 workers, working on a two-stories building roof to install panels. The roof height is 20 feet. There are some materials on the roof.

Figure 2. "Roof" Scenario for 4D simulation

6 Simulation Development

6.1 Simulation Parameter Determination

The objective of this step was to identify different simulation parameters necessary to vary the simulation conditions and determine their values to evaluate the physical risks of drones under multiple conditions. Based on previous studies (see section 2.3), speed, altitude, and failure rate are selected as three parameters to mimic different flight conditions for each simulation (Figure 3.). Varying speed helped study the impact of the drone's dynamic movement through the virtual environment on its likelihood of colliding with other entities. Varying altitude can evaluate the impact of relative position between the drone and other virtual objects. Finally, the failure rate was a collective parameter for several characteristics which influence the drone's flight stability but are difficult to quantify. These include operator error, program error, hardware error, and weather conditions.

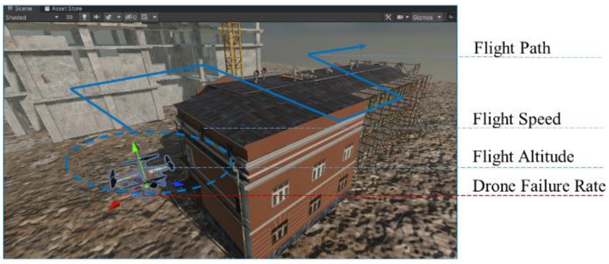


Figure 3. The Flight Parameters of Virtual drones

The flight parameters of virtual drones in Unity3D scenarios need to be designed based on actual drone flight characteristics in the real construction sites while performing specific tasks to mimic realistic construction sites and drone integration scenarios. According to the regulation for small unmanned systems issued by the Federal Aviation Administration [27] and the memorandum for the use of Unmanned Aircraft Systems in Inspections by the Occupational Safety and Health Administration [28], the drone must not be operated higher than 400 feet above the ground, except when within 400 feet of a structure; the flight speed of drone must not exceed 100 mph. More literature was reviewed to determine the range of flight parameters of virtual drones used in physical contact risks simulation scenarios.

Speed

Usually, the flight speed is fixed for visual data capture when drones are used for monitoring and inspection-related tasks. For example, Ibrahim and Golparvar-Fard [29] set the drone speed to 11 mph (5m/s) to optimize 3D flight templates and generate an algorithm that maximized visual quality and minimized flight execution duration. Similarly, a drone flight speed of

3m/s was used to accomplish surveying applications to a medium-sized building [30]. In a safety monitoring and inspection application case study for a four-story building, the drone performed a task at 3m/s speed outside the boundary of the construction site [31]. In a study analyzing drone photogrammetry's potential application, the drone flight speed was fixed at 2.5m/s to capture visual information in three-dimension and over different epochs for a building zone [32]. In a mapping application experiment study, conducted on a university campus and a residential construction site, the drone speed was suggested to be 4m/s based on the software developer's recommendation [33]. DroneDeploy, a commercial drone flight planning platform, usually sets the flight speed to 13mph (5.8m/s) for construction inspection [34]. Considering the previous literature, a flight speed range of 2-6m/s was selected for this simulation.

Altitude

The Drone flight altitude varies with different construction types and applications. The flight altitude in the context of this study is defined based on the distance from the drone to the surface or boundary of the building. When a drone is performing inspection or monitoring tasks, the distance needs to be such that it ensures that the drone can capture visual information with good quality while avoiding collision with the structure. A study of quality assessment for the drone applications on visual inspection for structure damages indicated that usually under suitable environmental conditions, the detailed image could be captured from 5m to 25m to provide detailed information on structures [35]. In a study for building 3D model reconstruction, the drone was set to keep a distance of 5-meters from the building and 25-meters from the objects to capture clear and sharp images with the required quality [36]. In another study, a distance of 12m away from the building surface was applied to capture images [37]. In a field test for an automatic point cloud registration method for the drone, a two-story building was selected for method validation, and a commercial drone path planner designed the flight height of the drone as 20m (around 10m-14m distance from the roof) [38]. According to the literature review, the distance of the drone from the building surface can range between 5m to 25m. Therefore, the altitude of virtual drones in simulation scenarios should be the height of the building surface, adding 5m to 25m. According to the scenario content developed in the previous step, the virtual building roof's height is 20 feet (6m). Therefore, the altitude range of the virtual drone, which is performing inspection tasks in simulation, should be 11m to 31m.

Failure Rate

Various factors decide the failure rate of the drone. Intrinsic reliability, which stands for system vulnerability is one of the essential factors that cause drone failures. The hierarchy of the intrinsic reliability assessment shows that critical factors are located in different subsystems: ground control system, mainframe, power system, navigation system, electric system, and payload [39]. Human error is another critical factor that causes drone accidents. Human factor issues are related to flight system operation, incorporated automation, and user interfaces [40]. Analysis based on military UAV mishap statistics suggests that most mishaps are caused by unsafe actors of the operators [41]. The top errors related to the operator's behavior are skill-based, decision-making, and cognitive factors. Research also suggests that higher mental demands cause more errors during drone flight operations performed by simulators [42]. The external environment can also lead to drone failures. For example, a bird strike is a potential factor for drone accidents, especially during takeoff and landing [43]. Adverse weather conditions will also impact the success of drone flight and task performance [44].

The failure rate applied in simulation needs to be a combined parameter from several characteristics, including intrinsic reliability, human errors, and external environments, to mimic realistically done failures comprehensively. This study assumes the failure rate of virtual drones ranges from 10% to 50% due to potential internal or external influential factors. Based on the failure rate value, the drones were programmed to suddenly fall while performing tasks in their flight path. The probability of this happening was the same as the failure rate value set for that simulation run.

6.2 Simulation Demonstration and Validation

The objective of this step was to run the simulation with varying simulation parameters and observe drone interaction in these varying conditions. Three levels were set for each parameter in the 4D simulation, representing low, medium, and high levels of value, to mimic different flight conditions in the realistic construction site (Table 2.). Two virtual drones were used in the simulation with drone 1 representing a drone that has close interactions with workers (such as material delivery) and drone 2 simulating an inspection type of drone that does not come close to workers. For each simulation run, the parameter value was randomly made to fall in one of the selected levels. Having 3 parameters with each of the three levels, there were 27 different combinations of parameter levels. For each type of combination, 10 simulations were run resulting in a total of 270 rounds of the simulation conducted in Unity3D.

Table 2. Different levels of parameters

Parameter Type	**Level of Parameter** Low	Medium	High
Speed (m/s)	1.5-2.5	3.5-4.5	5.5-6.5
Altitude (meter)	15-17	20-22	25-27
Failure Rate	0-0.1	0.2-0.3	0.4-0.5

In Unity3D, the Rigidbody Component is used to provide the object's gravity and could mimic the falling incidents of the drones. The Collider Component is used to detect the collisions between virtual drones and other virtual objects, including workers, equipment, building, and ground, and would collide with other objects. The real drone's rotors may continue working even if it fell but would stop after hitting something. This was mimicked in simulations by adding a delay of 2 seconds after the virtual drone collides with other objects before it ultimately stops working. The number of collisions between each drone with the worker, building, equipment, ground, and another drone was counted.

Table 3 shows the results of 270 simulation runs of this demonstration. The total collisions of drones 1 and 2 with other objects are used to detect drone-related potential safety risks for the system in the virtual scenario.

Table 3. Collisions Counted in Simulation Validation

Collision Type	Count
Total Collisions	773
Collisions Between drones and Building	45
Collisions Between drones and Workers	58
Collisions Between drones and Equipment	17
Collisions Between drones and Ground	653
Collisions Between drones	0

7 Conclusion and Future Work

This study provides a 4D simulation development framework that provides a methodology to mimic and simulate realistic drone-integration construction sites. Such simulations are used to study the safety challenges of workers working with or around drones on construction sites. First, simulation scenario content was developed based on the analysis of past construction injury reports, which identified the most frequent factors that caused fatal injuries. Furthermore, drone tasks and flight paths are designed to incorporate virtual workers as supplementary scenario content. Second, speed, altitude, and failure rate were selected to mimic different flight conditions of drones in the 4D simulation. These three parameters, which designate how the integrated drones perform their tasks, were defined based on realistic parameter ranges. Finally, this simulation was run multiple times with varying parameters to observe and evaluate the likelihood of drone contact risks under these varying conditions. The 4D simulation detected potential collisions between drones and human workers or other objects. The validated 4D simulation can provide a valuable source for future comprehensive safety risk identification and assessment of drone integration in construction.

Since the interactions with drones and the dynamic construction activities depend highly on the scenario content, the quantitative result from this study can only provide insights for a specific type of drone integrated construction scenario. However, the identified risks and the relationship between different drone parameters and the number of incidents can provide valuable information that applies to other scenarios. Future research should include more scenarios within the 4D simulation to cover more realistic construction site conditions and include more complicated object movements and interactions. For example, the workers might sometimes randomly move in the working area, communicating with each other and exchanging their positions. These need to be captured in future simulations. Besides, other high-risk scenarios such as working on a ladder, or scaffolding, which are also prone to risks posed by drones, should be included in the simulations. Finally, there can be more types of drone flight paths according to their performing tasks and flight scenarios. Comprehensive safety risk assessment of drone integration in construction sites can be conducted through more complicated simulation development based on the preliminary work produced by the current study.

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References

[1] The Rise of Drones in Construction | DroneDeploy, (n.d.). https://www.dronedeploy.com/blog/rise-drones-construction/ (accessed December 8, 2021).

[2] State of the Drone Industry Report 2021 |

DroneDeploy, (n.d.). https://www.dronedeploy.com/resources/ebooks/state-of-the-drone-industry-report-2021/ (accessed December 8, 2021).

[3] S. Zhou, M. Gheisari, Unmanned aerial system applications in construction: a systematic review, Constr. Innov. 18 (2018) 453–468. https://doi.org/10.1108/CI-02-2018-0010.

[4] I. Jeelani, M. Gheisari, Safety challenges of UAV integration in construction: Conceptual analysis and future research roadmap, Saf. Sci. 144 (2021) 105473. https://doi.org/10.1016/j.ssci.2021.105473.

[5] Y. Xu, Y. Turkan, A.A. Karakhan, D. Liu, Exploratory Study of Potential Negative Safety Outcomes Associated with UAV-Assisted Construction Management, (2020) 1223–1232. https://doi.org/10.1061/9780784482865.129.

[6] M. Khalid, M. Namian, C. Massarra, The Dark Side of the Drones: A Review of Emerging Safety Implications in Construction, in: EPiC Ser. Built Environ., EasyChair, 2021: pp. 18–27. https://doi.org/10.29007/x3vt.

[7] X. Li, W. Yi, H.-L. Chi, X. Wang, A.P.C. Chan, A critical review of virtual and augmented reality (VR/AR) applications in construction safety, Autom. Constr. 86 (2018) 150–162. https://doi.org/10.1016/j.autcon.2017.11.003.

[8] U.S. Bureau of Labor Statistics, (n.d.). https://www.bls.gov/home.htm (accessed January 9, 2022).

[9] CPWR | Construction Fatality Map Dashboard, CPWR |. (n.d.). https://www.cpwr.com/research/data-center/data-dashboards/construction-fatality-map-dashboard/ (accessed January 9, 2022).

[10] D.L. Lucas, J.R. Lee, K.M. Moller, M.B. O'Connor, L.N. Syron, J.R. Watson, Using Workers' Compensation Claims Data to Describe Nonfatal Injuries among Workers in Alaska, Saf. Health Work. 11 (2020) 165–172. https://doi.org/10.1016/j.shaw.2020.01.004.

[11] M. Gheisari, J. Irizarry, B.N. Walker, UAS4SAFETY: The Potential of Unmanned Aerial Systems for Construction Safety Applications, (2014) 1801–1810. https://doi.org/10.1061/9780784413517.184.

[12] G. Albeaino, M. Gheisari, B. Franz, A Systematic Review of Unmanned Aerial Vehicle Application Areas and Technologies in the AEC Domain, Electron. J. Inf. Technol. Constr. 24 (2019) 381–405.

[13] M. Gheisari, J. Irizarry, A User-centered Approach to Investigate Unmanned Aerial System (UAS) Requirements for a Department of Transportation Applications, in: 2015.

[14] P. Klingstam, P. Gullander, Overview of simulation tools for computer-aided production engineering, Comput. Ind. 38 (1999) 173–186. https://doi.org/10.1016/S0166-3615(98)00117-1.

[15] C.D. Pegden, Advanced tutorial: Overview of simulation world views, in: Proc. 2010 Winter Simul. Conf., 2010: pp. 210–215. https://doi.org/10.1109/WSC.2010.5679161.

[16] O. Bokor, L. Florez, A. Osborne, B.J. Gledson, Overview of construction simulation approaches to model construction processes, Organ. Technol. Manag. Constr. Int. J. 11 (2019) 1853–1861.

[17] J.C. Martinez, Methodology for Conducting Discrete-Event Simulation Studies in Construction Engineering and Management, J. Constr. Eng. Manag. 136 (2010) 3–16. https://doi.org/10.1061/(ASCE)CO.1943-7862.0000087.

[18] C. Boton, Supporting constructability analysis meetings with Immersive Virtual Reality-based collaborative BIM 4D simulation, Autom. Constr. 96 (2018) 1–15. https://doi.org/10.1016/j.autcon.2018.08.020.

[19] E. Paravizo, D. Braatz, Using a game engine for simulation in ergonomics analysis, design and education: An exploratory study, Appl. Ergon. 77 (2019) 22–28. https://doi.org/10.1016/j.apergo.2019.01.001.

[20] Y. Wang, W. Zhang, Four-rotor UAV Virtual Simulation System for Agricultural Sowing, in: 2018 IEEE 4th Inf. Technol. Mechatron. Eng. Conf. ITOEC, IEEE, Chongqing, China, 2018: pp. 1097–1101. https://doi.org/10.1109/ITOEC.2018.8740368.

[21] Y. Li, M.M. Karim, R. Qin, A Virtual Reality-based Training and Assessment System for Bridge Inspectors with an Assistant Drone, ArXiv210902705 Cs. (2021). http://arxiv.org/abs/2109.02705 (accessed September 20, 2021).

[22] A. Al-Mousa, B.H. Sababha, N. Al-Madi, A. Barghouthi, R. Younisse, UTSim: A framework and simulator for UAV air traffic integration, control, and communication, Int. J. Adv. Robot. Syst. 16 (2019) 172988141987093. https://doi.org/10.1177/1729881419870937.

[23] G. Albeaino, R. Eiris, M. Gheisari, R.R. Issa, DroneSim: a VR-based flight training simulator for drone-mediated building inspections, Constr. Innov. ahead-of-print (2021). https://doi.org/10.1108/CI-03-2021-0049.

[24] R.-X. Wang, R. Wang, P. Fu, J.-M. Zhang, Portable interactive visualization of large-scale simulations in geotechnical engineering using Unity3D, Adv. Eng. Softw. 148 (2020) 102838.

https://doi.org/10.1016/j.advengsoft.2020.102838.
[25] M. Kurien, M.-K. Kim, M. Kopsida, I. Brilakis, Real-time simulation of construction workers using combined human body and hand tracking for robotic construction worker system, Autom. Constr. 86 (2018) 125–137. https://doi.org/10.1016/j.autcon.2017.11.005.
[26] Establishment Search Page | Occupational Safety and Health Administration, (n.d.). https://www.osha.gov/pls/imis/establishment.html (accessed January 30, 2022).
[27] 14 CFR Part 107 -- Small Unmanned Aircraft Systems, (n.d.). https://www.ecfr.gov/current/title-14/chapter-I/subchapter-F/part-107 (accessed November 16, 2021).
[28] OSHA's use of Unmanned Aircraft Systems in Inspections | Occupational Safety and Health Administration, (n.d.). https://www.osha.gov/memos/2018-05-18/oshas-use-unmanned-aircraft-systems-inspections (accessed November 16, 2021).
[29] A. Ibrahim, M. Golparvar-Fard, 4D BIM Based Optimal Flight Planning for Construction Monitoring Applications Using Camera-Equipped UAVs, (2019) 217–224. https://doi.org/10.1061/9780784482438.028.
[30] J.G. Martinez, G. Albeaino, M. Gheisari, W. Volkmann, L.F. Alarcón, UAS Point Cloud Accuracy Assessment Using Structure from Motion–Based Photogrammetry and PPK Georeferencing Technique for Building Surveying Applications, J. Comput. Civ. Eng. 35 (2021) 05020004. https://doi.org/10.1061/(ASCE)CP.1943-5487.0000936.
[31] J.G. Martinez, G. Albeaino, M. Gheisari, R.R.A. Issa, L.F. Alarcón, iSafeUAS: An unmanned aerial system for construction safety inspection, Autom. Constr. 125 (2021) 103595. https://doi.org/10.1016/j.autcon.2021.103595.
[32] J. Unger, M. Reich, C. Heipke, UAV-based photogrammetry: Monitoring of a building zone, ISPRS - Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci. XL–5 (2014) 601–606. https://doi.org/10.5194/isprsarchives-XL-5-601-2014.
[33] J. Irizarry, D. Costa, A. Mendos, Lessons learned from unmanned aerial system-based 3D mapping experiments, in: 2016. chrome-extension://efaidnbmnnnibpcajpcglclefindmkaj/viewer.html?pdfurl=http%3A%2F%2Fascpro0.ascweb.org%2Farchives%2Fcd%2F2016%2Fpaper%2FCPRT157002016.pdf&clen=503377&chunk=true.
[34] DroneDeploy, (n.d.). https://help.dronedeploy.com/hc/en-us (accessed November 25, 2021).
[35] G. Morgenthal, N. Hallermann, Quality Assessment of Unmanned Aerial Vehicle (UAV) Based Visual Inspection of Structures, Adv. Struct. Eng. 17 (2014) 289–302. https://doi.org/10.1260/1369-4332.17.3.289.
[36] M.N. Zulgafli, K.N. Tahar, Three dimensional curve hall reconstruction using semi-automatic UAV, ARPN J. Eng. Appl. Sci. 12 (2017) 3228–3232.
[37] T. Rakha, A. Gorodetsky, Review of Unmanned Aerial System (UAS) applications in the built environment: Towards automated building inspection procedures using drones, Autom. Constr. 93 (2018) 252–264. https://doi.org/10.1016/j.autcon.2018.05.002.
[38] J. Park, P. Kim, Y. Cho, Y. Fang, AUTOMATED COLLABORATION FRAMEWORK OF UAV AND UGV FOR 3D VISUALIZATION OF CONSTRUCTION SITES, in: 2018.
[39] E. Petritoli, F. Leccese, L. Ciani, Reliability assessment of UAV systems, in: 2017 IEEE Int. Workshop Metrol. Aerosp. MetroAeroSpace, 2017: pp. 266–270. https://doi.org/10.1109/MetroAeroSpace.2017.7999577.
[40] K.W. Williams, A Summary of Unmanned Aircraft Accident/Incident Data: Human Factors Implications, FEDERAL AVIATION ADMINISTRATION OKLAHOMA CITY OK CIVIL AEROMEDICAL INST, 2004. https://apps.dtic.mil/sti/citations/ADA460102 (accessed November 25, 2021).
[41] S. Giese, D. Carr, J. Chahl, Implications for unmanned systems research of military UAV mishap statistics, in: 2013 IEEE Intell. Veh. Symp. IV, 2013: pp. 1191–1196. https://doi.org/10.1109/IVS.2013.6629628.
[42] G.G. De la Torre, M.A. Ramallo, E. Cervantes, Workload perception in drone flight training simulators, Comput. Hum. Behav. 64 (2016) 449–454. https://doi.org/10.1016/j.chb.2016.07.040.
[43] A. Kumar Jha, S. Sathyamoorthy, V. Prakash, Bird strike damage and analysis of UAV's airframe, Procedia Struct. Integr. 14 (2019) 416–428. https://doi.org/10.1016/j.prostr.2019.05.051.
[44] B. Zhang, L. Tang, M. Roemer, Probabilistic Weather Forecasting Analysis for Unmanned Aerial Vehicle Path Planning, J. Guid. Control Dyn. 37 (2014) 309–312. https://doi.org/10.2514/1.61651.