Investigating the Safety Challenges of Unmanned Aerial Vehicles (UAVs) in the Construction Environment

by

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The technologies associated with Unmanned Aerial vehicles (UAVs) have revolutionized the construction industry, simultaneously demanding a comprehensive understanding of the underlying safety implications in order to reduce the risk of personal injury, property damage, lost productivity, and financial damage. Construction is one of the most hazardous sectors, with a wide range of complexity inherent in the nature of its activities, and widespread integration of UAVs without adequate safety management expertise, training, and strategies may exacerbate existing hazards. An increasing volume of research is being conducted on the potential benefits of UAV utilization. However, there is a scarcity of knowledge and development of UAV-based safety frameworks, which might have an impact on the construction sector in the near future. This study aims to investigate the potential safety risks presented by UAV use in the construction environment. In the lack of quantitative and structured data on the effects of UAV-related incidents in the construction environment, the workforce is exposed to an array of unwarranted safety risks. The data was collected through a questionnaire survey that was constructed by a series of designed questions to provide quantitative results in a context aligned to the original research goal. The findings identify a variety of potential and actual risks associated with UAV integration, as well as a substantial perception difference concerning UAVs across industry practitioners. Collision with person and property, trespassing, system malfunction, and inexperienced pilot are the safety risks of

high importance with high potential to cause substantial damage and halt productivity. The study further created a construction-specific UAV safety training program that addressed the identified risks and hazards, with the goal of increasing familiarity with UAV uses in conjunction with construction dynamics. Adopting the research study's results and improvements would allow construction practitioners to rapidly detect UAV-based safety concerns with the help of special training and excel in construction safety performance without compromising productivity.

Investigating the Safety Challenges of Unmanned Aerial Vehicles (UAVs) in the Construction Environment

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by

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CHAPTER 1: INTRODUCTION

We live in a time where technology is advancing at a breakneck pace where fiction is constantly being challenged and outpaced by the facts. The dexterity of the ability to manipulate a device from a stretch to accomplish desired objectives has always drawn enormous interests of humans. Situations where technology with the capacity of introducing endless opportunities with measurable outcomes, can essentially outstrip the limitations of manual labor. The construction industry's interest has significantly grown because of UAVs' demonstrated efficiency and versatility in commercial applications. As a consequence, incorporating cutting-edge technology is transforming the commercial development business in every field. The focus has been set to investigate further into the construction industry, which has experienced rapid growth and essentially the most significant integration of drone technology within the last few years. Usage of UAVs has increased due to the flexibility of operating them from convenient locations and allowing the opportunity to obtain resourceful information from various construction jobs and site activities with the help of mounted technologies. According to DroneDeploy, the usage of drones surged 239% in 2017, and construction is the leading sector to integrate them in multifarious roles (DroneDeploy, 2018).

Starting from a simple topographic survey (Opfer & Shields, 2014) to conducting an efficient safety inspection (Irizarry et al., 2012), many aspects of the construction industry have been taken over by UAV technology. The extreme popularity of UAV is pushing the adoption process to the next level; as a result, industrial and commercial applications are vastly being blanketed by the ascendancy of UAVs. As a progression of the research project suggesting diverse safety challenges introduced by UAVs, the following approach will be directed towards further investigation and analysis of associated safety risks posed to the workforce of construction job sites. Drones are still in their formative stages in the construction industry. Despite their skyrocketed growth in recent times, and concerns have been raised about their safe operations. In pursuit of addressing the operational safety challenges, researchers have developed and conducted risk analysis approaches to explore the severity of the endangering circumstances (Allouch et al., 2019; Björkman, 2011; Izadi Moud et al., 2020; Sanz et al., 2015). In addition to the risk assessment approach, the safety assessment process should be documented with the objective of continuous improvement. Also, the developed risk assessment database can be utilized for pre-flight checks and communications that can improve risk mitigation, monitoring, and reporting systems (Wackwitz & Boedecker, 2015).

Although it can be predicted that the integration of UAVs will be increasingly growing every day in most industrial and commercial sectors, the safety limitations remain inexact regarding the emerging safety risks to people, property, and privacy. The most popular operational limitations of the drones can be related to the short flight time due to limited battery capacity (Kardasz et al., 2016), flight termination due to severe weather (York et al., 2020), and loss of GPS signal (Kerns et al., 2014).

1.1 Problem Statement

In all of their forms, drones, from fixed-wing planes to multi-rotor quadcopters, pose substantial safety and security risks to construction work for which the industry has yet to prepare. On the other hand, the constantly changing nature of construction sites demands the introduction of novel techniques for increasing production efficiency. Workers are repeatedly placed in situations in which they are accustomed to dealing in one environment and then have their surroundings unexpectedly altered, or a different assignment, material, or equipment is implemented the very next day. This significantly impacts their risk perception and hazard recognition attributes, hindering their overall safety performance.

1.2 Goal and Objectives

The primary purpose of this study is to discover and better understand the fundamental safety dangers associated with unmanned aerial vehicles and enhance the safety framework by analyzing the operational difficulties that provide a safe environment for UAV-construction interactions. As a step in reaching the objective, this thesis endeavors to provide answers to three specific research questions:

(1) What are the potential safety hazards associated with using UAVs in construction job sites?

(2) Which hazards have the highest associated safety risks?

(3) What practical safety countermeasures are there to address the safety issues and bring risks within a manageable range?

1.3 Study Limitations

This research study is limited to exploring the inherent safety risks associated with UAVs and demonstrating their relative impacts on the construction workforces' health and safety outcomes. The data utilized for analysis were obtained from literature review, accident data investigation, and questionnaire survey.

1.4 Organization of the Thesis

The following chapters make up this thesis: (1) Introduction; (2) Literature Review; (3) Research Methodology; (4) Data Analysis and Results; and (5) Post-Hoc Case Study, and (6) Conclusions. The holistic and methodical search approach used to identify relevant material from an online database is described in Chapter 2, followed by a detailed review. The data collection and technique used to demonstrate the safety risk categorization and their relative significance supported by results are described in Chapters 3 and 4. In Chapter 5, a post-hoc case study of a unique UAV accident is discussed. The discussions and recommendations stemming from this research are presented in Chapter 6.

CHAPTER 2: LITERATURE REVIEW

2.1 Evolution of Drones

In most industrial or recreational industries, an Unmanned Aerial Vehicle (UAV) or Unmanned Aerial System (UAS) is referred to as a drone. The usage of drones has been brought into the general aspects originally by the military applications. The Defense Advanced Research Projects Agency (DARPA) and NASA started researching techniques that UAVs could be used for tactical objectives in the 1990s.This project resulted in many widely utilized UAVs, such as the Helios, Proteus, Altus Pathfinder, and Predator, which were eventually deployed by the United States of America in the Gulf War (Nonami et al., 2010). One of the most popular drones, known as the 'Predator' was created in the early 1990s to carry out tasks for the United States Air Force (USAF) and the Central Intelligence Agency (CIA). This was initially utilized for military activities such as surveillance and weapon deployment.

2.2 Advancement of UAV Applications

UAVs have established their strongholds by gaining unparalleled appraisal and receiving significant attention in many construction-based applications starting from site surveying to on-site safety inspections (Ham & Kamari, 2019; Irizarry et al., 2012; Li & Liu, 2019). The commercial applications of UAVs have skyrocketed over the last decade (Izadi Moud et al., 2018), and UAV-based construction operations have grown exponentially in the project sites (Greenwood et al., 2019). The commercial applications have converted into routine practices for applications such as site monitoring (Wen & Kang, 2014), structural health evaluation (Fernandez-Galarreta et al., 2014), 3D, and information modeling with BIM integrations for safety and job execution (Akram et al., 2019; Li & Liu, 2019), infrastructure evaluation and management (Ellenberg et al., 2016), etc. Drones have grown in popularity as a result of their increased use among industrial appliances and hobbyists; the production of these devices has grown enormously, making them more significantly inexpensive and accessible to a broader range of users. This has brought in the risk of flying these systems without proper permission in restricted and regulated areas with the increased chance of safety risks and privacy invasions (G. Wang et al., 2016). A tremendous year-to-year growth rate of drones was estimated to be 239% in the year 2018, which is indicative of the increased drone application in the construction industry, making it the leading sector for mass adoption (Oudjehane et al., 2019). According to Goldman Sachs Research (2016), the construction sector will be solely accountable for around $11.2 billion out of $100 billion of commercial expenditure generated from drones (Sachs, 2016). However, along with the emerging rate of UAV integration in recent years, there remains a series of concealed safety challenges to the workplace occupants and properties on the ground that have not been effectively identified yet due to the scarcity of relevant research (Barr et al., 2017; Sanz et al., 2015). In the lack of extensive experience with the hazards of UAV operations, particularly in construction, a complete understanding of the safety concerns is urgently needed to limit the likelihood of workplace accidents.

2.3 Drones' Contribution towards Safety Challenges

The emerging proliferation of UAV applications brings new and unimaginable possibilities in the construction sector. As construction sites constantly undergo dynamic changes, unlike fixed industrial facilities, the workforce is more transient. The constant change in the physical forms of the job sites exposes the workers to a continual change in the environment and variations in its dynamics (Sacks et al., 2009). These changes can potentially affect the way conventional thought-processing works as well as safety performance pertaining to construction equipment usage. The construction industry is adopting complex systems more than ever before, and one of the primary drivers of tragic occurrences is a lack of expertise combined with risky construction equipment operations (Izadi Moud et al., 2019). UAVs can be subjected to minimal safety features and impose the threat of significant damage to the surroundings (Afman et al., 2018). They can potentially involve collisions with humans and properties, leading to severe personal injury and damage to the properties on the job site (Belcastro et al., 2017). For example, high-velocity rotation of UAV rotors that keep the device airborne can cause bodily damage to the personnel present in the proximity. According to a collision-related study of UAVs, construction site personnel can be exposed to ground collision impact hazards with the associated risks of laceration, blunt force trauma, penetration, and fractured bones (Arterburn et al., 2017). For construction-related activities, the head and shoulder areas of the personnel are the most significant injury concerns while the UAVs are operational in various altitudes and speeds (Arterburn et al., 2017). Apart from losing control of the drone, it can be set off-course due to weather from the pre-destined route or simply distracting workers on the job site (Tatum & Liu, 2017). In addition to that, drones can be subjected to an array of systematic malfunctions such as navigational error and limited battery capacity (McCabe et al., 2017), making them stall and fall onto personnel with more minor or no warning (Namian, Khalid, Wang, & Kermanshachi, 2021). According to a recent study, the personal zone around humans usually varies between 0 ~ 3.05 m, and a UAV breaching into that space can potentially trigger stress, distraction, and discomfort (Izadi Moud et al., 2020). For construction workers who are to have the safety sphere or cylinder around, as mentioned by (Teizer et al., 2010), and the violation of this proximity may become even more dangerous as the workers are constantly subjected to mentally and physically demanding activities on the job sites. The study found a number of possible risk variables, which are depicted in Figure 1.

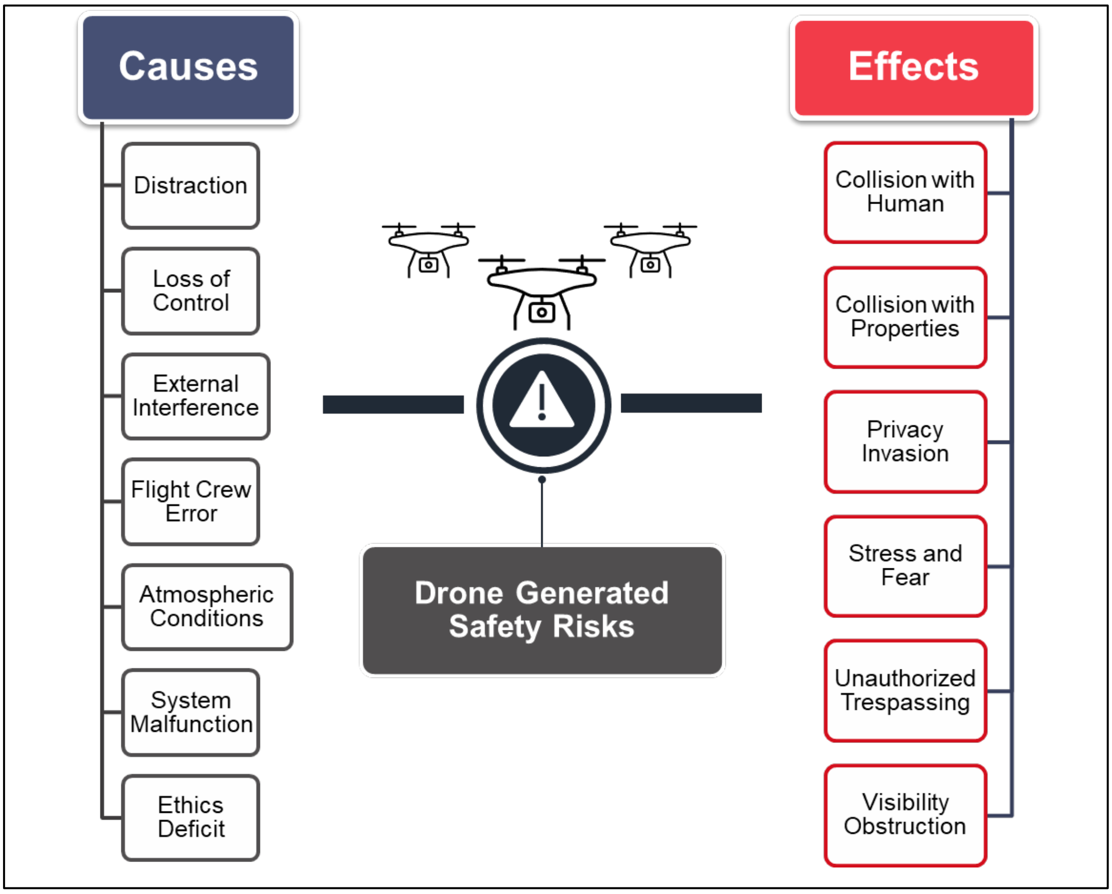


Figure 1: Classification of drone-generated safety risks.

The drone-generated safety risks have been categorized in terms of causes and effects. The seven causes are identified as the primary contributors in triggering the six effects from almost virtually any drone-related operation in the construction job site. These are helpful for the construction practitioners to familiarize themselves with the potential aspects of drone mishaps in the complex construction environment. Table 1 has been organized to demonstrate five possible unsafe scenarios with the environmental condition and consequences of the UAV-construction accidental interactions.

Table 1: Consequences of Scenarios from UAV-construction accidental interactions.

	Scenarios	Conditions	Consequences
1	Collision of drone with personnel	Struck by flying objects	Cut
			Bone damage
		Struck by falling objects	Bruise
			Laceration
2	Collision of drone with properties	Construction equipment ▪ Crane ▪ Excavator ▪ Piling barge	Windshield crack; Decrease visibility from the operator cabin leading to erroneous maneuver
		Critical properties or equipment ▪ Oil-petrochemical storage ▪ Onboard lithium battery	Fire hazard
		Critical payloads ▪ Suspended loads	Damage or destruction of structures
3	Distraction	Auditory ▪ The sound generated from the drone ▪ Cross-communication between flight and construction operations	Look away; Try to find the source of noise, impeding attention required for the critical task
		Visual ▪ The sight of the *'flying gadget.'*	Unfamiliarity raising the propensity to look away from the assigned task (see Figure 2)
4	Psychological stress (Worker)	Surveillance ▪ Close monitoring	Fear of disclosing lost/ idle time and geo-location
			Fear of accountability for productivity
		Worker's personal space ▪ Drone closing in dangerously	Fear of crashing and subsequent harm
		Blackmail/ exploitation ▪ Illegal immigrant worker ▪ Captivation by stored information	▪ Fear of being reported to law enforcement and deportation ▪ Unsafe reactions
5	Situational awareness (Pilot)	Distraction or interference by construction operation	▪ Erroneous flight maneuver ▪ Decreased flight reliability ▪ Loss of control
		Physical Stress ▪ Long operating hours ▪ Adverse weather ▪ Construction disturbance	
		Psychological Stress ▪ Sensory overload	

2.4 Distraction of Drones

The construction job environment is subjected to disruption by drones because of a lack of autonomy. Unlike automated manufacturing plants, construction usually requires human labor and their commands to establish materializations from scratch. The dynamic nature of construction makes workers' tasks more sophisticated and challenging, demanding more cognitive performance in terms of attention, vigilance, physical integrity, and reflex. However, a drone flying above a construction site has been shown to draw a lot of attention from the workers conducting their routine and monotonous day-to-day jobs (Figure 2).

Figure 2: Distracted construction workers. Image Credit: Mohammad Khalid.

Research has supported the idea of a drone being one of the primary sources of distraction in the workplace (McCabe et al., 2017). UAVs are reported to have the distinct ability to attract attention by disrupting the worker's concentration from their job assignments (Li & Liu, 2019; Martinez et al., 2020). This can potentially gather more dangerous attributes to the distracted construction workforce and existing properties in the proximity. For effective execution of any vital activities while avoiding the possible safety risk, construction workers must commit their enhanced physical and mental competencies, including situational awareness, attention, and risk identification (Craik, 2014). Cognitive capabilities towards a task completion help an individual recognize potential safety hazards in a timely fashion and act to address and minimize the gravity of the safety risk. Impaired cognitive capacities may lead to perceptual misinterpretation, which may underestimate the seriousness of any situational threat. Research suggests that most construction-related accidents happen due to the failure to recognize the hazard and risk factors before they actually occur (Namian, Zuluaga, et al., 2016). It is also suggested that distraction in the construction workplace can influence workers to undertake risk-taking behavior, elevating the likelihood of human-initiated errors, hazard susceptibility, and loss of productivity (Namian et al., 2018). Although a substantial share of the safety hazards remains unrecognized by the construction workers, researchers concluded that there is a pattern of hazard recognition that allows the workers to be proficient in recognizing certain hazard types (Uddin et al., 2020). Therefore, drones can impose a heightened level of safety challenge because the application and concealed risks are still relatively new to the community, if not totally unknown. Apart from the workers, pilots can be subjected to awkward body postures, stress, and fatigue generated from the activities of monitoring a drone as it requires the flight crew to stare upwards for a prolonged period in an attempt to maintain the visual line of sight (Sakib et al., 2021).

2.5 Ethics Deficit and Risk of Privacy

The advantages of employing drones are clear but transparent guidelines on how and where they may be used and what they can do to ensure safety and privacy are considered indispensable. When flying above construction sites, drones capture massive amounts of data, which might contain confidential or sensitive information about privately-held properties or personal acts. Many people are opposed to the use of UAVs for monitoring and surveillance of the general public because they believe it violates their privacy (Finn & Wright, 2012). Drones are a formidable piece of advanced surveillance equipment because of their ability to record massive quantities of data and transmit it in real-time. It is ambiguous how corporations should preserve and disseminate personal data, what sorts of data should not be accessed, or how individuals and businesses can protect their privacy rights, owing to the extensive interpretation of the term ‘personal data.’

The use of technology to monitor workers may generate discomfort and distrust since they are continually observed and subject to performance evaluations (Hovden et al., 2010). Nobody can stand the discomfort of always being observed, no matter how reassuring and secure it may feel to have drones hovering around the job site (Lidynia et al., 2017). In the hazard-infested construction environment, the psychological discomfort created by drones with onboard sensors and cameras can raise valid privacy concerns in most circumstances, whether public or private (Y. Wang et al., 2016). Workers may feel uneasy and increase their degree of suspicion, making it more difficult for them to execute their usual tasks with desired productivity and safety performance (Khalid, Namian, & Behm, 2021). The use of UAVs on construction sites to monitor on-site employees for improved output is one way these small devices are hindering workers’ typical workflow. Figure 3 shows a group of construction workers who are being monitored by a drone.

Figure 3: Construction workers are being watched by a drone. Image Credit: Emre Ucarer/Shutterstock.com

The existing regulatory framework does not sufficiently address privacy concerns of construction job sites. According to a study, drones are being brought into the workplace at a rapid pace without adequate safety and privacy management procedures in place to safeguard personnel from physical and emotional harm (Khalid, Namian, & Massarra, 2021a). According to the theoretical area of behavioral psychology, human conduct is primarily an expression of one's psychological state (Ajzen, 1991), and in the workplace, a worker can deviate from his required behavior if psychological distress intervenes. The distress can be linked to the presence of familiar or unfamiliar objects such as drones hovering around them. This instance may make the workers feel threatened of their privacy and adopt unsafe actions with the potential of triggering dangerous outcomes.

2.6 Factors Affecting UAV’s Flight Reliability

2.6.1 Weather Conditions

Bad weather conditions can trigger a series of error-prone events leading the operational UAV into an underestimated accident. This involves a heightened level of risk to pilots, visual observers, and people located under the UAV’s proximity. The weather may be a challenge for UAVs since it might create deviations from their intended paths. Declined weather may reduce visibility and cause loss of connection between the pilot and the aircraft leading to loss of the aircraft (Khalid, Namian, & Massarra, 2021b). In addition, in missions where Visual Line of Sight (VLOS) is necessary, they may contribute to the possible risk factors. Besides, pilots and ground crew are susceptible to being exposed to rough weather, resulting in impaired health and mental incapacity to sustain the aircraft’s control (Ranquist et al., 2017).

2.6.2 Battery Capacity

Limited battery allocation and high battery consumption can be regarded as one of the most important challenges of UAVs. Stored liquid fuel or lithium batteries fitted with the drone may overheat, creating a fire threat to the workers on the job (Opfer & Shields, 2014). Moreover, rapid discharge and swelling are significant concerns with the ability to cause the battery unit to disintegrate from the UAV, and the flight should be terminated immediately (Namian, Khalid, Wang, & Turkan, 2021). Such a case was considered during this research, and the photograph of the dislodged battery pack is presented in Figure 4.

Figure 4: Overheated and swelled battery pack dislodged from UAV. Image credit: Len Savage.

2.6.3 External (Physical) Interferences

During the course of a single drone flight, it may face a variety of physical interferences. Birds can act as an interceptor for drones, bringing the flight to a halt (Figure 5). Nowadays, birds are also professionally trained to catch and seize flying drones ("Eagles Trained to Takedown Drones," 2016). In order to assure the UAV's flying reliability, particular construction sites should be evaluated, and extra safeguards must be considered where birds are more likely to intervene.

Figure 5: A drone being intercepted by a bird. Image credit: Martin Mecnarowski/Shutterstock.com

2.6.4 Signal and Network Limitations

Every day, the construction job site develops, and in terms of newer buildings and equipment, monitoring and revised planning are required to keep the operations unhindered. Once the UAV type for the intended application has been selected, it is necessary to assess the existing situation of the site, with a focus on networking complexities. It is essential to consider the flight duration and energy constraint before deploying the UAVs, as they directly influence network performance (Mozaffari et al., 2019). There are several possibilities of signal interference because of the complicated networking system on the construction sites. For example, the UAV's GPS network may be disrupted while examining steel structures due to electromagnetic induction. The wireless communication among the workers and remote pilots may coincide and create potential interference, which would endanger both the construction and the flight activity. Figure 6 represents a schematic diagram of potential inter-networking factors that may affect the operations of construction.

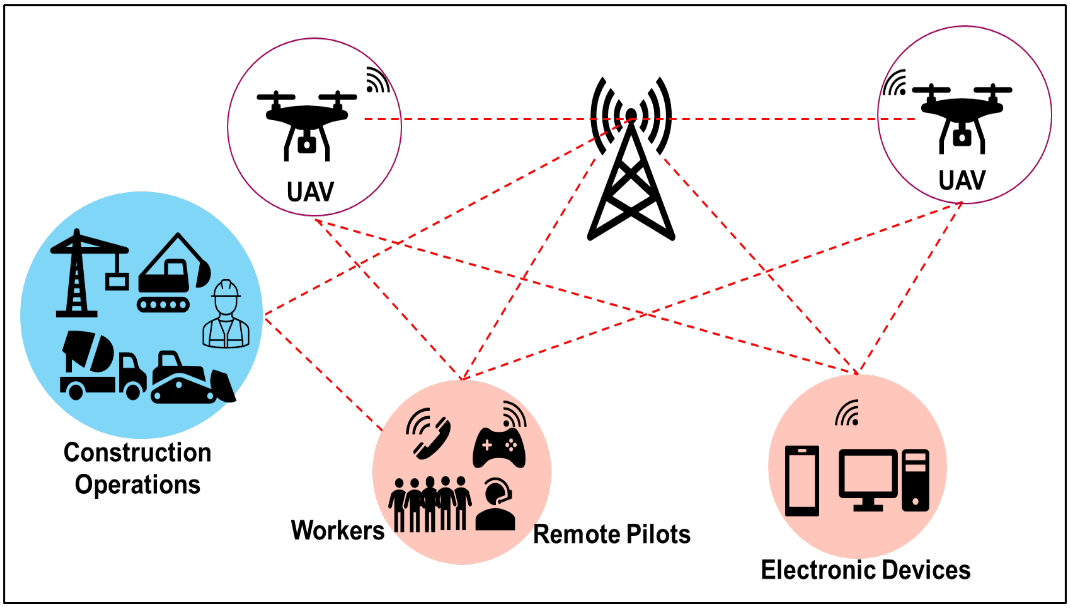


Figure 6: Potential networking factors on the construction site.

2.7 UAV Operating Regulations by FAA

According to the provided figures, the Federal Aviation Administration (FAA) estimates that almost 1.5 million drones and 160,000 UAV pilots are registered in its system (*U.S. Department of Transportation Issues Proposed Rule on Remote ID for Drones | US Department of Transportation*, 2019). Moreover, FAA's forecast suggests that the purchase of UAVs in the US are set to almost double within four years, reaching approximately 4.3 million annually in the year 2020 (*FAA Releases 2016 to 2036 Aerospace Forecast*, 2016), and the proliferation is set to create 100,000 new jobs by 2026 (Press Release – DOT and FAA Finalize Rules for Small Unmanned Aircraft Systems, 2016). The FAA in the United States has produced measures to regulate the use of small UAVs in response to the widespread expansion of UAVs, in order to establish safe usage of unmanned aircraft and public. For example, small UAVs weighing within the range of 0.55 lbs. and 55 lbs., have to be registered in the FAA system before they can be flown (Villasenor, 2014). FAA has also published the application B4UFLY *(B4UFLY Mobile App, 2021)* that can be used in a handheld smartphone to obtain information about the restrictions in the intended location of UAV operation. Another initiative in the form of a campaign, *Before You Fly* is available from FAA, which is aimed to educate and create awareness among the general public about UAV safety and responsibilities (Barrado et al., 2010; Vattapparamban et al., 2016). Moreover, it is mandatory to fly the drone under 400 feet from the ground and outside the radius of 5 miles of any airport. It is also instructed to constantly maintain a clear visual line of sight of the UAV at any given instance to execute the maneuvering safely. UAVs should not exceed the speed of 100 miles per hour. The pilot the drone to be at least 16 years of age who shall possess a remote pilot certificate or be directly supervised by someone with such a certificate. The competency of the operator must be demonstrated by qualifying for a remote pilot certificate through aeronautical knowledge or holding an existing non-student *Part 61 pilot certificate*. However, the rules do not particularly deal with the privacy contravention issues of the UAVs (*Press Release – DOT and FAA Finalize Rules for Small Unmanned Aircraft Systems*, 2016). FAA has proposed a new rule pertaining to Remote Identification (Remote ID), which has been finalized after public feedback, where the UAV will be required to be equipped with standard Remote ID technologies (*Remote Identification of Unmanned Aircraft Systems*, 2019). However, FAA does not require any hands-on expertise and prior experience to gain the pilot certification, which raises the question of safety understanding of UAV operations. Despite being instructed to be flown over unpopulated areas, construction sites are typically densely populated, and these variables heighten the possibility of a risky scenario and increase the likelihood of damage.

2.7.1 Flight over People and Structures

Initially, FAA set the requirement of flying UAVs only over unpopulated areas, which must be accompanied by the operator's Visual Line of Sight (VSOL). Initially, FAA imposed a 2-step verification and certification process of the operable UAVs to be allowed in the National Air Space (NAS). The users must have obtained an airworthiness certificate followed by a waiver (Certificate of Authorization, COA) pertaining to the UAVs' operability and collision avoidance capabilities (Loh et al., 2009; Office of Force Transformation, 2002). A person who is not beneath a safe cover, such as a protective building or a parked vehicle, is prohibited from flying a small UAV straight over them. However, the final rule issued by the FAA allows the operation of UAVs over people, vehicles, and night-time under specified conditions, without obtaining a waiver. When allocated and advised by the Remote Pilot in Command (RPIC), a small UAV may be flown above an individual who is directly engaging in the control of the UAV, such as the remote PIC, another person manipulating the controls, a visual observer, or crew members of the flight, who are considered essential for the UAV's safe operation. The eligibility of such operation of flying over people is categorized into four different criteria.

For category 1, the drone must weigh less than 0.55 pounds (with all onboard accessories) and have no exposed revolving part capable of lacerating human skin. Category 1 eligibility does not require the waiver or airworthiness certifications. In addition to the restriction of category 1, categories 2 and 3 impose additional performance-based qualifying requirements for flying drones above persons weighing more than 0.55lbs and not possessing the airworthiness certificate under part 21. Category 2 restricts a remote pilot in command may from flying drones above people gatherings in the open air. However, category 3 clarifies that the pilots are allowed to operate the drones over people only if it is within or over a secure or restricted-access site and the people have a visual of the drone above them. Category 4 enables flight over persons with operational limits as defined in the authorized flight manual or otherwise by the Administrator. In addition to the operation over people, the new rule enables operations over moving vehicles as well.

Further operating limitations for small UAVs restrict them to fly faster than 87 knots (100 miles per hour). Small UAVs cannot fly higher than 400 feet above ground level (AGL) unless within 400 feet of a building and not more than 400 feet above the tallest point of the structure (Figure 7). The minimum visibility or visual line of sight (VSOL) should be measured from the pilot's position, which needs to be at least three statute miles.

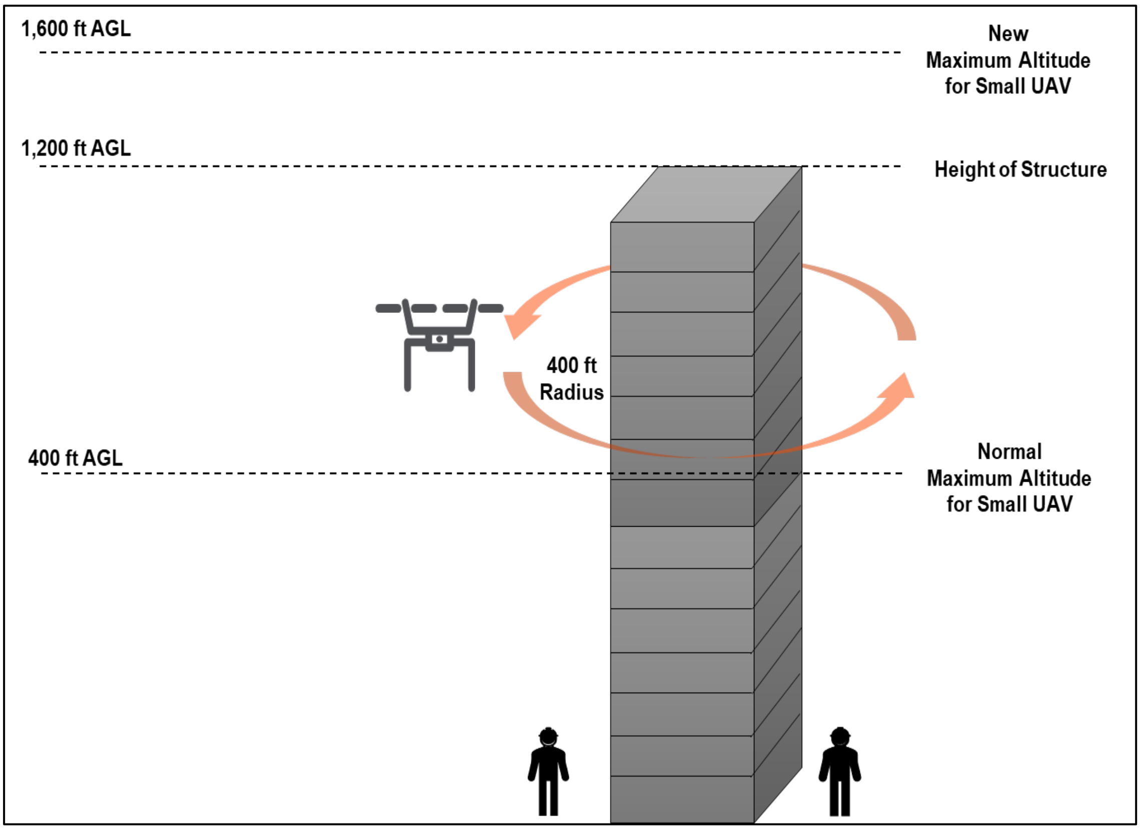
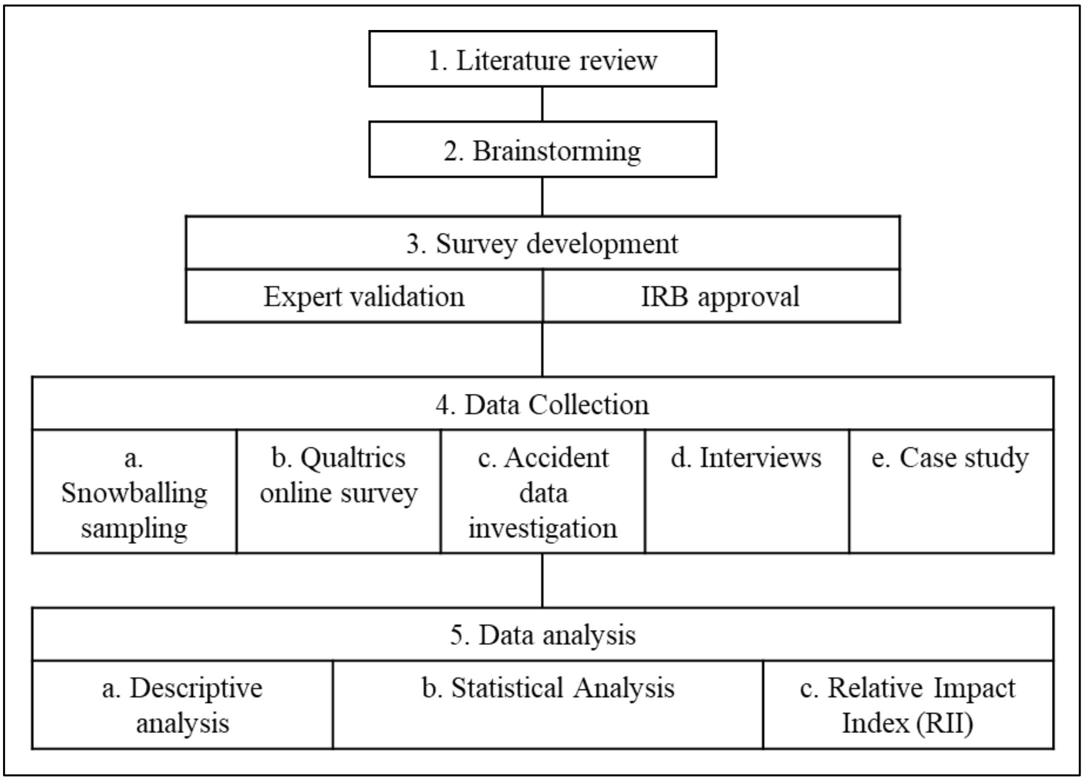


Figure 7: Permissible drone trajectory around structures.

CHAPTER 3: RESEARCH METHODOLOGY

Drones are expected to change the way we think about and understand construction productivity as they proliferate worldwide. However, not all of the changes brought about by the worldwide proliferation of drones will be beneficial. UAVs are relatively a new addition to construction applications. The safety limitations and risks are not entirely understood by the relevant project people, which leaves the safety risks of these flying gadgets to our vivid imagination. Therefore, extensive research must be conducted to ensure that the existing regulations governing the UAV systems' safe design, manufacturing quality, maintenance procedures, and operational viabilities are well-defined to ensure that the safety objectives are fulfilled (Clothier & Walker, 2006).

The use of drones in the construction industry may pose a number of safety concerns and that have not yet been adequately addressed. Drones bring with them a new set of hazards and difficulties that must be addressed to curb the chances of unintended accidents from happening. The research study aims to intervene in the paradigm of safety risks and hazards associated with adopting UAVs in the construction sector. In order to accomplish the objectives, the research was planned and executed in multiple stages, as presented in Figure 8, involving literature reviews, questionnaire survey, analysis of the recorded data, and the development of UAV-Construction safety training.



3.1 Literature Review

A holistic and systematic search method was adopted to find relevant literature from the internet database, followed by a comprehensive review. The review was expected to produce information pertaining to drone adoption trends and sectors of concentration required to improve safety effectively. The review revealed multi-layered safety threats introduced by drones that need appropriate safety and strategic management techniques for risk minimization.

3.2 Industry Collaboration and Brainstorming

In order to strengthen the study's applicability, the study sought industrial collaboration and professional assistance from Kevin Capps of S.T. Wooten Corporation, who holds the role of "UAV Mapping Specialist." Kevin is a commercial drone operator who possesses the FAA remote pilot license. In addition, he has over 15 years of construction surveying experience, especially in North Carolina. He was asked to participate as a research advisors for this project, and he provided practical insights that have proven to be pivotal. Furthermore, a brainstorming session took place among the research team members to develop a guiding track and possible outcomes for the study. It was added by the research advisor that he personally experienced a drone-related accident due to battery malfunction, which did not claim any injury but had the potential to descend from the sky and collide with workers on the ground.

3.3 Questionnaire Survey Design

A questionnaire survey was created to extract the operational and behavioral parameters from a construction viewpoint in order to move forward in studying the safety risks associated with UAV deployment. Various types of questions reflecting the assessment of the associated safety risk factors, worker behavior, and construction productivity were outlined in the questionnaire and classified into several aspects for comprehensiveness. Initially, based on the experts' guidance, opinion, and validation, the questionnaire was designed with an advanced and logic-specific collection of questions to extract helpful information directly connected with the original study purpose.

3.4 IRB Approval

The questionnaire surveys were evaluated by research advisers and subject matter experts. It was tailored to the study's objectives and their applicability. The questionnaires were updated and submitted for evaluation and approval to the University and Medical Center Institutional Review Board (UMCIRB). The surveys were authorized as "exempted," allowing them to be distributed to the people deemed suitable for this study.

3.5 Data Collection

Despite the plan to conduct the data collection efforts in-person, certain measures had to be adopted to limit exposure to COVID-19 which led to the data being collected online. By searching the internet resources and evaluating the characteristics of their expertise in construction and UAV applications in the sector, the contact information of study respondents was systematically compiled. Due to a lack of UAV-related information in the construction industry, the study was aided by the use of the snowball selection method to relay the online survey, which is rather a common method used by construction-related research studies (Loosemore & Malouf, 2019; Öney-Yazıcı & Dulaimi, 2015). A non-probability sampling approach is defined as snowball sampling or chain-referral sampling. The construction projects all across the United States were randomly selected for the online survey based on their involvement with UAV technologies, and no specific active construction sites were visited for data collection purposes. The complete survey included 63 individuals from diverse construction organizations and their UAV system integrators. Nine individuals only partly provided feedback, so their responses were disregarded as incomplete and were not included in the final analysis of the data. The remaining 54 (sample size) individuals shared their safety perceptions and experiences regarding UAV-related incidents. They also answered seven questions concerning demographic and professional information, such as their age, experience, job, location, and type of project, as well as their safety training and drone pilot credentials. To comprehend the background of the participants, their pertaining demographic information was compiled. The data can be seen in Table 2 and Figure 9.

Table 2: Participants' demographic (designation, certification, age) information

Designation		Certificate/license		Years of experience	
Project manager	5 (9%)	OSHA 30	15* (28%)	0–5 years	24 (44%)
CEO/owner	11 (20%)	OSHA 10	13* (24%)	5–10 years	8 (15%)
Project engineer	7 (13%)	OSHA 10 and 30	7 (13%)	10–20 years	9 (17%)
Safety specialist	3 (6%)	No OSHA training	35 (65%)	20–30 years	4 (7%)
UAV specialist	6 (11%)	FAA license	34 (63%)	>30 years	9 (17%)
Other managerial	9 (17%)	No FAA license	20 (37%)		
Other destinations	13 (24%)				

Note: CEO = Chief Executive Officer; FAA = Federal Aviation Administration; OSHA = Occupational Safety and Health Administration; UAV = Unmanned Aerial Vehicle; * 7 (13%) of the participants had both OSHA 10 and 30.

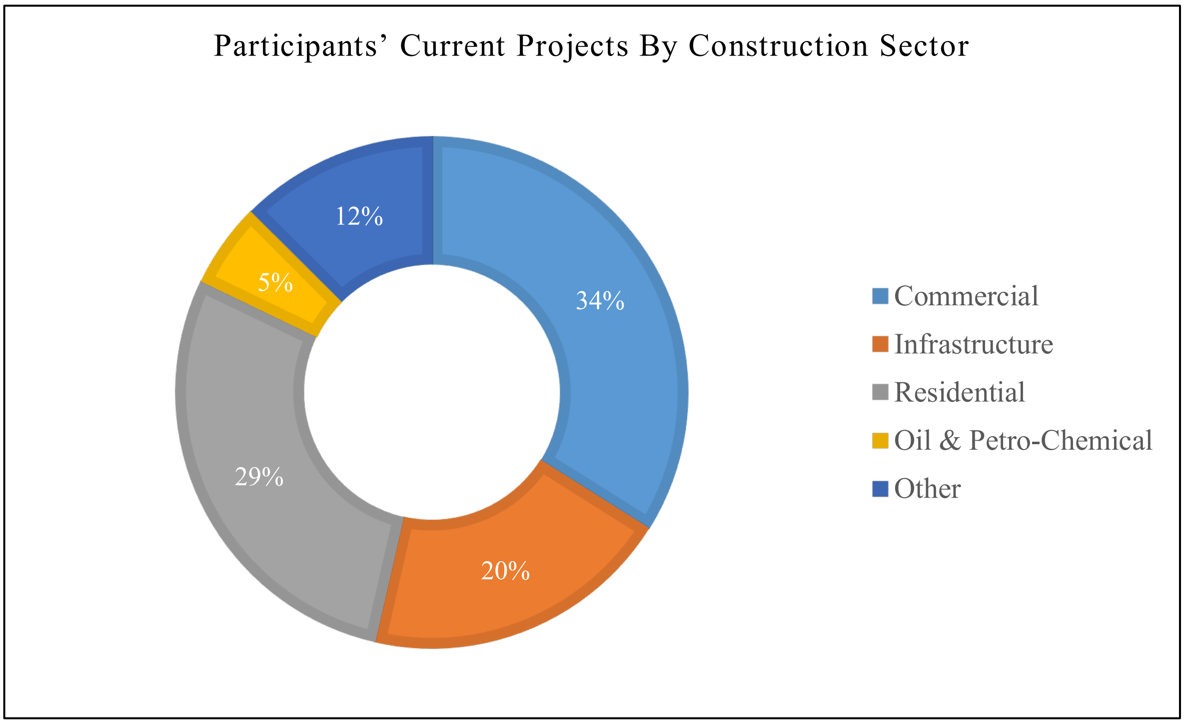


Figure 9: Participants' current projects by the construction sector.

3.6 Accident Data Investigation

The study also looked into the National Transportation Safety Board's (NTSB) Aviation Accident Database to see whether there was any relevant information on drone incidents. The objective of this investigation was to identify the contributing factors depicted in Figure 10. The NTSB database is the official repository of recorded accidents. Accidents are investigated by the FAA in order to maintain operating safety. However, the detailed investigative reports are prepared by NTSB. However, the research outreach was unable to get a clear understanding of the entirety of the database, specifically pertaining to drone-related accidents. Only three reports were chosen to investigate and describe the relevant variables that could aid in gaining a better grasp of actual contributing factors in reported accidents.

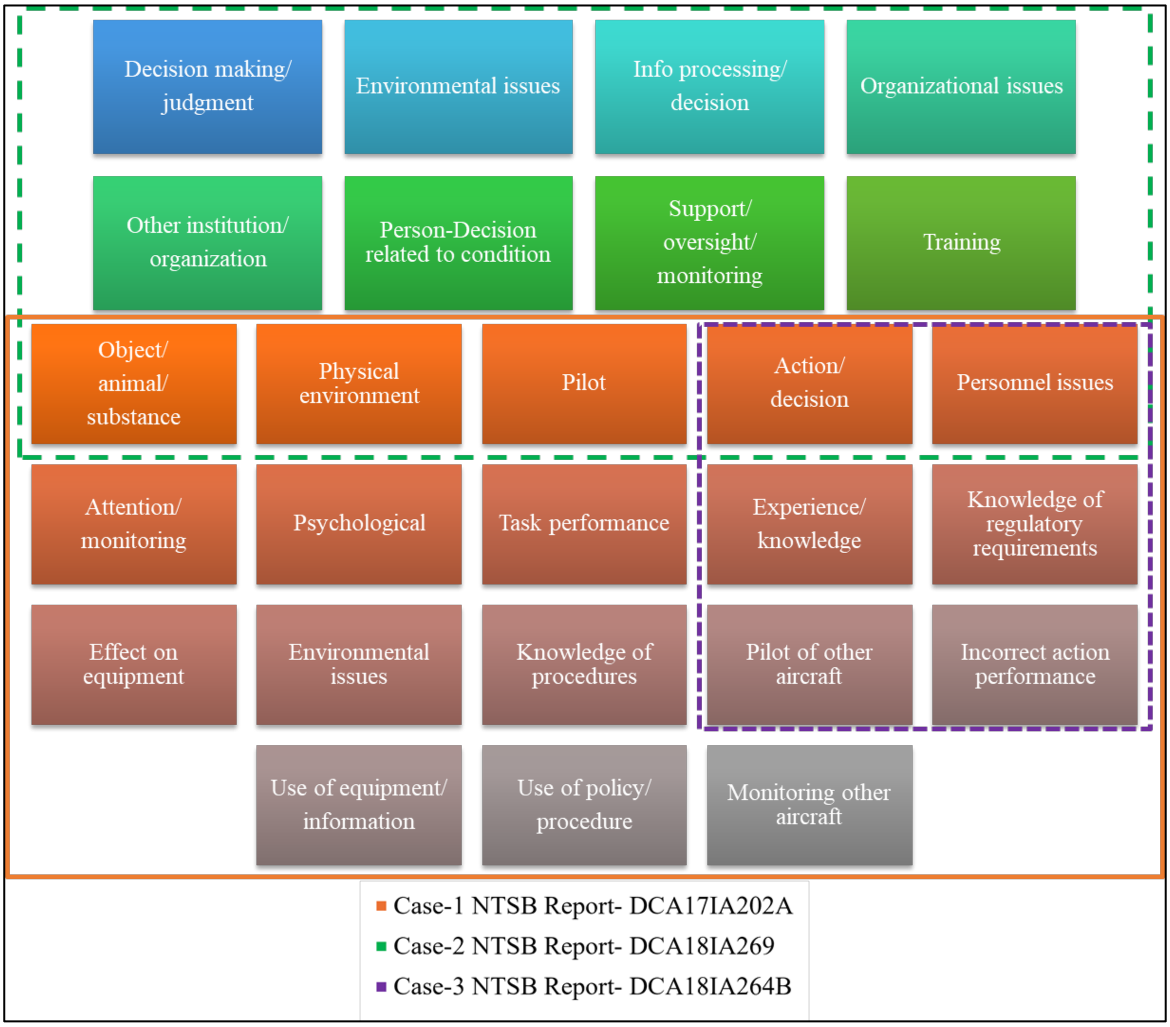


Figure 10: Data from the National Transportation Safety Board (NTSB) demonstrating important contributing factors in reported UAV accidents.

Figure 11 depicts the number of contributing factors for each case and the number of injured persons in each drone mishap case.

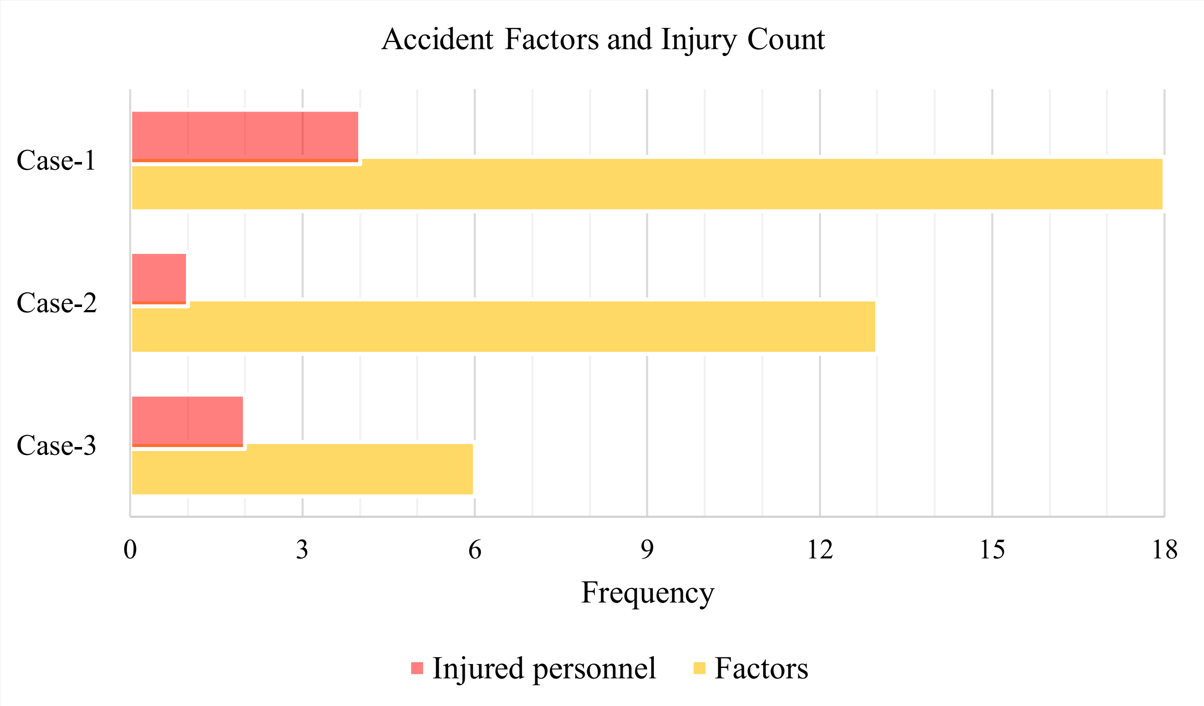


Figure 11: Accident contributing factors and involved injured personnel count.

The data was identified in NTSB's database, not by selecting the category 'drone' or 'UAV' because the accident database does not contain such options. Therefore, the keyword 'DJI', the name of a popular drone manufacturing brand, was used to search for related accidents.

3.7 Development of the UAV-Construction Safety Training

To reduce the safety hazards posed by UAVs in the construction environment, a comprehensive safety training program based on FAA-approved safety and strategical drills have been designed. By definition, the implementation of UAV-based safety management is a comprehensive method to managing health and safety that includes frameworks, governance, policies, and practices. Incorporating comprehensive safety management with the support of appropriate training and education may positively impact many of the potentially dangerous scenarios associated with UAVs. This training program aims to deliver hands-on strategic planning and action sequences in terms of UAV operation at most construction sites. This training recollects the study's key findings and allows an instructional approach to working-class construction employees through the development and presentation of checklists, animated videos, pictures, and case studies. A pre-survey and post-survey will be conducted with the training based on their grouping arrangement to figure out if the learning outcomes from the training were effective. The training focuses on equipping the workforce with the necessary knowledge and strategic approaches. Moreover, it improves the likelihood of ensuring everyone involved with the small UAV operation is aware of the operating conditions, emergency procedures, possible hazards, and roles and functions of each individual participating in the operation. As shown in Figure 12, the elements of the training program are categorized into three modules. Breaking down the program into multiple modules based on a typical drone operation sequence would help the construction workforce better understand and prepare to manage the safety risks more effectively.

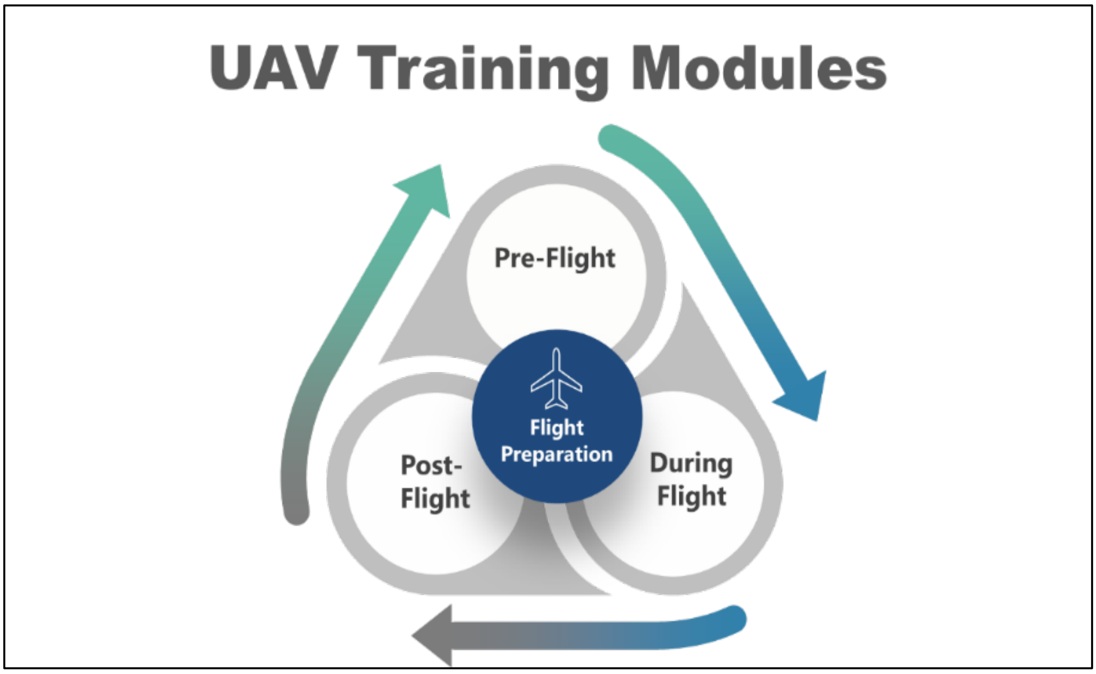


Figure 12: UAV-Construction safety training modules.

CHAPTER 4: DATA ANALYSIS AND RESULTS

4.1 Descriptive Analysis

Participants were invited to submit information regarding their drone-related experiences on construction job sites for various activities, accidents, predicted hazards, and safety precautions in a questionnaire survey. The interviewees were requested to assess the severity of a variety of drone-related risks, and the average ratings for every safety concern were computed, which is illustrated in Figure 13. The statistics clearly indicate that using drones in construction entails a considerable risk of mishaps.

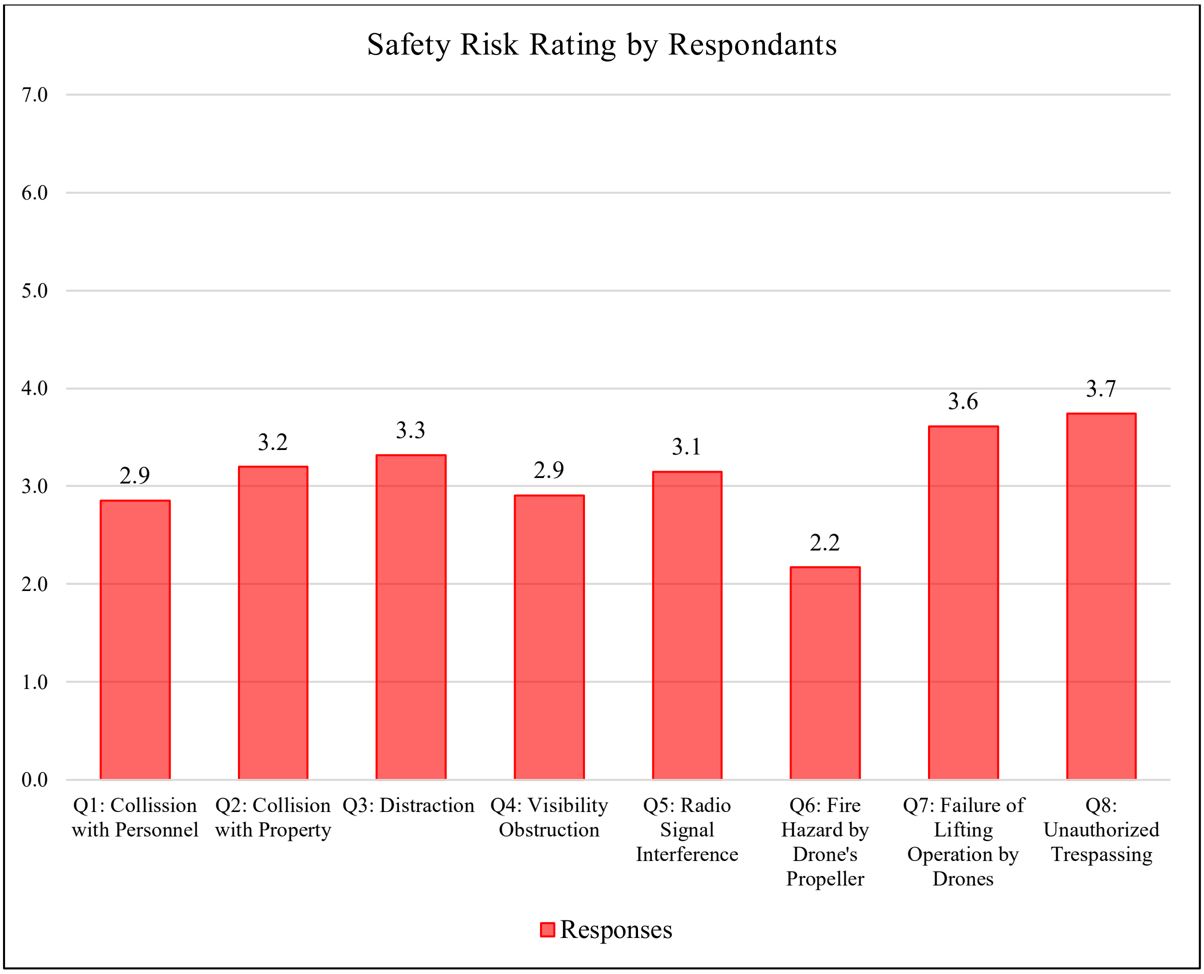


Figure 13: Average risk rating for each of the eight survey questions.

4.2 Relative Impact Index (RII) Calculation

In addition to the descriptive analysis, Equation 1 was used to compute the Relative Impact Index (RII) for each safety risk. The RII technique is a basic but frequently used method for examining and evaluating the effects of various variables.

$$RIIi = \frac{\sum ni = 1Wi}{(AN)} \quad (1)$$

Where,

W = sum of all ratings of participants for each question;

A = highest possible score (7);

N = number of recorded responses for each question.

This approach has been used in a number of construction safety research projects to date (Namian, Albert, et al., 2016). RII ratings are standardized and simple to understand, ranging from 0 to 1, with 1 indicating the greatest influence for a specific component. Table 3 lists the assessed safety hazards in order of their importance, from highest to lowest. Based on some exposure, relative risk determines whether an occurrence is more likely or less likely to occur. In addition, the rank indicates which hazards are more likely to occur compared to others in the same group. Also, it is one of the most effective techniques of presenting study findings to assist construction practitioners in prioritizing the risks and making more informed decisions.

Table 3: Calculated and ranked safety risks and their Relative Impact Index (RII).

Rank	Safety Risks	RII
1	Unauthorized trespassing and collection of sensitive information breaching the personal property rights	0.534
2	Drones capable of conducting lifting operations creating the risk of malfunctioning and crashing, or falling onto person or property	0.516
3	Distraction causing loss of concentration and erroneous maneuvers of the construction equipment resulting in severe accidents	0.474
4	Collision with property causing damage to the assets and surrounding personnel	0.457
5	Interference of radio signal causing communication hazard	0.450
6	Obstruction of the vision during critical lifting or installation operations	0.415
7	Collision with working personnel causing bodily injury	0.407
8	Rotating blades of drones causing a fire hazard in the controlled environments	0.310

4.3 Statistical Analysis

Further review of the data indicates that 22% of the surveyed participants had OSHA 30 or 10. And 13% had both trainings, which leaves 65% of the participants who did not receive any sort of safety training (Figure 14).

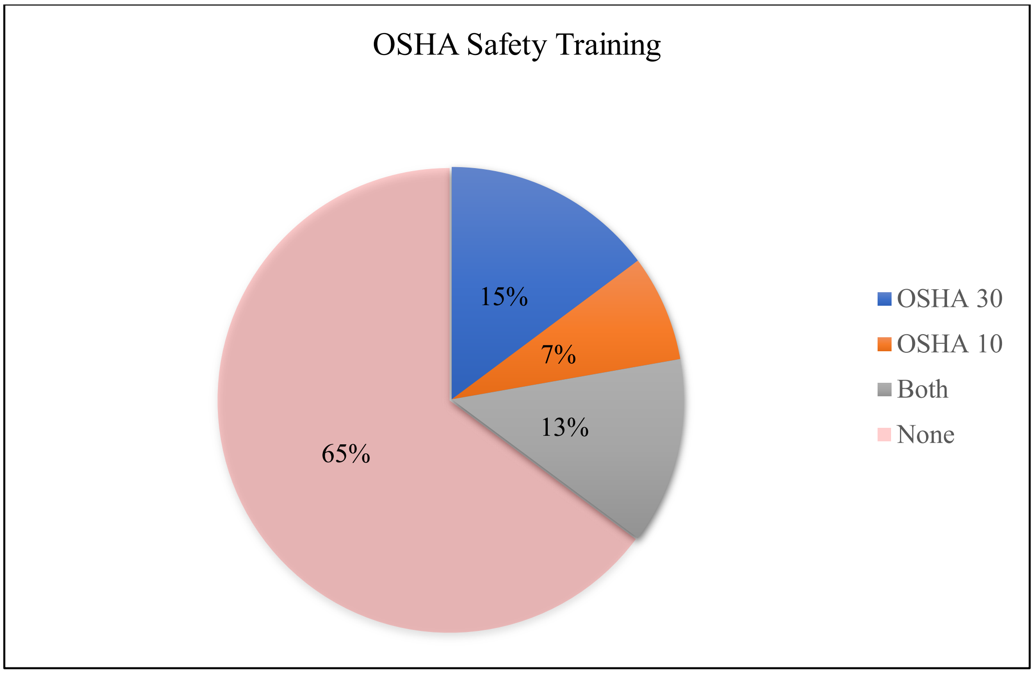


Figure 14: Percentage distribution of participants with OSHA training.

Figure 15 reveals that individuals who received safety training reported a higher threat level than those who did not receive any form of safety training. A statistical approach for t-test for two independent samples was adopted to determine the significant difference. When the risk perceptions of two groups of individuals were compared using a two-samples t-test, only distraction (Q3) (p-value 0.1) showed a statistically significant difference (Figure 13). Specifically, the data clearly indicates that the individuals with both safety training have specific perceptual differences than the participants without or any one of the safety training (OSHA 10 or OSHA 30), which potentially enabled them to contemplate more risk-taking situations. Participants who had received safety training were able to apply a portion of their newly learned information, which might have been generalized, to assess drone-related safety hazards to some extent.

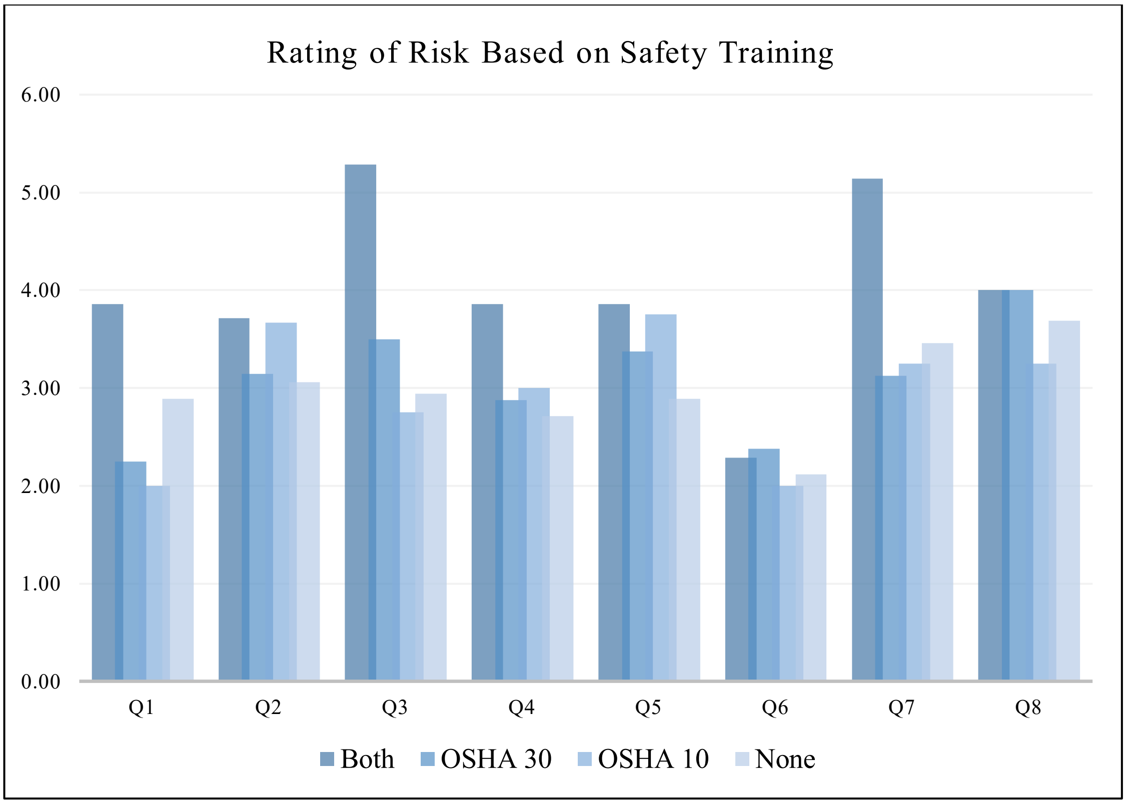


Figure 15: Risk perception based on obtained safety training.

On the other hand, drones might introduce specific and distinct risks that necessitate the development of advanced safety training, especially for the construction industry. Similarly, the data were analyzed based on the factor of having an FAA operating license, which is regulatory compliance with flying drones at the commercial capacity. Only 37% of those who took the questionnaire survey possessed an FAA pilot license to operate drones. The total number of recorded responses was pooled and statistically evaluated using a two-samples t-test based on the factor of holding an FAA license, which indicated a significant difference (p-value < 0.0001) in the respondents' risk assessments. As a result, the responses to each question were statistically examined to determine whether there were any disparities throughout them. Their risk perception rating was analyzed, and the variations are shown in Figure 9.

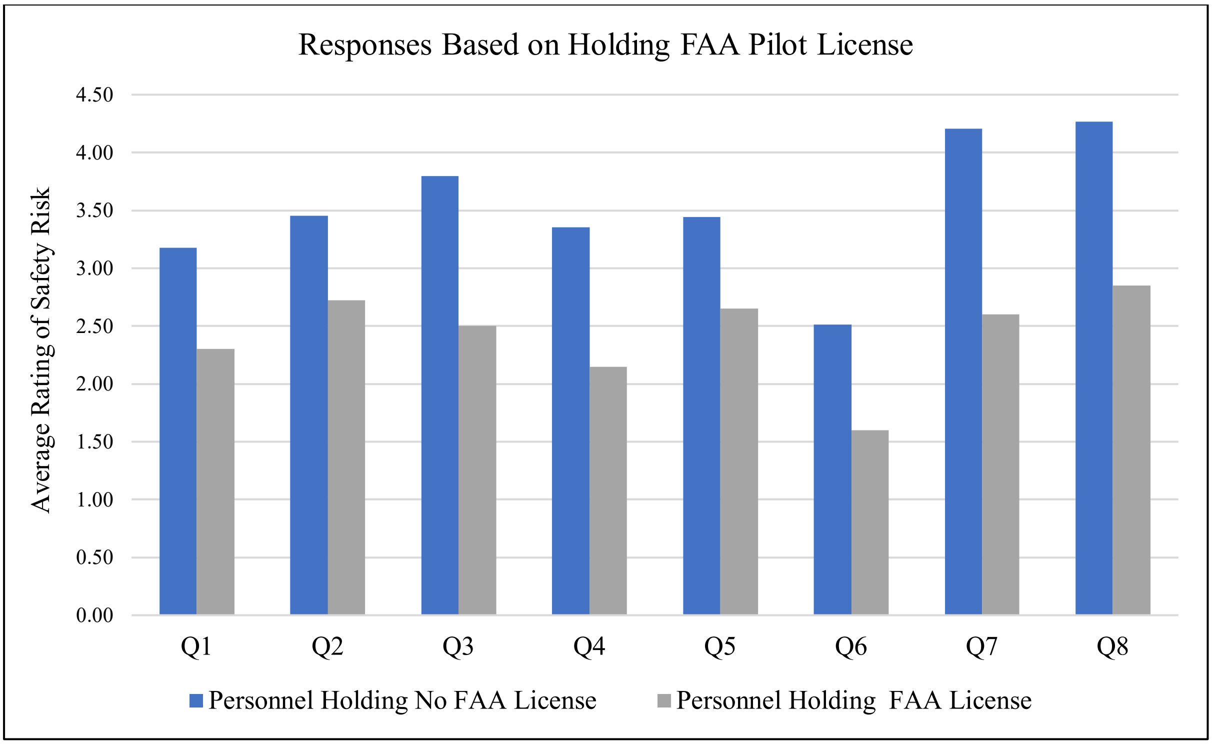


Figure 16: Participants' risk perceptions based on their possession of an FAA pilot's license.

The survey was designed to categorize the participants based on numerous factors, and attention was given to identifying any difference in their drone-risk perception based on their first-hand experience with drones. Practical usage of drones in construction was found to be common among the participants, with 54 percent having direct experience in the operations. Participants' risk perceptions were compared between those who had no prior experience with drones and those who had direct encounters with drones. The results of the data analysis in Figure 17 reveal a variation in risk perception between individuals who have had direct experience with drones and those who have not.

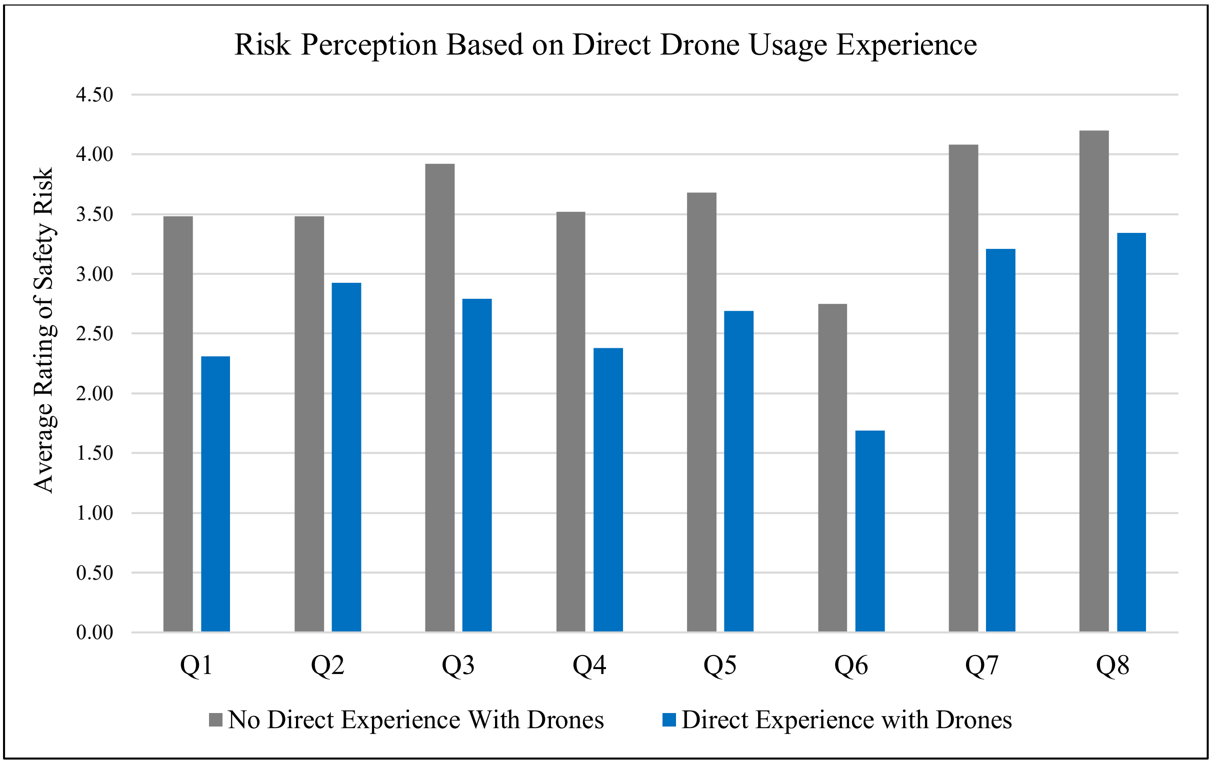


Figure 17: Risk perception based on drone usage experience.

Participants were also questioned if they had been involved in any mishaps when utilizing drones in workplaces. According to Figure 18, 16% of the participants agreed that they have encountered or witnessed accidents that may be linked to drone-based operations in the construction environment. Compared to other construction-related accident rates, this is a significantly higher rate (Dong et al., 2015). Besides, 17% of the total participants agreed that they have heard about drone-related accidents via their professional networks.

Percentage of participants with accident experience

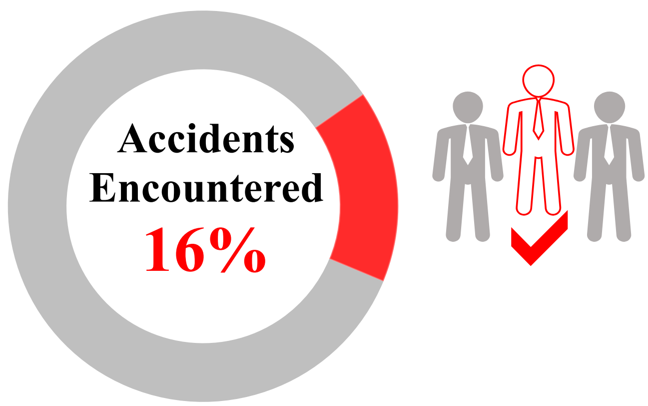


Figure 18: Percentage of participants with accident experience.

The data collected from the survey were examined for any possible pattern between participants' age range and perception of safety risks. Moreover, the groups were separated on the factor of holding FAA remote pilot license. Figure 19 depicts that there is a distinct variation in the rated safety risks based on their years of experience in the construction environment. The interpretation suggests that individuals with up to the first two years into the on-site construction experiences perceived a higher than average level of risk with drone-based applications. The chart also reveals that construction or drone pilots are outside the norm of receiving any license through the FAA to engage in drone operations.

Similarly, relatively higher risk perception was identified with the participants who had spent more than ten years in the construction. When the data was examined more extensively, it was shown that the risk perception levels are positively connected to their specific range of years in construction. The risk perception tends to rise upward from the point of 5 years of experience and beyond and up to 40 years of experience. This pattern may indicate a few trends in the construction sector, such as professionals up to their first 2 to 5 years in construction not being in the practice of acquiring FAA remote pilot license. Similarly, professionals with 40 or more years of experience in construction have shown the trend of receiving no FAA remote pilot license.

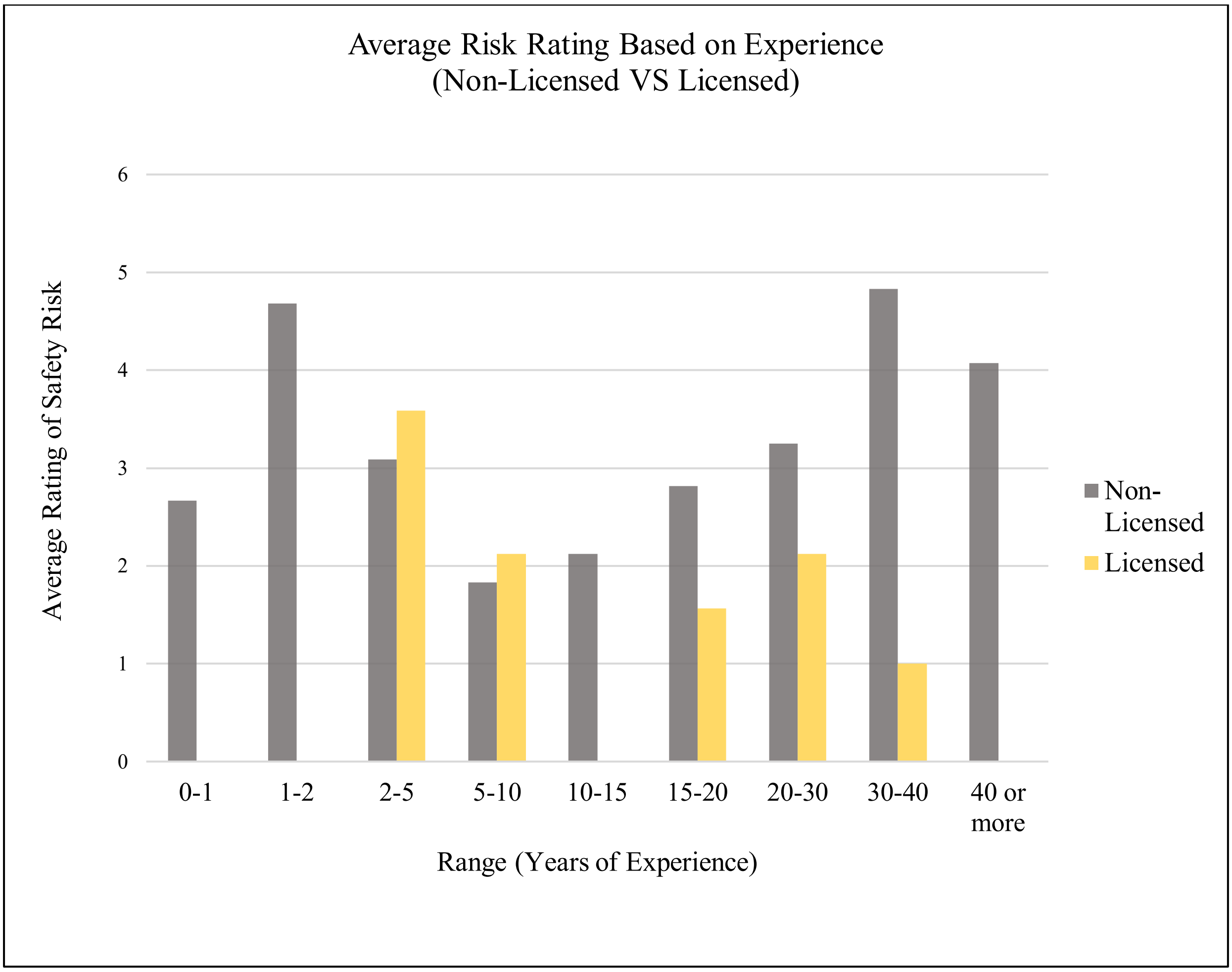


Figure 19: Average risk rating based on years of experience and FAA license.

Further analysis had been initiated to explore the types of accidents experienced on the construction job sites and the contributing causes. Figure 20 depicts various types of accidents recorded through the questionnaire. Data suggests collision with properties (67%) to be the most common category of accident that the construction personnel has experienced. Collision with properties (67%) is followed by collision with personnel (22%) and distraction leading to injuries to the site personnel (11%). In order to understand the contributing causes behind these accidental outcomes were taken into account for further examination.

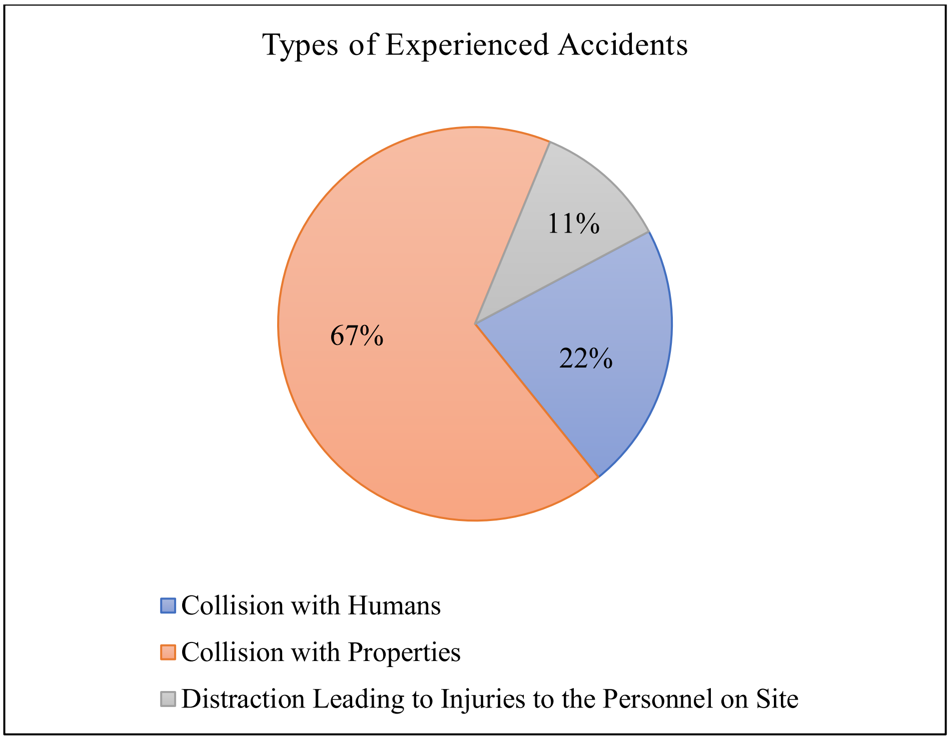


Figure 20: Types of experienced drone-related accidents.

Figure 21 presents the percentages of underlying causes behind the accidental scenarios that were generated within the construction environment. As indicated by the data, the two most rated causes were chosen as system malfunctions (33%) and loss of control (25%). In addition to these, adverse weather or atmospheric conditions (17%), flight crew error (17%), and lack of planning in-flight operations (8%) were also identified as the causes behind the accidental outcomes in construction workplaces. It is evident from the collected data and investigated reports that the drone-related mishaps in the construction environment can be contributed by more than one cause.

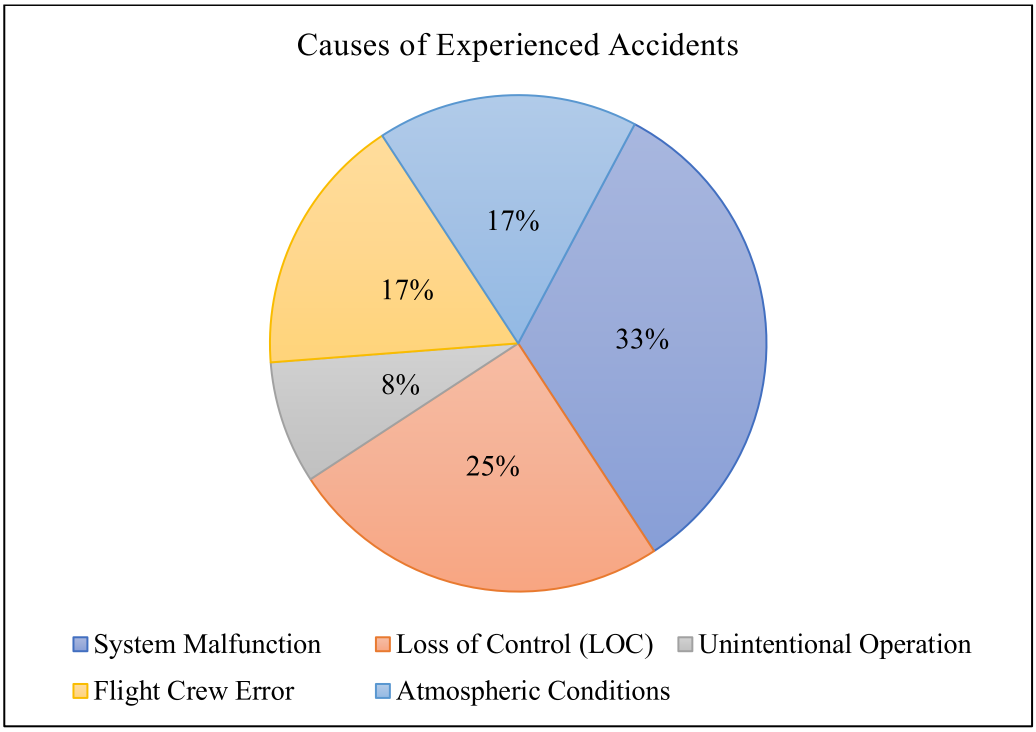


Figure 21: Contributing causes of experienced drone-related accidents.

Participants were asked to identify the projected accident frequency based on the consequences and causes of the scenarios presented in the survey. The data shown in Figure 22 indicates that the most projected effect and cause of drone-related accidents are projected to be the collision with properties and external interferences, respectively. There were no new safety risks recorded from the participants' ends other than those presented to them.

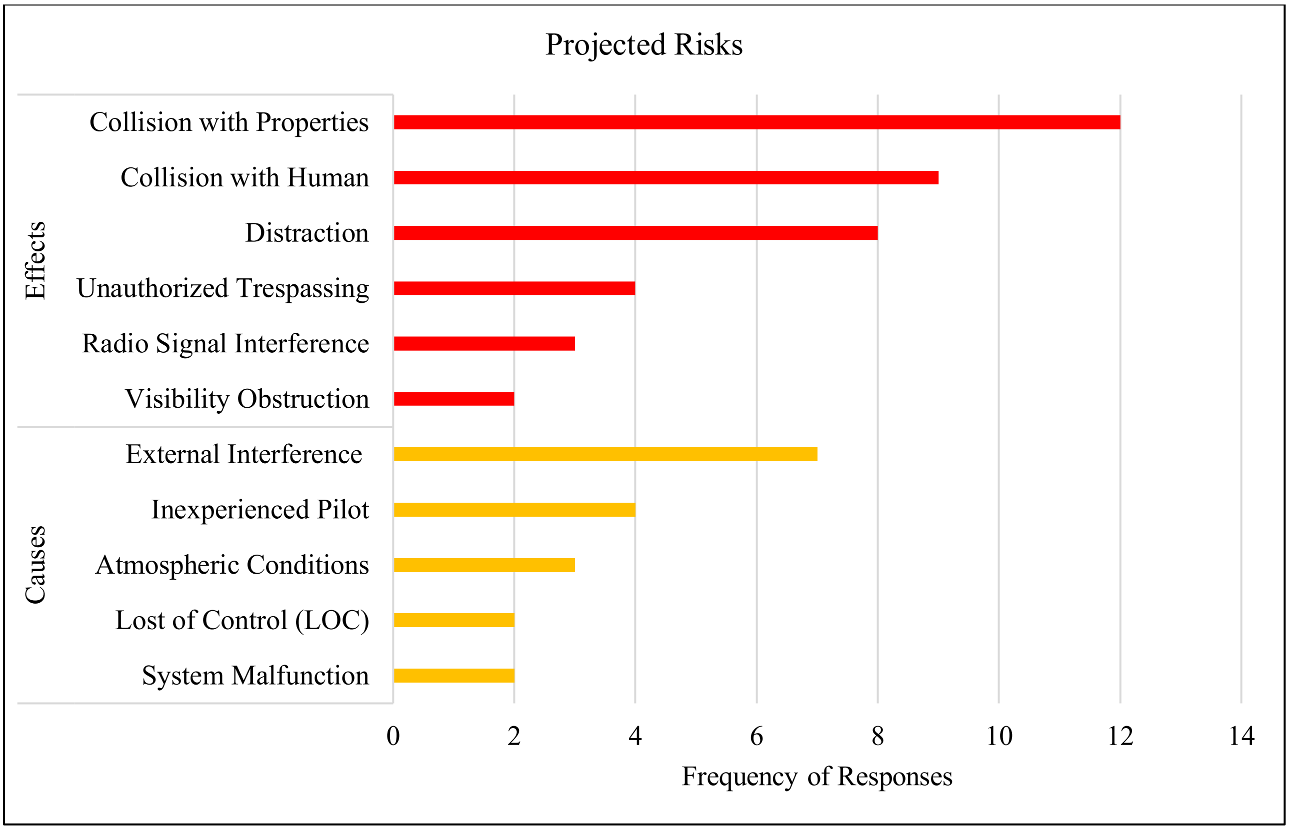


Figure 22: Frequency distribution of drone-associated projected safety risks.

The survey further asked the participants to share their suggestions on the preventive actions that could potentially reduce and bring the drone-related safety risks to a manageable level. This question was sequenced at the final part of the survey in order to familiarize the participants with the relevant risk scenarios and consider all of them to suggest the best possible preventive measures. According to Figure 23, based on their personal experiences, 53% of the participants chose various preventative methods that they feel may be used to mitigate the possible threats linked with drones. The feedbacks were categorized into 15 countermeasures based on resemblance, duplication, or distinct phrasing. The results indicate that the top three most preferred prevention strategies are "qualified and competent flight crew," "proper model selection and maintenance," and "communication and awareness."

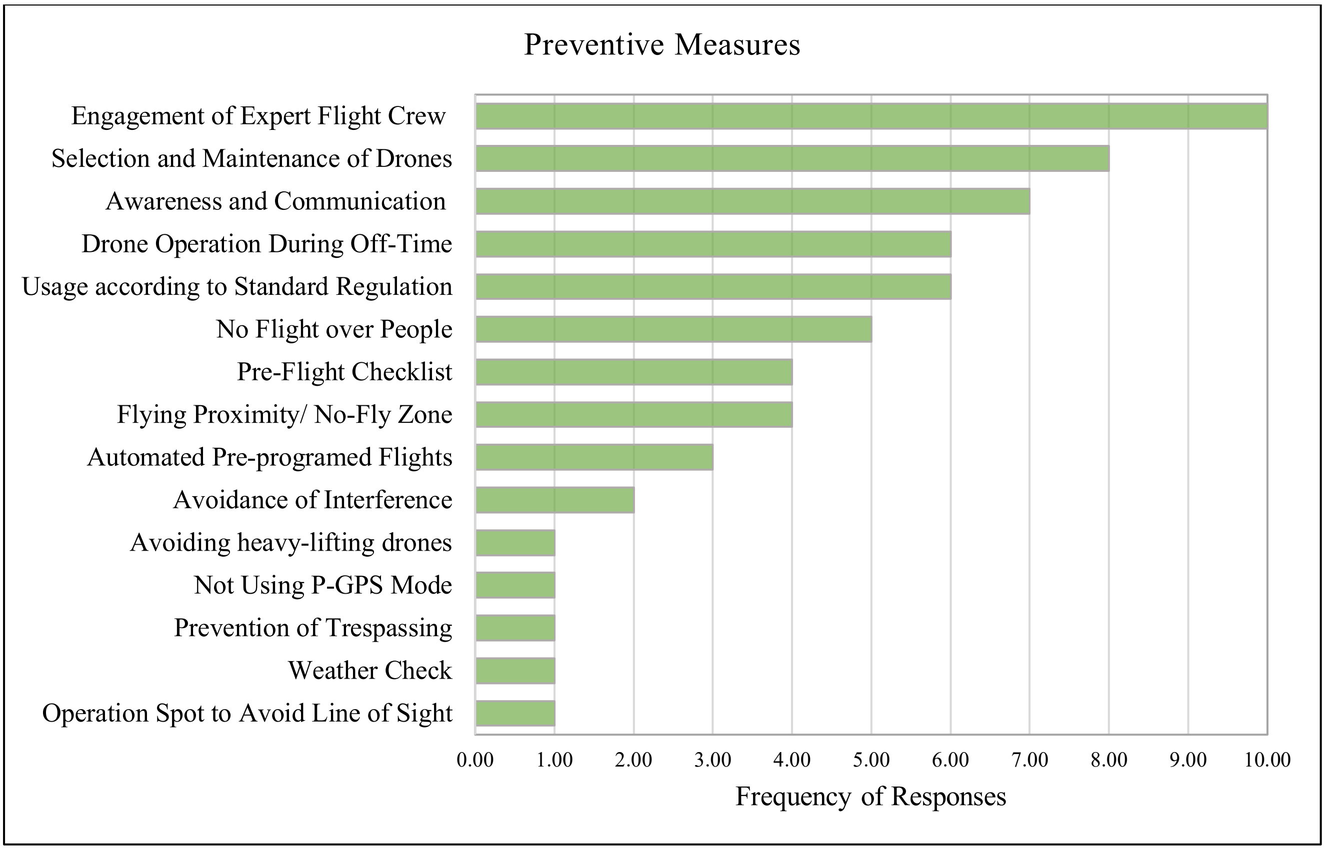
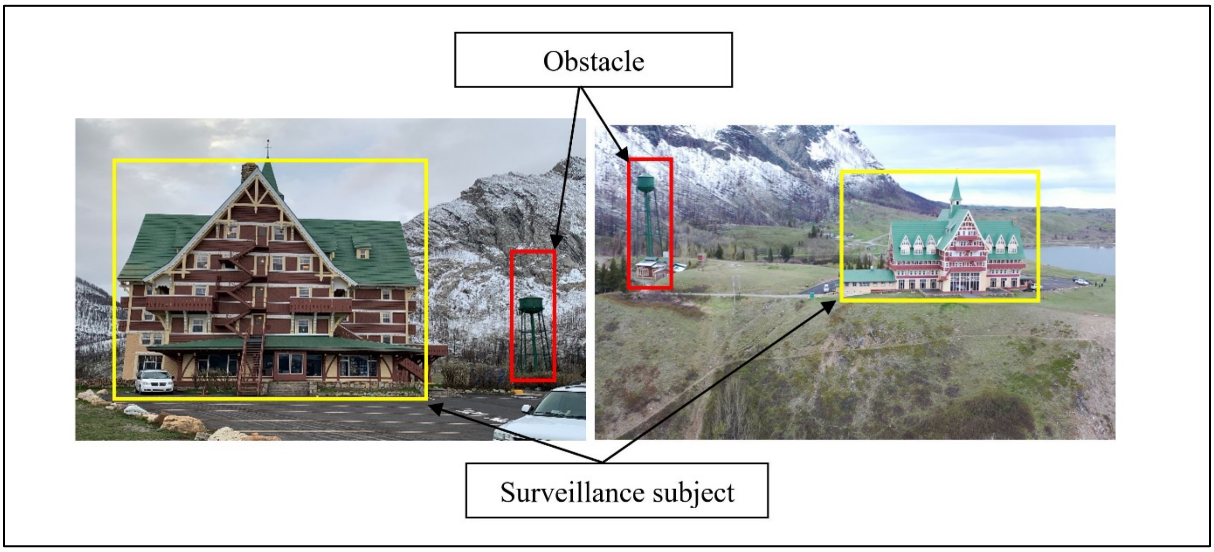


Figure 23: Participants' evaluations on preventive measures.

These are the actual data from the construction workforce that represents the realistic need of the industry to manage UAV-associated safety risks. The findings of this data have been utilized to produce safety training centered on UAV-construction interactions and their complexity.

CHAPTER 5: POST-HOC CASE STUDY

This study has been progressed in the manner of exploration, and during the process of that, an important piece of information was recorded in the survey. The participant was contacted further to share more details about the incident, which took an unexpected turn during a drone operation over a hotel. Based on the information provided, identification of the subject of surveillance and obstacle (Figure 24) was completed to advance with the case study.



A drone service agency initiated a flight operation over the hotel area located in North America. The purpose of this mission was to acquire aerial surveillance on a hotel. The flight crew designed their flight route in advance by the book but essentially missed out on a massive water reservoir tower that could have come within the flying trajectory. The UAV collided with the reservoir tower during its circling maneuver, leading to various operational difficulties and major damage to the UAV, as seen in Figure 25, the last registered footage from the UAV before the impact with the reservoir.

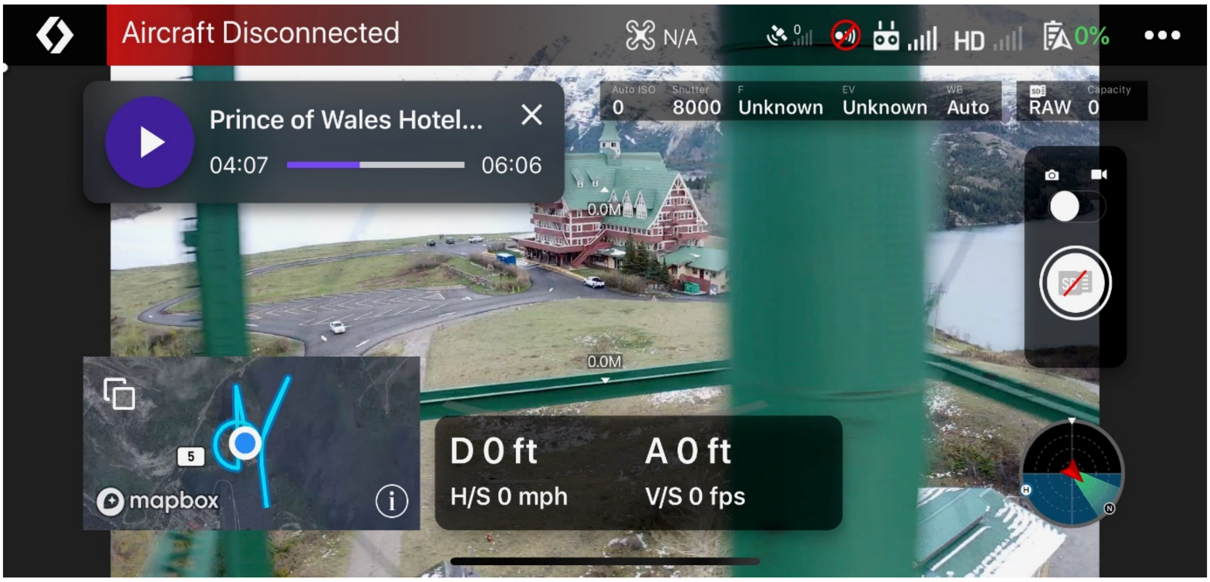


Figure 25: Last retrieved footage from the UAV system. Image Credit: anonymous source, included with permission.

As a result of the UAV's catastrophic impact with the tower, the incident generated a series of accidental outcomes including, 'loss of control' from the pilot, immediate 'flight termination', and 'falling object' from the sky. Fortunately, there was no one present at the crash site, which otherwise could have been threatening to the personnel. The severity of the hazard can be seen from the retrieved drone in Figure 26. The drone was severely damaged, and parts were dismembered (battery, airframe, and rotor-blades) from the original unit.

Figure 26: Wreckage of the recovered drone from the crash site. Image Credit: anonymous source, included with permission.

The case study indicates that the obstacle identified in Figure 24 was fairly visible in the line of sight of the flight crew. However, failure to incorporate it within the complete flight planning. As a result, the accident occurred in the absence of the flight crew's prior hazard recognition and safety risk perception to anticipate probable mishap situations. The case study adds significant knowledge to the research related to drone and construction safety. Furthermore, recommendations can be drawn from this case study to restrengthen drone-specific hazard recognition and safety risk perception procedure within the construction job sites to prevent such accidents from happening.

CHAPTER 6: CONCLUSIONS

Military, academics, researchers, and recreational users have comprised the bulk of UAS users in the previous decade. To get the most out of this technology, these users need to explore and understand what to expect in terms of operational performance and the development of UAV applications. A growing body of research has focused on the beneficial sectors of drone technology and has successfully advanced in innovating cutting-edge developments. In contrast, there is a deficiency of research on the operational complexity of drone deployment. The focus of this research was to highlight the practical difficulties of drone deployments to enable construction researchers and practitioners better grasp the range of factors that must be considered before and during drone flights on the job sites. This study has been advanced through the investigational techniques for determining the critical risk factors related to UAV mass integration and quick adaptation in the construction environment. It further examines commercial uses of drone technology across the construction sectors to evaluate its effect on the safety performance of the workforce. Federal Aviation Administration (FAA) has enacted rules requiring pilots to complete knowledge tests for the new pilots as well as recurrent training periodically for the existing license holders before being allowed to fly in specific areas and beyond visual line of sight (BVLOS). The updated FAA requirements cover a broader range of public and offer a better level of safety assurance, but the construction industry falls between the cracks, necessitating an organized and effective safety framework for risk management. The research has been aimed toward creating a specifically prepared questionnaire survey presented to the construction sector workforce to analyze and extract essential information about drone usage. The questionnaire emphasized issues such as participant demographics, drone-related familiarity, training, certification, risks, privacy, ethics, and safety viewpoints. Based on the responses collected, the data was evaluated, and the results were interpreted to focus on the urgent risks that stakeholders must address for further action. In addition, designated officials from different regulatory and safety agencies were contacted in order to gather drone-related accident information and determine whether instances may be included for further investigation. Based on the study's findings, a detailed UAV-Construction training program aimed at the construction sector will be developed to accommodate the complex dynamic encounters between UAVs and construction operations, with the goal of increasing drone familiarity and safety planning.

Drone-powered applications are not merely emerging flash trends in the construction industry. Drones outfitted with cameras and sensors provide businesses with more significant and detailed insights into their operations, as well as the strengths and weaknesses they confront. The technology has to offer a plethora of opportunities to construction productivity and contribute to other important aspects such as safety, efficiency, security, and project delivery. This opens up an area for construction researchers and practitioners to develop on the current features and improve the beneficial outputs of UAVs to an advanced level. However, while talking about the continual development of new drone applications, it is necessary to think about the safety aspects to maintain the workforce's uncompromised safety performance. The risks remain significant as the use of UAVs expands its branches further into multifarious activities.

The most pressing issue confronted by the industrial sector is ensuring supervision and safety control of commercial drone operations, particularly those operating in the construction environment with densely populated regions. The study has identified a lack of a precise safety framework governing UAV-based operations on construction sites encompassing construction and flight safety considerations. To reduce the possibility of UAV-associated accidental situations at the workplace, supervision and safe control of the UAV operations should consider implementing stricter requirements established for the responsible pilots and develop specialized UAV-construction safety management systems.

The significance of having an ethical approach to drone activities is also discussed in this paper in order to detect and minimize any conflicts connected with drone use in construction areas. The discussion takes a standpoint in describing the need for safety supervision in drone usage in construction facilities. The risks that come with drones are real, and they have the full potential to impede people's safe behavior. The study data depicts a considerable variation in the safety perception of construction personnel about drone usage, which strengthens the idea that the industry is not yet fully ready to incorporate drones among the hazard-prone job locations.

6.1 Limitations And Future Recommendations

Due to specific limitations, future research planning was restricted to the aforementioned emphasis points. However, based on the findings, this research will further into the development of immersive virtual reality (VR)-based video games that can simulate the construction environment and infiltrate UAV-related safety challenges. This could potentially generate data on workers' safety performance and develop prediction models. In addition, after effectively addressing the fast-rising safety problems with UAV usage, a quantitative risk assessment supported by job hazard analysis techniques can be established, with the objective to effectively identify potentially dangerous attributes of UAV usage and allowing time to take necessary precautions. Validating safety management systems for UAVs and implementing operating guidelines for these systems for flying over people in construction will require more testing.

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