Drone-Related Deployment Limitations in Construction: A Research Roadmap

Gilles Albeaino[1]; Masoud Gheisari, Ph.D., A.M.ASCE[2]; and Raja R. A. Issa, Ph.D., F.ASCE[3]

[1]Ph.D. Student, Rinker School of Construction Management, Univ. of Florida, Gainesville, FL (corresponding author). ORCID: https://orcid.org/0000-0001-9900-3882.
Email: galbeaino@ufl.edu
[2]Assistant Professor, Rinker School of Construction Management, Univ. of Florida, Gainesville, FL. ORCID: https://orcid.org/0000-0001-5568-9923. Email: masoud@ufl.edu
[3]Rinker Distinguished Professor, Rinker School of Construction Management, Univ. of Florida, Gainesville, FL. Email: raymond-issa@ufl.edu

ABSTRACT

Drones' recent advancements, distinctive flying capabilities, and ability to efficiently accomplish tasks have allowed these platforms to shift from passively following humans' control commands to actively collaborating and interacting with other robots and construction personnel on jobsites. This shift has highlighted the need for advanced research on deployment challenges associated with drone usage on construction jobsites with the aim of better integrating this technology in the domain. A narrative review was conducted to propose a research roadmap and discuss the challenges and requirements of drone-related deployment limitations in construction. The paper categorizes and discusses four elements of this proposed roadmap: (1) drone technology improvement; (2) operator training and psychological effect assessment; (3) flight space and weather condition adaptation; and (4) legislative and ethical rule standardization on jobsites. The contribution of this study is to better understand the human-drone interaction requirements that would ultimately ensure safe and efficient drone adoption in construction.

INTRODUCTION

Drones, aka Unmanned Aerial Systems (UASs) or Unmanned Aerial Vehicles (UAVs), emerged as efficient and flexible tools on construction jobsites, being capable of accomplishing a variety of applications in a safe, timely, and cost-effective manner. These tasks, which cover the entire lifecycle of a project, range from the pre-construction stage (e.g., site feasibility studies, site planning) to construction (e.g., structural inspection, energy assessment, earthwork calculations) and post-construction (e.g., building maintenance, post-disaster reconnaissance) (Albeaino et al. 2019). In construction, the most common and traditional human-drone interaction modality is telemetry, with data (i.e., communication and information) being transferred wirelessly and in real-time from the drone to the ground control station. Similar to other types of robots and automated machinery, drones are expected to permeate jobsites and work collaboratively with other robots and construction workers in the near future. This integration of automation stems from the ongoing decline in the productivity rates and the insufficient number of skilled workers within the construction domain (Johari and Jha 2021).

The following study aims at (1) identifying the drone-associated challenges discussed in the literature and (2) proposing a research roadmap to resolve those identified challenges. Specifically, the methodology adopted in this study was first discussed. The drone-associated challenges that were most encountered in the construction literature were then exhaustively reviewed and categorized. Based on the identified challenges, a research roadmap was proposed and discussed, providing researchers and practitioners with research areas warranting additional exploration. Researchers and practitioners can benefit from this study to have a better understanding of the construction industry requirements by recognizing and mitigating the drone-related challenges that hinder this technology's adoption in this setting. This ultimately ensures safe and efficient drone integration in construction.

METHODOLOGY

A narrative review was adopted in this study with the aim of covering a broad perspective on the different challenges of drones in the construction, human-drone and human-robot interaction research fields. Google Scholar, IEEE Xplore, and Association for Computing Machinery (ACM) Digital Library were queried using relevant keywords that were arranged using the following search syntax: ("Unmanned Aerial Vehicles" OR "Unmanned Aerial System" OR "UAV" OR "Drones" OR "UAS" OR "human-drone interaction" OR "human-robot") AND ("Construction" OR "Interaction" OR "Research" OR "Applications" OR "Challenges" OR "Advantages"), yielding 154 potentially relevant records. Only articles within the past decade (2011-2021) were included in the literature search, given that this period witnessed increased number of drone-mediated applications within the domain (Albeaino et al. 2019). After search completion and duplicates removal, these studies were screened by title and abstract, and then fully reviewed to determine their inclusion eligibility (i.e., discussing the drone deployment challenges), resulting in a total of 21 articles.

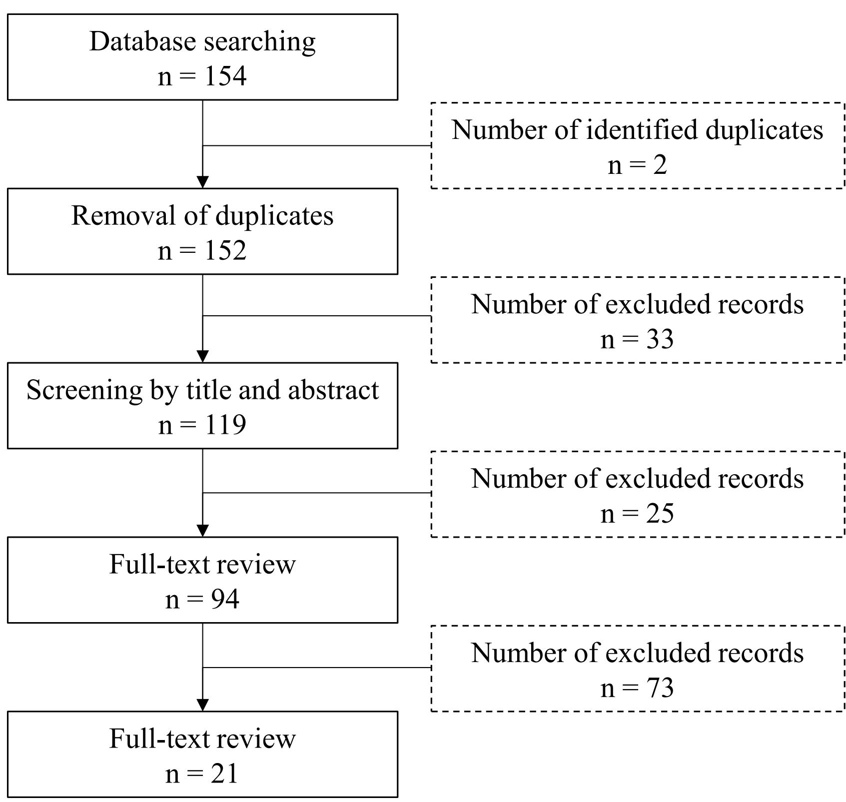

Figure 1. Article screening workflow.

DRONE DEPLOYMENT CHALLENGES IN CONSTRUCTION

Multiple researchers in the construction field have stated different deployment limitations while adopting drones on jobsites. This section exhaustively summarizes the most frequent drone-related deployment limitations (Figure 2), which served as the basis for the proposed research roadmap.

Drone-related Challenges. Multiple software- and hardware-related technical challenges have been indicated by construction researchers as hindering the full implementation of human-drone types of interactions. Stated technical limitations mainly consist of losses or failures in the radio communication and Global Navigation Satellite System (GNSS) [or Global Positioning System (GPS)] signals (Albeaino et al. 2019; Golizadeh et al. 2019; Ham et al. 2016; Morgenthal and Hallermann 2014). The radio communication signal ensures a well-established communication link between the drone (along with its onboard sensors) and the ground control station, allowing the aerial platform to either be manually or autonomously operated by pilots. Poor communication link and/or GNSS signal loss potentially result in a loss in pilot control during the drone flight mission, jeopardizing the safety of construction workers and causing drone crashes on jobsites (Gheisari and Esmaeili 2019). In addition, GNSS or GPS signal loss could cause drone navigational errors, often resulting in deviations from the original pre-defined waypoint locations in the autonomous flight paths (Golizadeh et al. 2019; Martinez et al. 2021). Signal loss or magnetic interferences could also result from the presence of highly conductive equipment such as power lines, steel members, and metallic structures, which also cause drone positioning inaccuracies and provoke onsite hazardous situations (Alizadehsalehi et al. 2018; Gheisari et al. 2018; Gheisari and Esmaeili 2019; Kim et al. 2020; Martinez et al. 2020). Another limitation that could be faced by researchers and practitioners is the level of user interface complexity encountered while using ground control stations or drone management software tools (Golizadeh et al. 2019; Kim et al. 2016; Martinez et al. 2021). Such limitation could cause distraction, mental fatigue, and stress among drone pilots and affect their abilities to safely operate aerial platforms (Gheisari et al. 2014; Irizarry et al. 2012). The drone payload weight has also been often found to be hindering aerial platforms from operating at their optimal capacities (Eschmann et al. 2012; Golizadeh et al. 2019; Martinez et al. 2021; Morgenthal and Hallermann 2014; Siebert and Teizer 2014). This limiting factor has a significant influence on the performance of the drone and its onboard batteries, restricting the overall flight duration and requiring frequent battery charging and/or replacement to cover the entire pre-planned mission. Another stated limitation is the poor quality or failure of the onboard hardware components (e.g., batteries, imaging devices, inertial measurement units and other positioning devices, motors, propellers) which could render drone-mediated flight missions either unsafe (in the case of navigational and positioning sensor deficiencies) or inefficient (in the case of imaging sensor defects) (Albeaino et al. 2019; Alizadehsalehi et al. 2018; Gheisari et al. 2018; Gheisari and Esmaeili 2019; Golizadeh et al. 2019; Kim et al. 2016; Martinez et al. 2020, 2021; de Melo et al. 2017; Mendes et al. 2018; Roberts et al. 2017).

Human-related Challenges. In addition to the drone-related challenges, humans are also considered as influential elements in terms of improving or worsening human-drone interactions on jobsites. Given that construction is characterized by its dynamic, risky, and complex nature, the integration of aerial platforms within the domain heavily depends on humans' drone piloting skills and training. In fact, pilots should develop high levels of hands-on drone navigation skills and train for relatively long periods of time in order to become proficient in flying and operating these aerial platforms within such hazardous environments. This is particularly important, especially since insufficient piloting skills, expertise, and training might cause pilots to operate drones uncontrollably and incompetently while having their judgment and decision-making negatively affected (Alizadehsalehi et al. 2018; Martinez et al. 2021; de Melo et al. 2017; de Melo and Costa 2019). These factors render drone operation difficult and potentially lead to adverse safety-, health-, and monetary-related outcomes on jobsites (Gheisari and Esmaeili 2019). Onsite drone presence might also cause negative psychophysiological effects among workers and other onsite construction personnel (Alizadehsalehi et al. 2018; Gheisari et al. 2018; Gheisari and Esmaeili 2019; Kim et al. 2020; Martinez et al. 2020; de Melo and Costa 2019). These effects, which include stress, anxiety, mental fatigue, and reduced situational awareness, affect workers' behaviors, potentially creating hazardous situations that might even result in fatal injuries.

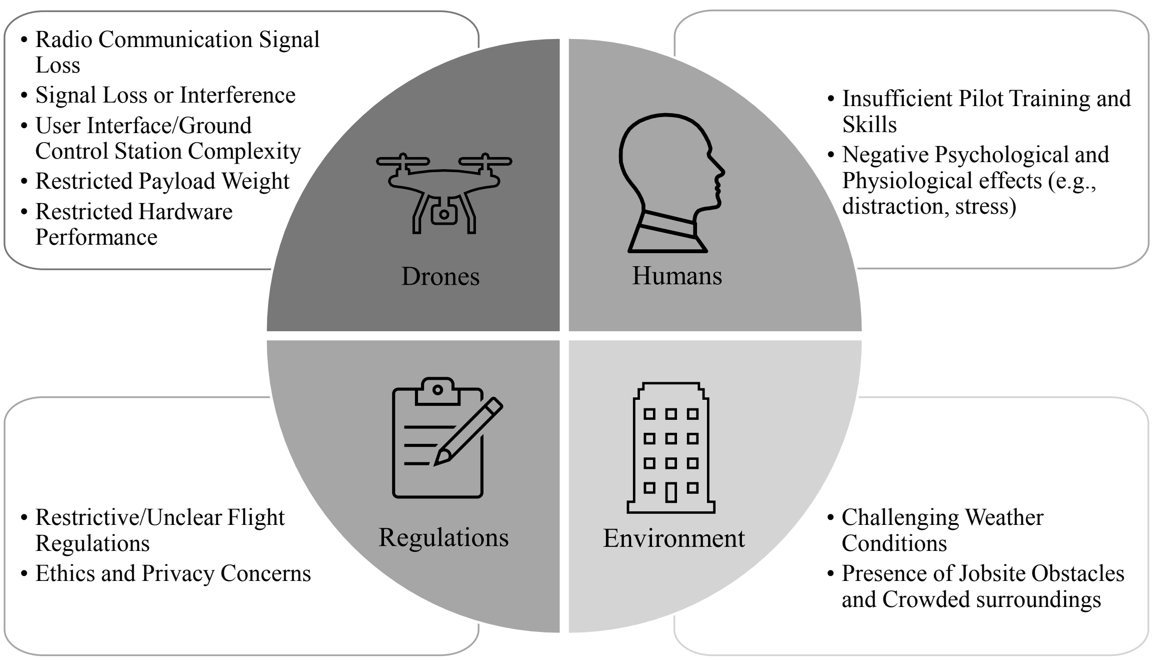

Figure 2. Challenges of Human-Drone Interaction in Construction.

Environment-related Challenges. The interaction between drones and humans in construction is also hindered by the prevailing environmental conditions during the flight mission (Albeaino et al. 2019; Alizadehsalehi et al. 2018; Golizadeh et al. 2019; Kim et al. 2016, 2020; Martinez et al. 2020; de Melo et al. 2017; Mendes et al. 2018). Operating aerial platforms in inclement weather such as windy or stormy environments, or even during increased sunlight reflectivity conditions, degrades pilots' abilities to efficiently control drones and collect visual information. In addition, the jobsite's flight space conditions which might often be overcrowded (i.e., high-density urban cities with congested adjacent buildings), together with the presence of jobsite obstacles (e.g., cranes, automated machinery, cantilevers), also render drone operations difficult (Golizadeh et al. 2019; Irizarry and Costa 2016; Kim et al. 2016; Martinez et al. 2020, 2021; de Melo et al. 2017). Consequences of operating drones under such environmental settings are many. For example, drones could drift from their pre-defined flight paths, potentially leading to crashes and struck-by accidents with nearby jobsite components and personnel (Gheisari and Esmaeili 2019). Inefficient or inaccurate visual data collection could occur during inclement weather conditions due to, for example, the glare effect in the case of increased sunlight reflectivity. Environments characterized as stormy or windy with increased sunlight reflectivity might also cause reductions in: (1) the pilots' drone controlling capabilities due to the low visibility conditions; and (2) the flight durations due to the aerial platforms' multiple attempts trying to compensate for the air hovering instability, resulting in early battery depletion (Martinez et al. 2021).

Regulation-related Challenges. Multiple aviation authorities across the US and Europe have been updating their policies to standardize the commercial use of drones in their airspaces. For example, the United States Federal Aviation Administration (FAA) Part 107 requires drones weighing between 0.55 lbs. and 55 lbs. (including payloads) to be controlled only during the hours of daylight, at a maximum speed of 87 knots (100 mph), and within 400 ft ground level (AGL) horizontally and vertically from a structure (US Department of Transportation 2016). Drones are required to be hovering within the visual line of sight (VLOS) of the flight operators and only over people who are part of the drone flight team or directly involved in the mission (US Department of Transportation 2016). It should be noted that some of these limitations such as operating beyond visual line of sight (BVLOS) could be overcome through an FAA-approved waiver. Despite these efforts, regulations established by worldwide aviation authorities are restrictive and not yet properly designed for the construction industry and its unique, dynamic, and complex environment (Gheisari et al. 2018; Gheisari and Esmaeili 2019; Kim et al. 2016; Martinez et al. 2020; de Melo et al. 2017). As an example, jobsite personnel tend to bypass the FAA regulation that prohibits drone operation over active jobsites and people who are not directly involved in the drone flight by considering all construction jobsite workers as part of the drone flight team. This highlights the need for additional collective agendas to come up with more jobsite-specific and applicable regulations. In addition to the aviation regulations, other regulation-related challenges include the ethical and privacy concerns associated with drone utilization in construction (Gheisari and Esmaeili 2019; Herrmann 2016; Kim et al. 2016; Martinez et al. 2021). Such concerns, which are most commonly found in overcrowded and urban environments, could be encountered within and outside jobsite boundaries. Specifically, workers might not accept the jobsite use of camera-equipped drones especially since these platforms are capable of continuously monitoring workers' movement, potentially resulting in some disruptive behavior (Herrmann 2016; Martinez et al. 2021). Passersby, especially individuals who expect to have some privacy in public places or ones who did not agree to be tracked in the first place, might also consider drone usage as a civil liberty intrusion.

RESEARCH ROADMAP

Four different elements are discussed in this proposed roadmap: (1) drone technology improvement; (2) operator training and psychological effect assessment; (3) flight space and weather condition adaptation; and (4) legislative and ethical rule standardization on jobsites. Each of these elements will be discussed in detail in the following subsections.

Drone Technology Improvement. Unmanned Aerial Systems (UASs) not only consist of the aerial platforms along with their mounted onboard sensors, but also include ground technologies such as ground control stations that establish communication links between interactants (i.e., humans and drones). Based on the identified drone-related challenges discussed in the previous section, collaborative work involving researchers within the construction and engineering domains should focus on two different drone-related technology improvement aspects: (1) onboard and (2) ground technologies.

Future studies on the onboard drone technologies should be mainly focusing on enhancing the efficacy and robustness of the platform-mounted hardware components and sensors, including Red-Green-Blue (RGB) and thermal imaging devices, Light Detection and Ranging (LiDAR) and obstacle avoidance sensors, as well as video transmitters, batteries, motors, and propellers. Of particular importance are the onboard navigation and communication sensors which include GNSSs or GPSs, electronic speed and flight controllers, regulators, radio controller receivers/transmitters, and telemetry modules. Ultimately, such improvements not only ensure a reliable and safe drone deployment in case of, for example, any onsite signal interferences, but also enhance the efficiency of the overall drone-mediated flight planning, data collection, and data processing methods. Future research should also investigate drones' physical characteristics such as platform shapes and types, which include, in addition to the widely known rotary-wing and fixed-wing drones, vertical takeoff and landing (VTOL), electric- (e.g., eVTOL) and solar-based drones, airships, and flapping wing vehicles.

As for ground drone technologies, future research must focus on making ground control station interfaces less complex, more accessible, and user-friendly. Such a need was indicated by multiple researchers exploring drone utilization within the construction field. Minimizing the complexity of the user interface and improving its usability help avoid additional drone-related hazards from happening. In addition, simple user interfaces reduce the stress among pilots, especially novices who did not develop sufficient levels of hands-on drone navigation skills that would enable them to operate drones safely and assertively on jobsites. Future studies must also aim at incorporating fast and reliable communication networks (e.g., 5G) which allow for an efficient and low-latency pilot-drone control and interaction while enabling pilots to operate drones BVLOS. BVLOS operations are of particular importance to the construction industry, mainly for linear, large-sized, high-rise, or industrial types of projects. In these cases, BVLOS drone operations could be conducted to communicate or deliver material to workers on jobsites, assist aerially in different construction tasks, or even inspect offshore structures.

Human-drone interaction modalities are expected to become more natural in the future, especially with the use of gesture, speech, gaze, brain control, and touch as control modalities. As of today, there is only a handful of drones that are capable of being programmed and operated using such modalities, as the majority of the commercial platforms rely upon traditional or telemetry-based drone control. For this purpose, future research on drone technologies should also improve the integration of these intuitive modalities within construction, especially in outdoor environments. For example, ground control stations should be capable of decoding and translating users' input, regardless of the interaction modality type, into different actions that aerial platforms should perform. The input can be communicated verbally through microphones in the case of speech-based interactions; through brain signals captured using electroencephalography in the case of brain-controlled interactions; or even through motion or eye-tracking sensors in the case of gesture- or gaze-based interactions.

Operator Training and Psychological Effect Assessment. Through training programs, future research should aim at training novice pilots on how to interact with drones on jobsites, regardless of whether this interaction is performed using traditional telemetry or through the use of more natural control modalities. Training could be conducted in a safe, repeatable, and controlled environment through the use of experimental laboratories and virtual/augmented reality (VR/AR)-based real-world simulations. Developing such VR/AR simulations are of particular importance, as these provide room for pilot operational errors (e.g., poor judgment) that, if otherwise took place on real-world jobsite environments, result in hazardous consequences. In addition, future studies should investigate workers' behaviors around drones by measuring their performance, stress, situational awareness, mental workload, and comfortable approach distance. For example, workers at height might exhibit different behaviors (e.g., higher levels of stress and mental workload) compared with ones on the ground when being approached by drones. Such research: (1) improves drone integration within the construction industry; (2) provides a better understanding of the psychophysiological effects associated with onsite presence of drones on construction personnel; and (3) assesses whether drones are an additional safety hazard to an already unsafe environment and whether these aerial platforms effectively improve safety on construction jobsites.

Flight Space and Weather Condition Adaptation. Regardless of the prevailing flight space conditions on the jobsite, future drones must be robust enough and capable of performing at full capacity even when being operated in windy or inclement weather. The development of more robust aerial systems can be accomplished by improving the onboard and ground drone technologies (discussed in the Drone Technology Improvement subsection) which aim at preventing drones from falling. However, additional failsafe and energy reduction systems can be mounted onboard drones to minimize the falling impact and safety risk severity associated with any aerial platform malfunctioning over people or equipment. Failsafe and energy reduction systems have different types, ranging from sensor redundancies (e.g., multiple sets of inertial measurement units within a system) and autonomous flying functions (e.g., guarded motion, auto takeoff/landing, auto return) to recovery systems (e.g., airbags, parachutes), propeller guards, protective cages, and failsafe algorithms.

Legislative and Ethical Rule Standardization. Future collaborative work should focus on standardizing drone usage on jobsites through construction-specific rules and regulations that have not been established yet by worldwide regulatory authorities. Of particular importance to the construction industry is the need for regulating drone operation in indoor environments. The usage of aerial platforms in such GPS-denied environments is common for many applications (e.g., safety inspection, indoor crack and damage assessment) and is also required for some of the new control modalities (e.g., gesture, speech, gaze, brain control, touch), which necessitate collocated types of jobsite environments. Additional exploration should also standardize the safety and health regulations pertaining to both indoor and outdoor usage of drones on jobsites. These safety and health regulations are typically passed by regulatory agencies such as the Occupational Safety and Health Administration which, in the case of drones, should explore the safety risks associated with drones and establish regulations accordingly. More specifically, regulatory agencies should set programs and standards, enforce them, and perform periodic evaluations to ensure safe working conditions for construction workers operating near drones. On the other hand, these standards should not compromise the potential of drone technology within the construction domain. Ultimately, it is expected that current drone-associated ethics and privacy concerns will be alleviated should the flight- and safety-related legislation become clear and established. Insurance companies could also benefit from these regulations to provide comprehensive insurance policies that not only guide construction entities in case of any dispute but also cover any potential liabilities associated with onsite drone accidents.

CONCLUSION

Drones are expected to become an integral part of construction environments, being capable of collaborating with other robots and automated machinery to accomplish a wide variety of tasks.

However, the full integration of drones within the domain is hindered by multiple challenges that have been extensively categorized and discussed in this study. A narrative review was adopted in this study to systematically identify all drone-related challenges within the construction industry. Based on the literature, these challenges were mainly drone- (i.e., onboard and ground drone technologies), human- (i.e., pilot training, psychophysiology), environment- (i.e., weather and jobsite conditions), and regulation-related (i.e., flight regulations, ethics). In addition, a research roadmap providing construction professionals with areas warranting further exploration was provided in order to better understand the needs of the construction industry and mitigate these drone-related challenges. Four elements were included in this proposed roadmap: (1) drone technology improvement; (2) operator training and psychological effect assessment; (3) flight space and weather condition adaptation; and (4) legislative and ethical rule standardization. Ultimately, this roadmap ensures safe and efficient drone integration in construction.

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