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Safety Challenges of UAV Integration in the Construction Industry: Focusing on Workers at Height

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Abstract

Unmanned aerial vehicles (UAVs) are increasingly being used on construction sites, which are already dangerous. While offering benefits, UAVs' introduction can adversely affect the health and safety of workers, especially those who work at height. UAVs can cause distraction, which can increase the likelihood of falls. Working with these flying robots, because they are capable of recording worker activities, can also affect the psychological or emotional state of workers.

This study evaluated the impact of working with or near UAVs for construction workers at height. A virtual construction site was developed to simulate different high-risk scenarios, and user experiments were conducted to evaluate, using wearable sensors and self-reported questionnaires, how UAVs affected workers' attentional and psychophysiological states. A total of 153 subjects participated in two experiments in this study. The results of the first experiment indicate that UAVs cause distraction and reduce workers' attention on the tasks at hand. The results of the second experiment suggest that UAVs at some distance cause more distraction to workers than UAVs in close proximity. The experiments did not provide evidence to indicate that UAVs cause significant psychological or emotional distress.

Key Findings

- Construction professionals generally have a negative attitude towards working with or near UAVs.
- A hands-on V.R. interaction with UAVs helped participants view UAVs with a less negative attitude.
- Working with or near UAVs causes distraction and reduces the attention devoted to the task at hand.
- The analysis of physiological data and the self-reported questionnaires did not provide any evidence to support the hypothesis that working with UAVs causes significant psychological or emotional distress.
- The results indicate that UAVs working at some distance (12 ft. and 25 ft.) cause more distraction than UAVs in close proximity (1.5 ft. and 4 ft.), as participants looked away from their tasks more when the UAV was at some distance
- The distance of the UAVs neither impacts workers' psychophysiological or emotional states nor affects workers' attitudes towards UAVs.

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Introduction

Construction is one of the most dangerous industries to work in [1–4]. In 2017-18, out of 4674 occupational fatalities in U.S. private industries, 971 (20%) were from construction [5], which employed just over 5% of the workforce. In the past two decades, more than 28,000 U.S. construction workers have died at work, and every year about 200,000 nonfatal injuries are reported [6]. In addition to the pain and suffering these accidents cause to the workers and their families, the financial burden of injuries on the industry is enormous. A fatality costs an average of $991,027 in hospital costs [7], and the indirect costs from injuries—including lost work time, wage losses, production losses, and expenses of administering workers' compensation—can be as much as 17 times more than direct costs [7].

Statistics indicate that falling from heights is the leading cause of fatalities and injuries in construction, accounting for about 30% of deaths and 48% of serious injuries [8]. In fact, one-third of all construction accidents are related to falls [9]. As construction environments are often characterized by temporary and elevated work zones, such as scaffolds, ladders, or roofs, workers at such locations are at a much higher risk of fatal and nonfatal injuries.

Over the last few decades, the construction industry has also seen a lag and, in some instances, a decline in productivity growth. Owing to the need to improve performance and counter a growing labor shortage, the construction industry is rushing along the path of increasing automation. One such area that has seen tremendous growth in recent years is the use of Unmanned Aerial Vehicles (UAVs), aka drones. Over just one year (2017 to 2018), the use of UAVs in construction grew by 239%, making the construction industry the fastest commercial adopter of UAVs [10]. UAVs can move more quickly than humans into hard-to-reach areas of job sites, and they can be equipped with devices such as video cameras, sensors, and communication hardware to transfer real-time data for construction applications. UAVs can also perform tasks similar to those of crewed vehicles in construction but more quickly and at a lower cost [11,12]. UAVs are used through different phases of a construction project, from site surveying and mapping [13] to progress monitoring [14] to building inspection [15] and structural maintenance [16]. In addition, advancements in UAV design in terms of battery duration, global positioning system (GPS) navigation capabilities, and control reliability have made the development of new low-cost, lightweight aerial systems possible[17]. The availability of such low-cost and easy-to-fly UAVs has significantly increased their use over the past decade [18], a trend that is expected to continue.

UAVs have already begun changing how infrastructure is designed, constructed, operated, and maintained, and evidence indicates that those changes will continue. The advancement of artificial intelligence, the Internet of Things, sensors, and wireless technologies will enable UAVs to become ubiquitous on construction sites. Since construction is still a worker-driven industry, UAVs must work symbiotically with people. As the trends indicate, there is a paradigm shift underway where the role of UAVs is changing from passive observers to active agents interacting with human workers. UAVs have the potential of assisting these workers in a wide range of construction tasks, from material handling for roofers or ironworkers on elevated heights to safety monitoring of blind spots for crane operators. With the predicted increase in construction activities to address the nation's growing infrastructure needs, there is expected to be more interaction between human workers and autonomous agents such as UAVs.

While the benefits of UAVs have widely been discussed, their integration in construction environments raises novel occupational safety and health issues that have not been empirically evaluated yet. Co-PI Gheisari conducted a recent national survey to study social, legal, financial, and logistical factors that might affect the use of UAVs for construction applications [19]. The two most essential concerns as rated by respondents were related to liability concerns and safety challenges of using UAVs. Safety concerns are associated with flying robotic machines on a job site full of people and the unsafe circumstances that this might create, ranging from collision or falling objects to the distraction of workers.

Integrating UAVs in construction job sites can exacerbate the causal factors of falls, affecting the health and safety of workers at height, who are already at a higher risk. UAVs can cause visual and cognitive distraction, increasing the likelihood of a fatal fall. In fact, being distracted at work while at a significant height is one of the leading cause of falls [20]. The human brain possesses a limited amount of attentional resources [21], and when this limited resource is diverted to a distracting stimulus (i.e., a UAV), performance in other tasks often deteriorates [22]. As a result, workers may be unable to quantify the risk associated with the task rationally, resulting in unsafe actions. Distraction may also cause impaired situational awareness [23], limiting the workers' ability to properly assess safety risk levels, resulting in unsafe behavior and a potential accident.

Besides distraction, which has an immediate effect, UAVs can also affect workers’ long-term psychological health. While the primary purpose of these UAVs might not be monitoring workers, their cameras inevitably capture worker activities. As such, individual elements of work can be monitored, and non-essential human actions or inappropriate activities can be identified in real-time. This microlevel monitoring can create a feeling of "being watched" among workers and can result in anxiety and stress that adversely affects a worker's mental health [24]. The fear of being struck by a fast-moving flying machine while already working in a high-risk environment can also provoke a stress response. Persistent exposure to such psychosocial stressors for an extended period can lead to mental or psychophysiological illnesses due to chronic emotional and biological arousal [24]. In addition, the perception of being watched increases the work pace or time pressure. This can add to the cognitive demand of the task and can have secondary effects like fatigue, which again increases the likelihood of falls [25].

Therefore, these new health and safety challenges must be investigated, and appropriate safety measures developed to ensure the safe operation of UAVs around human workers and other machinery. While there is a significant body of research about the use and benefits of UAVs in construction, there is a dearth of research examining the impact of working with or near UAVs on the health and safety of workers, including their safety performance. In this study, we employed virtual reality technology to study these health and safety challenges posed by UAVs.

Objectives

This project aimed to evaluate how UAVs affect workers' attentional and psychological states while they perform tasks at height. The specific objectives of the study were to assess distraction, acute stress, and the negative emotional state of workers caused by UAVs in their work environment. To achieve our specific aim and to address identified problems, the study had three research objectives:

- ***Objective 1:*** Develop a hyper-realistic virtual construction environment that simulates various fall hazard scenarios in construction job sites with multiple virtual UAVs
- ***Objective 2:*** Evaluate the impact of UAVs on attentional distraction (*Distraction*) and psychological state (*acute stress & negative emotional state*) of workers at height using previously developed virtual scenarios.
- ***Objective 3:*** Evaluate the effects of distance from UAVs on the attentional and psychophysiological impacts of UAVs.

Based on the accident reports collected by OSHA over the last ten years, falls from roofs, ladders, and scaffolds account for 56% of all fall-related accidents in construction [5]. Therefore, in this exploratory study, we limited the scope to workers on roofs, ladders, and scaffolds (e.g., roofers, painters, electricians), as they already operate in high-risk work environments that the presence of UAVs could further exacerbate.

Research Method

To achieve our specific aim and to address the identified problems, the research was conducted in four phases as follows (Figure 1):

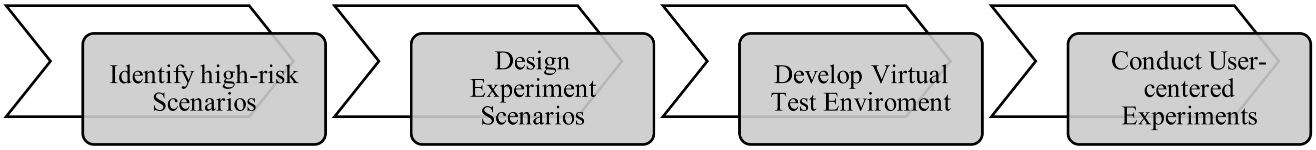

Figure 1. Research tasks

Task 1: Identifying High-risk Scenarios

In this task, different construction scenarios were identified in which workers are at height and are most exposed to the risks imposed by UAVs. In 2019, according to CPWR - The Center for Construction Research and Training, there were 1,102 fatal injuries in the construction industry. Falls, slips, and trips were the most frequent type of fatal events, representing 37.9% of all fatalities (418 of 1,102), and there was a 22.9% increase in fatal falls, slips and trips from 2018 [26]. Falls to a lower level has remained the leading cause of construction fatalities. From 2015 to 2017, there were 1,005 deaths related to falling accidents, and more than half of the fatal falls were from a height below 20 feet [27]. Roofs, ladders, and scaffoldings are the three primary sources of fatal falls on construction [28], accounting for about 75% of falling fatalities [27]. Therefore, "roof," "ladder," and "scaffolding" were selected as keywords to identify the highest risk environments for scenario development.

A content analysis of the Occupational Safety and Health Administration (OSHA) Fatality and Catastrophe Investigation Summaries and the CPWR's fatality maps was performed for the period 2015 - 2019 to identify recurring patterns in fatal and nonfatal construction worker injury scenarios caused by falls from heights. The scope of content analysis was limited to falls from roofs, ladders, and scaffolds, which account for more than half of all fall-related worker accidents in construction over the last decade. Fatal accidents involving falls were filtered based on different categories of keywords. There were 337 incidents related to the keyword "roof," 179 related to the keyword "ladder," and 134 related to the keyword "scaffolding." The literature was also explored to identify different construction activities leading to falls from heights The details provided in the investigation reports were used to identify the key characteristics associated with each accident. Figure 2 shows the example of content analysis.

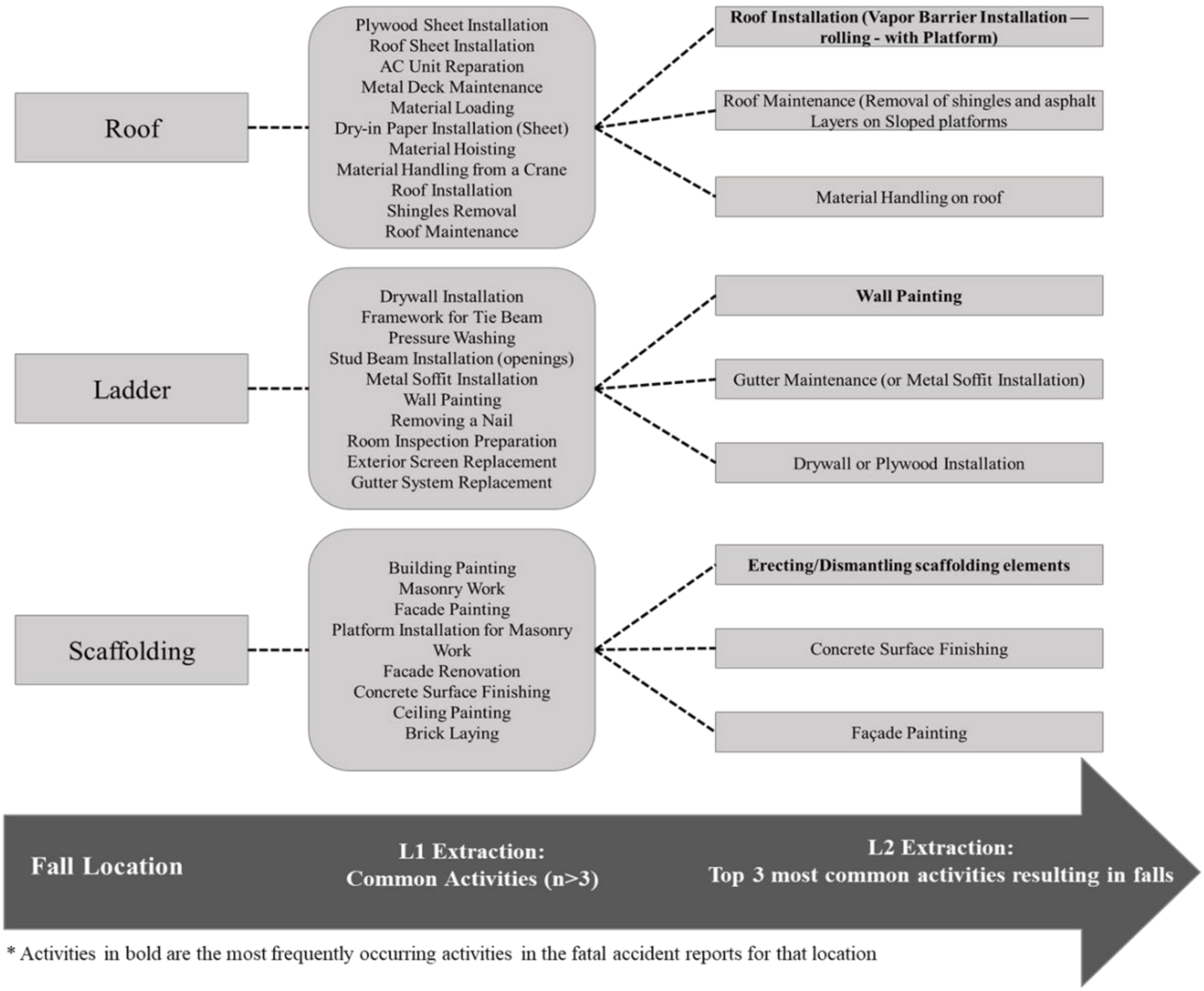

Figure 2. Common Fall Accident Scenarios and Tasks

Task 2: Designing Experiment Scenarios

After filtering the accident reports, the construction tasks that frequently resulted in fatalities were identified by analyzing the narrative descriptions in OSHA reports. The details of narrative descriptions provided the key characteristics of scenarios and settings that led to a fall-related accident. In each category of incidents, the most frequent words related to construction accidents and the most common falling height were identified (Table 1.). In the filtered 337 "roof" incidents, the most frequent construction task for workers falling from the roof was installing panels or trusses, and the most common falling height was 20 feet. In the filtered 179 "ladder" incidents, the most frequent construction tasks for workers falling from ladders were painting and installing gutters, and the most common height was 10 feet. In the filtered 134 "scaffolding" incidents, the most frequent construction task was installing scaffolding panels, and the most common height was 20 feet.

Table 1. The most common characteristics of "roof", "ladder," and "scaffolding" incidents

Working Location	Roof	Ladder	Scaffolding
Work Height	20 ft	10ft	20ft
Task	Installing Roof Panels	Painting	Erecting scaffolding

Given these findings, three V.R. case scenarios were designed to simulate the activities.

- ***Scenarios 1: Roof Installation:*** With the participant physically on the inclined platform, they were tasked with supervising the workers installing roof panels. They were required to communicate with their colleagues and provide them with real-time information.
- ***Scenario 2: Painting on a Ladder:*** While in the V.R. environment, participants were tasked to virtually paint the exterior of a residential building under construction while physically standing on a step ladder.
- ***Scenario 3: Erecting/Dismantling Scaffold:*** The participants were tasked with inspecting newly erected scaffolding while standing on it. They were standing on physical scaffolds, while adjacent to them, new scaffolds were being erected in the virtual world.

Task 3: Design and Develop a Virtual Construction Site

A virtual construction site was developed with buildings, equipment, UAVs, and workers and was then used to create the three scenarios developed in task 2. This involved developing a digital site that represented several distinct complex spatiotemporal scenarios of future construction projects, together with different UAVs (performing various functions) with which the experiment participants could interact. The virtual site was developed in the Unity game engine, allowing us to enhance the site's realism by adding different virtual elements (e.g., cranes, excavators, construction debris, material stockpiles, scaffolding, ladders), relevant effects (e.g., dust, smoke), and audio effects to simulate the sounds that are typically heard on a construction job site. These 3D models were imported as film box format (.FBX) into the Unity game engine and organized in a manner congruent with a typical construction site. The virtual environment was developed on a high-performance computer with an Intel Core i7-9700 CPU at 3.60 GHz processor, 64 G.B. of RAM, and an Nvidia GeForce RTX 2070 GPU. All models were rendered in the High Definition Rendered Pipeline (HDRP) for enhanced realism. Fruity Loops and Audacity were used to produce sound effects to emulate a real-world construction site.

In addition, several virtual UAVs were also designed to simulate different types of UAVs that workers at height are most likely to encounter in current and future construction job sites. These were programmed to operate similarly to their real-world counterparts and differed in design, functionality, and operation. The virtual UAVs include:

- Inspector-UAV: Progress Monitoring, Building Inspection, and Earthmoving
- Builder-UAV: Aerial Construction and Site Communication
- Safety-UAV: Safety Management, Security Surveillance, and Site Communication
- Delivery-UAV: Material Handling and Site Communication

The UAV sounds used in the virtual site were from a DJI Phantom 4 Pro, which is among the most popular UAVs used in industry and for personal use. The spatial blend was used to create spatial audio, which helped enhance the realism of sounds in the environment.

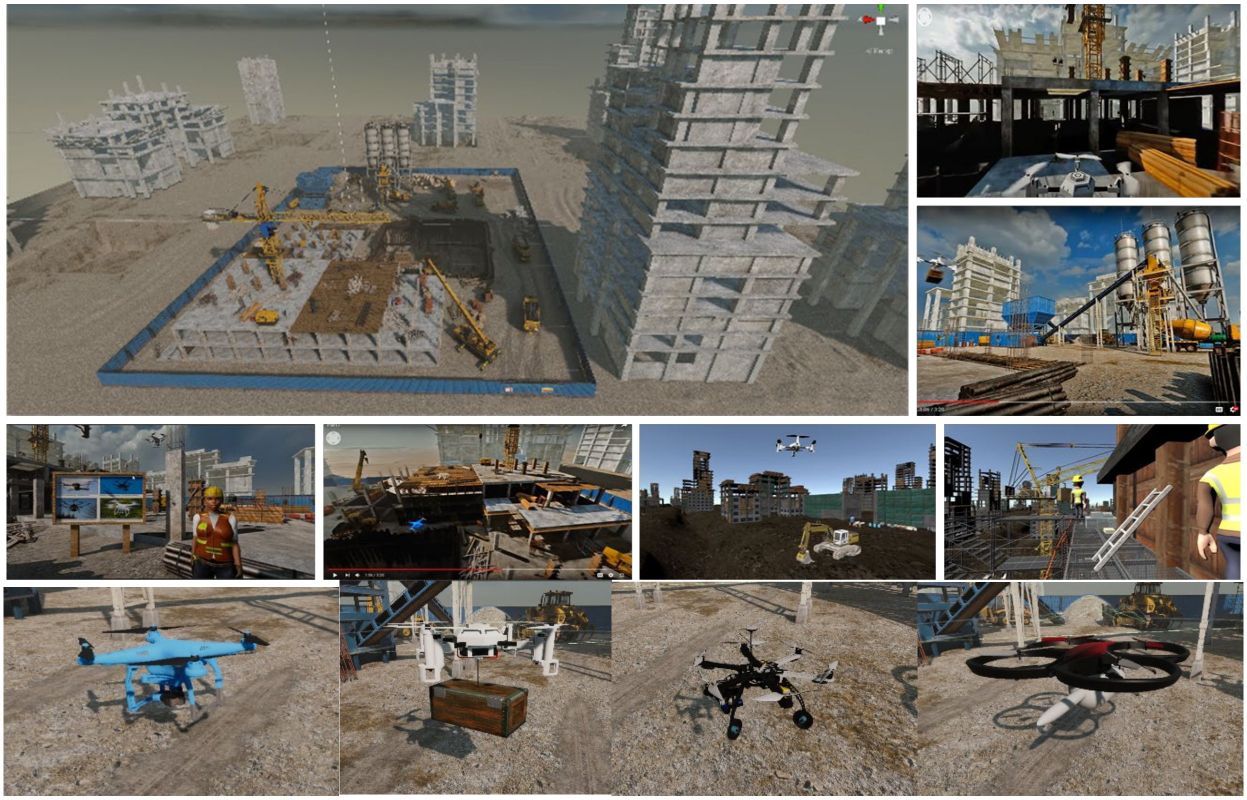

Figure 3. Top: snapshots from Virtual Construction Site, Bottom: Different types of Virtual UAVs

Task 4: Assess the Effects of UAV Integration on Construction Workers through User-centered Experiments

Two experiments were conducted to evaluate the effects of UAVs on workers' attentional and psychological states.

Experiment #1: Evaluating the attentional and psychological impact of working with UAVs while at height

This experiment evaluated the attentional and psychological impact of UAVs on workers in different high-risk scenarios. In this experiment, the participants were assigned to one of the following groups and their psychological, attentional, and emotional responses during different virtual tasks were compared.

- ***Control Group – V.R. Scenarios without UAVs:*** The construction workers explore the virtual scenarios (designed in Task 2) and perform virtual tasks within the virtual environment without any UAVs
- ***Experimental Group – V.R. Scenarios with UAVs:*** The workers in this group performed the same virtual tasks but with UAVs flying in their environment.

Before the experiment, the Shimmer® Bridge Amp and GSR+ wearable sensors were placed on the participants. The probes for the GSR+, which were used to measure photoplethysmogram (PPG) and electrodermal activity (EDA), were placed on the medial phalanx on the non-dominant

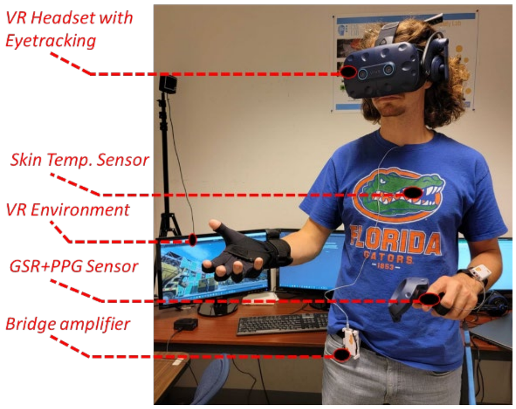

Figure 4. A participant with different wearable sensors

hand of the participant to allow for them to use their dominant hand for the assigned task. The skin temperature probe was placed below the collar bone (Figure 4). These sensors were selected because of their broad usage and ability to deliver clean, higher-quality physiological data (wired and snugly fit). Data was logged using the Shimmer Consensys Pro software and processed using different algorithms that computed participants' heart rate (H.R.) and heart-rate variability (HRV) from PPG data. Once the wearable sensors were connected correctly, the HTC Vive Pro head-mounted display (HMD), equipped with a Tobii Pro eye tracker, was placed on the participant. The eye-tracker was calibrated, and the HMD rendered the V.R. scene to the participants, who were asked to complete their designated scenario-based virtual task.

The target population for the experiment consisted of construction professionals with experience working on construction job sites. Before the start of the data collection, the study was approved by the University of Florida Institutional Review Board (UFIRB# IRB202003079). After hearing a description of the experiment and consenting, participants were asked to fill out a demographic questionnaire along with a validated Positive and Negative Affect Schedule (PANAS-SF) [29] to gain an insight into users' emotional state at the beginning of the experiment. The PANAS-SF is a 20-question self-assessment with ten questions evaluating the positive affect subscale and ten questions for the negative affect subscale. This questionnaire results in a score between 10 and 50 for the positive and negative affect. The higher the score on the positive affect subscale, the higher the positive affect levels, and the lower the score on the negative affect scale, the lower the negative affect in the individual. During the experiment, the physiological data from the two sensors was streamed via Bluetooth to the Shimmer Consensys Pro software and recorded synchronously at a sampling frequency of 128 Hz for the experiment.

The participants navigated the three virtual scenarios and performed the designated tasks designed in task 3. While performing the virtual tasks, sensors embedded in the head-mounted displays of workers recorded their eye movements. This data was used to examine workers' attentional allocation during the task to empirically evaluate the distraction the UAVs caused. In addition, a wearable biosensor (Shimmer PPG & EDA/GSR) measured the workers' galvanic skin response (GSR), skin temperature, and heart rate. This data, along with the eye-tracking data, was used to quantitatively assess the physiological response of workers to UAVs while at height. After the experiment, the Positive and Negative Affect Schedule (PANAS-SF) questionnaire was again administered to assess participants' emotional state after completing the experience with and without UAVs.

Physiological and eye-tracking data were processed in Matlab® to remove artifacts, outliers, and noises (e.g., originating from sensor movement) and ensure more accurate data analysis. Specifically, the EDA response was processed using a low pass filter (Braithwaite et al. 2013) [for non-EDA component removal; filter applied at a low cutoff frequency of 1.5 Hz to collect EDL (between 0 Hz and 0.05 Hz) and EDR (between 0.05 Hz and 1.5 Hz)] followed by a Hampel filter. In addition, a high-pass (high cutoff frequency of 0.05 Hz) filter and a Hampel filter were used to process the Skin Temperature data. The EDA physiological signals were decomposed into EDR (i.e., phasic) and EDL (i.e., tonic) components based on the convex optimization approach described in literature [30].

Experiment #2: Evaluating the impact of distance on the attentional and psychological effects of working with UAVs

To gain further insights, the objective of this experiment was to evaluate the effect of distance on distraction and the physiological responses of human workers when working near UAVs. A between-subjects design was chosen for this experiment. Four identical V.R. scenarios were used, and experiment subjects in each group were tasked to perform a simple supervisory task (count, for a defined period of time (i.e., 5 minutes), the number of trips that a virtual construction worker (3D avatar) makes while transporting material on the job site). Participants were randomly assigned and evenly balanced across four conditions (four scenes), each featuring a UAV at a different distance, based on Hall's distances: intimate (0 - 1.5ft), personal (1.5 - 4ft), social (4 - 12 ft), and public (>12 ft) [31]. The UAV was programmed using C# scripts in Unity® to hover at the defined Hall distances and remained within the users' field of view during the interaction. The eye-tracking sensors embedded in the HMD provided information about the level of engagement with the UAV to validate whether users were observing it during the experiment.

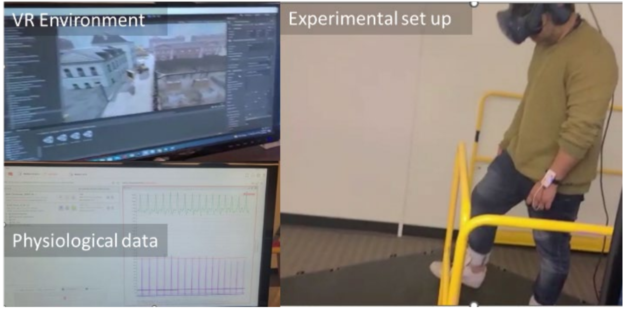

Figure 5. A subject in the roofing scenario

As participants were accomplishing their task, wearable physiological sensors (shimmer PPG and GSR) monitored their responses when working without a UAV (baseline) and the changes when a UAV appeared on the scene. The eye-tracking data also helped monitor participants' viewing behavior to evaluate distractions caused by UAVs at different distances. The PANAS-SF [29] and NARS [32] questionnaires were administered before and after the experiment to assess participants' emotional states and attitudes towards UAVs.

In addition, psychological metrics (Heart Rate, Heart Rate Variability, Skin Temperature, electrodermal response (EDR)) and attentional metrics (on-target fixation counts and fixation durations) were also collected (from physiological and eye-tracking sensors, respectively) and processed in the same manner as explained in experiment 3.1.

Obtained EDA, H.R., HRV, and S.T. physiological data means were compared using the paired t-test to test for any significant differences between pre- and post-UAV presence within each scene (i.e., comparing the means of physiological data of the first two-minute period collected without UAV presence against the second two-minute duration collected with UAV presence). The physiological and gaze data means were also compared using one-way ANOVA with posthoc Tukey's HSD to test for any significant physiological response differences between the interaction distances (i.e., across all four groups).

Data Analysis

Experiment 1: Evaluating the attentional and psychological impact of working with UAVs while at height

Demographics: Seventy-one construction professionals were recruited for this experiment and were randomly assigned to either the with-UAV (experimental, N=35) or without-UAV (control, N=36) group. Participants included those with less than one year (53.5%, N=38) of construction experience and individuals with experience of 1 to 5 years (24, 33.8%). Seven (9.9%) had between 5 and 10 years of experience, and two (2.8%) had greater than ten years of construction experience. While most participants were familiar with robots (95.5%, N=69), their experience of working with robots varied. 21 (29.6%) participants considered themselves not to be experienced at all, 26 considered themselves slightly experienced (36.6%), 19 were moderately experienced (26.8%), and only five (7%) individuals classified themselves very experienced. The 71 construction professionals' familiarity with V.R. ranged from not familiar at all (5.6%, N=4), to slightly familiar (39.4%, N=28), to moderately familiar (33.8%, N=24), to very familiar (20.1%, N=15). Regarding participants' self-reported baseline emotional states, 24 (33.8%) reported being happy, 38 (53.5%) stated they were satisfied, seven (9.9%) were neutral, two (2.8%) were sad, and none (0.0%) reported themselves as angry at the time of experiment.

Positive and Negative Affect Schedule (PANAS-SF): The average pre-experiment positive affect scores for the experimental (with UAV) group and the control (without UAV) groups were 34.06 ± 7.24 and 34.75 ± 5.93, respectively. Pre-experiment average negative affect scores between the groups were 19.89 ± 6.04 and 19.92 ± 5.42 for the with and without UAV groups, respectively. The differences were not statistically significant, indicating a good homogeneous group. The average post-experiment positive affect score for the experiment group was 35.31 ± 6.61 and 35.97 ± 5.89 for the control group. Post-experiment average negative scores were 19.37 ± 6.48 and 18.78 ± 5.47 for the experimental and control groups. No statistically significant differences ($p < 0.05$) were found between the experiment and control groups, indicating that **there was not enough evidence to support the hypothesis that workers working with UAVs in high-risk scenarios experience negative (or positive) emotional states**.

Physiological Data: Physiological data gathered during the experiment and analyzed included heart rate (H.R.), heart rate variability (HRV), and electrodermal response (EDR) and are shown in table 2. The control group had an average H.R. of 91.91 ± 11.61 bpm, while the experiment group averaged 85.21 bpm ± 13.01 bpm. The difference was statistically significant ($p = 0.02$). There was no statistical significance observed for other physiological metrics. Similar to PANASF, the analysis of **physiological data did not provide sufficient evidence that UAVs invoked any significant physiological response among workers**.

Table 2. Physiological metrics for experimental and control group

Physiological metrics	**Experimental Condition (With-UAV)** Mean ± S.D.	**Control Condition (Without-UAV)** Mean ± S.D.	**p-value**
HR	85.21 ± 13.01	91.92 ± 11.61	0.027
HRV	42.68 ± 25.07	39.21 ± 17.10	0.500
ST	34.89 ± 1.41	35.17 ± 1.05	0.354
EDR	0.25 ± 0.17	0.30 ± 0.24	0.333

Eye-tracking Data: To evaluate the attention focused on the task, the relevant eye-tracking metrics of interest included the number and total duration of fixations (greater than 100 ms) focused on the designated task for participants. In addition, the fixation number and durations were also computed for UAVs for the experimental group to assess how many times and for how long participants fixated on UAVs (assess distraction). Table 3 shows the eye-tracking data results.

Table 3. Eye-tracking metrics for experimental and control group

Eye-tracking metrics	**Experimental Condition (With-UAV)** Mean ± S.D.	**Control Condition (Without-UAV)** Mean ± S.D.	**p-value**
On-Task Fixation Count	124.6 ± 20.5	131.8 ± 30.4	0.067
On-Task Fixation Duration (s)	124.4 ± 31.7	132.4 ± 28.2	0.561

Participants in the group without UAVs fixated on their assigned task 131 times compared to 124 for the group with UAVs ($p = 0.07$), indicating that **people spent more attention on their task when UAVs were not present**. The participants without UAVs also spent more time focusing on their task (134 seconds compared to 129 seconds), but the difference was not statistically significant. On average, users in the experiment group spent 10.26 ± 5.34 seconds looking at the UAV while in the virtual environment.

Experiment 2. Evaluating the impact of distance on the attentional and psychological effects of working with UAVs

Demographics: Eighty-two construction management students participated in this experiment and were randomly assigned to each of the four human-UAV interaction scenarios. The overall study population's average age was 25.23 ± 4.93 years old. The participants' experience operating robots average on the lower end of the spectrum, with 32 (39.0%) stating they had no experience, 27 (32.9%) indicating slight experience, 18 (22.0%) moderate experience, and five (6.1%) considering themselves very experienced. Familiarity with robots ranged from very familiar (10, 12.2%), to moderately familiar (29, 35.4%), to slight familiarity (32, 39.0%), and down to no familiarity at all (11, 13.4%). Participants reported their V.R. familiarity to be extremely familiar (4, 4.9%), very familiar (7, 8.5%), moderately familiar (23, 28.0%), slightly familiar (37, 45.1%), or that they had no familiarity at all (11, 13.4%).

Gaze Data: The fixation counts and fixation durations on UAVs indicate the amount of distraction caused by UAVs in different scenarios. The results in Table 4 below indicate that when the UAV was 25 ft. from the subject, it caused the most distraction. Participants focused on it an average of 27.5 times and spent an average of 193 seconds fixating on the UAV. The distraction gradually decreased as the distance from the UAV decreased to 12 ft., 4 ft., and 1.5 ft. The differences were statistically significant at $p<0.05$ providing strong evidence that the distance at which UAVs operate from workers affects the distraction caused by them.

Table 4. Gaze data between-group analysis

Gaze Metrics	**Scenario 1** **(25 ft.)** Mean ± S.D.	**Scenario 2** **(12 ft.)** Mean ± S.D.	**Scenario 3** **(4 ft.)** Mean ± S.D.	**Scenario 4** **(1.5 ft.)** Mean ± S.D.	**p-value**
Fixation Number	27.50 ± 17.83	21.25 ± 9.48	19.00 ± 6.87	13.59 ± 11.19	0.004*
Total Fixation Durations (ms)	19396.64 ± 13096.42	15570.75 ± 5122.51	18442.59 ± 7608.34	10788.09 ± 9936.77	0.020*

Positive and Negative Affect Schedule (PANAS-SF)**:** On average, participants had lower pre-experiment positive (35.77 ± 6.54) and higher pre-experiment negative (18.26 ± 5.83) affect scores compared to their post-experiment average scores for positive (36.22 ± 7.01) and negative affect (16.83 ± 5.55). The results of the within-groups analysis (Table 5) show that no significant difference was observed, indicating that **there is not enough evidence to support the hypothesis that the distance of UAVs from users impacts the positive or negative emotional states of workers**. However, qualitative feedback from users indicated that participants were annoyed and discomforted "*when UAV flew too close to them.*"

Table 5. Average PANAS-SF Positive and Negative Scores across interaction scenarios

PANAS-SF Measures	**Scenario 1** **(25 ft)** Mean ± S.D.	**Scenario 2** **(12 ft)** Mean ± S.D.	**Scenario 3** **(4 ft)** Mean ± S.D.	**Scenario 4** **(1.5 ft)** Mean ± SD	**p-value**
Post-experiment Positive Affect Score	36.82 ± 8.39	36.45 ± 6.84	33.78 ± 4.77	37.41 ± 7.18	0.398
Post-experiment Negative Affect Score	15.95 ± 4.87	15.40 ± 6.17	18.67 ± 5.40	17.50 ± 5.55	0.246

Negative Attitude Toward Robots Scale (NARS)**:** Overall average NARS results showed that, in the pre-experiment stage, all participants had slightly higher levels of negative attitudes toward situations of interaction with robots (Subscale 1: 12.67 ± 3.23) and negative attitudes toward the social influence of robots (Subscale 2: 14.99 ± 2.86), as well as slightly lower levels of negative attitudes toward emotions in interaction with robots (Subscale 3: 8.68 ± 2.24) when compared to the post-experiment average scores (Subscale 1: 12.44 ± 3.28; Subscale 2: 14.63 ± 3.23; Subscale 3: 8.95 ± 2.68). This indicates that **V.R. experience with UAVs helped participants view UAVs with more positive attitudes (although not at a statistically significant level)**. The within-group analysis (Table 6) showed no statistically significant difference among groups indicating that **there is not enough evidence to support the hypothesis that distance from UAVs affects the attitude of users towards situations of interactions with UAVs**.

Table 6. Average NARS Scores across interaction scenarios

Subscale Scores	Scenario 1 (25 ft) Mean ± S.D.	Scenario 2 (12 ft) Mean ± S.D.	Scenario 3 (4 ft) Mean ± S.D.	Scenario 4 (1.5 ft) Mean ± SD	p-value
Situations and Interactions with Robots	12.23 ± 3.57	11.10 ± 2.59	12.44 ± 2.89	13.41 ± 3.54	0.149
Social Influence of Robots	14.77 ± 3.26	13.55 ± 3.58	14.11 ± 3.03	15.55 ± 3.35	0.248
Emotions in Interaction with Robots	8.36 ± 2.52	8.10 ± 2.75	9.83 ± 3.00	9.59 ± 2.26	0.096

Physiological Data: The different physiological metrics (heart rate, heart-rate variability, skin temperature, EDR) in the baseline condition (no UAV) to experiment condition (with UAV) for different groups are presented in the table below.

Table 7. Physiological data between-group analysis

Physiological Data Measures	Scenario 1 (25 ft) Mean ± S.D.	Scenario 2 (12 ft) Mean ± S.D.	Scenario 3 (4 ft) Mean ± S.D.	Scenario 4 (1.5 ft) Mean ± SD	p-value
HR Before	88.50 ± 13.34	86.62 ± 9.14	84.66 ± 17.84	86.26 ± 19.00	0.887
HR After	89.23 ± 13.46	88.64 ± 9.75	84.55 ± 18.03	86.31 ± 18.97	0.765
HRV Before	29.10 ± 11.78	31.40 ± 12.24	38.02 ± 17.23	36.44 ± 22.23	0.276
HRV After	28.11 ± 10.48	27.05 ± 11.46	41.00 ± 18.40	34.75 ± 20.82	0.027*
S.T. Before	35.18 ± 1.25	34.83 ± 1.54	34.80 ± 1.36	35.04 ± 0.90	0.748
ST After	35.15 ± 1.41	34.87± 1.51	34.84 ± 1.40	35.07± 0.93	0.851
EDR Before	0.63 ± 0.31	0.68 ± 0.36	0.54 ± 0.42	0.61 ± 0.39	0.732
EDR After	0.60 ± 0.26	0.69 ± 0.37	0.63 ± 0.34	0.67 ± 0.44	0.851

A between-group comparison revealed statistically significant differences in post-experiment HRV values between interaction scenarios (p=0.027). None of the other metrics showed statistical significance at p<0.05. Therefore, enough evidence was not found to support the hypothesis that distance from UAV has a significant impact on workers' psychophysiological states.

Accomplishments and Results, Relevance, and Practical Application

This project was the first to study the impact of UAVs on workers' attentional and psychological states when working with or near them. It included the development of a UAV-dominant virtual construction site that can be used for various experiments that include assessment of worker behavior and performance in different UAV populated scenarios and/or for training purposes. The self-reported questionnaire (NARS), which was administered before and after the V.R. experience, indicated that **participants viewed UAVs with slightly positive attitudes after their interaction with them in V.R**. The virtual environment can be used to help workers practice working with or around UAVs to help them get used to these flying machines, which can greatly reduce the distraction caused by such robots in the real world.

The study evaluated the attentional and psychological impact of humans working with UAVs in high-risk scenarios. **The results indicate that UAVs distract workers, and they pay less attention to their tasks when working in an environment where UAVs operate.** Being distracted from work, especially in high-risk environments (e.g., working at heights, operating equipment), can result in risky behavior leading to severe accidents. The results from physiological monitoring and self-reported questionnaire did not provide any evidence that indicates working with UAVs caused significant emotional or psychological distress among workers. The qualitative feedback received from the participants revealed that they felt distracted by UAVs and a little annoyed when they operated too close to them

The results of the experiments also provided some vital insights into human-UAV collaboration in construction. The results indicate that **UAVs operating farther from workers (i.e., 12 ft. and 25 ft.) have more impact on workers' physiological and attentional states than UAVs operating close to workers**. The participants exhibited: (1) lower levels of negative affect upon experiment completion ($p \leq 0.021$); (2) higher average H.R. values after the UAV appeared ($p \leq 0.044$); and (3) an increase in distraction when interacting with UAVs at farther distances (12 and 25 ft.) compared with closer (1.5 and 4 ft.) distances. While this may seem counterintuitive, the experiments showed that participants looked at UAVs and away from their work more when drones were farther. One of the possible reasons might be that UAVs operating in proximity to workers may be considered peers or team members. Although annoying, these UAVs were accepted by participants faster and trusted more as they could see these UAVs all the time. However, the UAVs at some distance may assume a surveillance type of role, which provokes higher distraction and negative attitudes among workers. This has been observed in several human-robot interaction studies as well. For example, Haring et al. (2013) [33] found that when people felt more familiar with robots as they came closer and "This effect was strong enough to go beyond the initial surprise effect this robot would have." Being at a distance, UAVs can provoke curiosity among workers, who are tempted to look away from their work to observe what the UAVs are doing. This, however, is only based on the observations from the experiments in the current study and results from human-robot interaction studies in different domains and needs to be studied further.

Ensuring safe integration of UAVs in construction

The current study revealed safety challenges of working with UAVs on construction sites. While the investigation of potential solutions and countermeasures needed to ensure the safe integration of UAVs in construction was beyond the scope of this study, some recommendations are provided. Judging by the trends of UAV usage in construction, future construction sites will feature more and more UAVs. Therefore, it is critical to prepare the workers who will work alongside UAVs, prepare UAVs to safely operate around human workers, and prepare our sites to support the safe integration of UAVs

Prepare Workers: As with any new technology, training the workforce is critical to smooth integration. UAVs are already changing how construction work is monitored, and very soon, they will have an impact on work procedures, safety measures, material transport, and even the building of infrastructure. Workers who will have to share their work environment and interact with these UAVs need to be properly trained. Specifically, what UAVs do, how and where they will work, the risks they introduce, and how to work safely with or around them. There are currently no specific OSHA standards or guidelines regarding UAVs on construction sites, so training workers is even more critical. The training content needs to be developed to not only educate workers about UAVs but also help familiarize them with working alongside UAVs. Virtual reality can be an excellent tool for creating immersive environments where workers can practice working with or around UAVs and get accustomed to them.

Prepare UAVs: While training workers is essential, it is also critical to design UAVs to limit the frequency and severity of risks they pose to the workers on site. The UAVs need to be equipped with systems to manage failures by detecting and correcting any faults through offline or online fault detection algorithms. They should also deploy features such as parachutes or airbags to reduce impact velocity or by carefully choosing innovative materials to minimize the crash impact. Finally, using advanced algorithm design, UAVs must be equipped with safety features such as obstacle avoidance, worker detection, safe flight routing path, and airspace awareness.

Prepare Job Sites: Finally, we must also prepare construction sites to ensure that UAVs work efficiently and safely around workers. Currently, the Federal Aviation Administration (FAA) regulates the commercial applications of UAVs in general, but there is a need to frame regulations specifically for the construction domain (or for industries where humans and drones work together) due to its unique risks, rapidly changing environment, and distinctive safety challenges of human workers sharing their congested and complex job sites with UAVs. These regulations must go beyond general regulations provided by the FAA (e.g., flight traffic, flight speed and altitude, weather considerations) and to address each of the safety risks identified in this and similar research. These include size, weight, and shape restrictions for different UAVs; material requirements for different UAV parts to ensure minimal impact on collisions (e.g., plastic, metal); UAV battery life, flight team, flight speeds, flight heights requirements, sense-and-avoid capabilities, recovery systems (e.g., parachute) requirements, and human-UAV proximity restrictions.

In addition to regulations that will provide high-level guidelines, it is also critical to develop or update procedures that help reduce the risk of injury caused by UAVs at the project level. These procedures include airspace design, flight corridors, dynamic geofencing, congestion management, route planning, separation management, sequencing and spacing, and contingency management, as each construction project has unique needs that may change over the project period. The procedures can leverage Hierarchy of Controls [34] to manage risks posed by UAVs as follows:

1. *Elimination:* Preventing workers from being in the area where UAVs operate. As much as possible, workers should schedule their work so that no one is working in an area when UAVs are operating there.
2. *Substitution:* Finding alternative methods whenever possible. UAVs need not be used for everything just because they are available. UAVs should be reserved for applications that offer significant benefits over traditional methods.
3. *Engineering Control:* Isolating people from UAVs when UAVs cannot be eliminated or replaced. Some examples could be putting physical barriers such as safety nets above the workers working under the drones or barricading the area where drones are working.
4. *Administration controls:* Designing work procedures and site rules to minimize exposure to risk from UAVs. A great example would be to avoid working directly under flying drones. Those who work closely with drones should also be cautious of the different moving parts of drones. A proper work procedure that the safety manager has reviewed must be followed for tasks that require working in proximity to drones.
5. *PPE:* Finally, workers should always use appropriate personal protective equipment (PPE) such as hard hats, safety glasses, and fall protection while working with UAVs. PPE will not eliminate the likelihood of an accident but will reduce the severity of an injury. When working with or in proximity to drones, workers should also use cut-resistant PPE gloves and avoid loose clothing that can get caught in propellers.

Changes/Problems That Resulted in Deviation From the Methods

- We encountered some delays in completing the evaluation and user experiments. This delay, which accumulated over time, was caused by multiple factors, including COVID restrictions at the beginning of the project, unexpected technical challenges faced during the development of the V.R. environment, changes in the development process necessary to improve the quality of the virtual environment (discussed below), and some difficulty in hiring V.R. development personnel for the project. To overcome the delays, we changed the sequence of the tasks and started multiple tasks concurrently. The project was completed with a delay of 3 months.

- The scenarios were initially planned to be built using 360° images to serve as the reality backdrop for the virtual environment. However, during the design phase, the research team decided to create the background using virtual elements (instead of 360° images) to provide better control over the environment. Unlike 360° images and videos, virtual elements are programable and can be customized to suit the needs of the designed scenarios. This change was also necessitated by the challenges of the pandemic, which prevented the research team from visiting construction sites physically to collect relevant 360° images. This change required adding more realistic virtual elements (e.g., construction entities, terrain, lighting) to achieve the same level of realism offered by a 360°-image backdrop. As such, the virtual site was enhanced by adding different elements (e.g., cranes, equipment, material stockpiles) and effects (such as dust, construction activities audio).
- Initially, only one experiment was planned to evaluate the impact of UAVs on workers' attentional and psychological states. However, to gain more insights, a second experiment was added to study if the distance from the UAVs has any effect on its attentional and psychophysiological impacts on human workers

Future Funding Plans and Funding Sources

Two projects are planned to further the research on human-robot interaction in construction:

1. Investigate approaches to achieve safe human-UAV synergy in construction jobsites by developing interaction protocols for human-to-UAV and UAV-to-human communication. (Proposal submitted to NSF)
2. Investigate the health and safety challenges of working with industrial robots in human-centric industrialized construction (Small Study letter of intent submitted to CPWR)

List Of Presentations/Publications, Completed and/or Planned

1. **Presentation and peer-reviewed conference proceeding:** Patrick Brophy, Gilles Albeaino, Idris Jeelani, Masoud Gheisari, Health, and Safety Challenges Associated with Human-Robot Interactions in Construction" *International Conference for Computing in Civil Engineering 2021*
2. **Presentation:** Idris Jeelani, Masoud Gheisari "Safety Challenges of Human-Robot Interaction at the Future of Construction Work" 2022 National Occupational Injury Research Symposium (NOIRS 2022), May 10, 2022
3. **Planned Journal Publication:** Gilles Albeaino, Patrick Brophy, Idris Jeelani Masoud Gheisari, "Working with UAVs while at height: Health and safety challenges for workers at height" *Safety Science 2022, (in preparation)*

Dissemination Plan

The results of this study were presented at International Conference for Computing in Civil Engineering 2021 (i3CE 2021) and the 2022 National Occupational Injury Research Symposium (NOIRS 2022). The preliminary findings were published in the i3CE conference proceedings, and the complete results will be published in the journal of Safety Science and presented in NOIRS 2023, HFES's ErgoX 2023, and different industry presentations/workshops organized through the Rinker School of Construction Management Industry Advisory Board.

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