Report for
80NSSC20M0261

Unmanned Aerial System (UAS) Research for Public Safety Applications

Task 3: Multi-Vehicle Management Final Report

Program Manager: Christine Dillard
Principle Investigator: Kenny Cheung

Prepared for:

NASA Ames Research Center
Moffett Field, California 94035

August 15, 2025

Technical Report Documentation Page

Title: Task 3: Multi-Vehicle Management Final Report
Report Date: August 15, 2025
Performing Organization: Oregon State University
Authors: Julie A. Adams, Christopher A. Sanchez, Vivek Mallampati, Joshua Bhagat Smith, Alejandra Hilbert, Emily Burgess, and Andrew Dassonville

Performing Organization and Address:
Collaborative Robotics and Intelligent Systems Institute, College of Engineering
School of Physiological Science
Oregon State University
Corvallis, Oregon 97331

Sponsoring Agency Name and Address:
Universities Space Research Association
7178 Columbia Gateway Drive
Columbia, MD 21046

Table of Contents

List of Figures

List of Tables

Table of Acronyms

ADS–B	Automatic Dependent Surveillance–Broadcast
AOI	Area of Interest
ATC	Air Traffic Control
BVLOS	Beyond Visual Line-of-sight
C2	Command and Control
CFR	Code of Federal Regulations
CONOPs	Concept of Operations
DAA	Detect and Avoid
DARPA	Defense Advanced Research Projects Agency
DFR	Digital Flight Rules
DSS	Decision Support System
FAA	Federal Aviation Administration
Fix/Min	Fixations per Minute
GPS	Global Positioning System
HITL	Human-In-The-Loop
IFR	Instrument Flight Rules
Inter/Min	Interactions per Minute
IRB	Institutional Review Board
IMPRINT	Improved Performance Research Integration Tool
LS	Lightning Strike
LTE	Long-Term Evolution
PD	Package Delivery
m:N	m humans to N uncrewed aircraft systems
OFFSET	Offensive Swarm-Enabled Tactics
OrSU	Oregon State University
PF	Pilot Flying
PIC	Pilot-in-Command
RTL	Return To Launch
SD	Standard Deviation
sEMG	Surface electromyography
UAS	Uncrewed Aircraft System
UE	Unexpected Event
UI	User Interface
UTM	Unmanned Aircraft System Traffic Management
VFR	Visual Flight Rules

Executive Summary

Commercial and public safety Uncrewed Aircraft Vehicles (UAVs) are currently limited by the Title 14 Code of Federal Regulations (CFR) §107.35 prohibition on operating multiple aircraft by one person. Public safety *m:N* operations will benefit from the recently released Part 108 regulation that will permit beyond visual line-of-sight (BVLOS) operations, and enable a smaller number of humans, m, to simultaneously deploy a larger number of N UAS. This task focused on specific criteria and use cases that are considered related to *m:N* operations specific to public safety. Solving the *m:N* problem is not as simple as identifying an appropriate number of N UAS that can apply generically for all public safety operations. Rather, this problem is exceptionally complex given the large set of potential factors that influence task performance across the multitude of public safety domains and applications. Prior research investigated use cases for multiple UAS public safety applications, but no actual systems were available when this project commenced. The prominent multiple UAS systems deployed with FAA approvals are delivery drones.

Task 3.1 focused on answering the question of what mission specific criteria and use cases needed to be considered related to *m:N* operations specific to public safety. This project developed two wildland fire response *m:N* use cases: (1) the small UAS lightning strike and wildland fire monitoring use case, and the (2) large UAS wildland fire mitigation use case.

The use cases were directly informed by Task 3.2 that focused on assessing the state-of-the-art industry *m:N* UAS disaster response offerings that were available, or in-development, when this effort began. The research team leveraged prior results, and gathered pertinent information from wildland fire subject matter experts and commercial UAS companies with *m:N* operations. While relevant UAS hardware existed (e.g., Drone Amplified's aerial ignition UAS), there were no plans to use these systems in *m:N* operations due to flight regulations. As a result, the team analyzed the similarities between the lightning strike and wildland fire monitoring use case and commercial delivery UAS, and found several parallels between these operations. This enabled Task 3.3 efforts, and provided a clear means to further explore *m:N*.

Task 3.3 focused on modeling and conducting human-in-the-loop evaluations. Both use cases, as well as delivery drone operations, were computationally modeled to understand the impacts of operations on human performance. Subsequently, two human-in-the-loop evaluations were conducted. The first evaluation–conducted in cooperation with a well-known delivery company–used trained UAS pilots and an operational simulator, and established that the commonly believed factors that impact *m:N* operations are in fact not the most important when predicting pilot performance. The second evaluation's participants all held at least a private pilot certificate, and were tasked with deploying multiple simulated large UAS to mitigate a wildland fire.

Key findings and knowledge gaps related to human performance when a single human supervises multiple UASs were identified across each task. Specifically, the effort defined and evaluated seven factors that are being shown to impact the allocation of m humans to N UAS. Fundamentally, there remain no multiple UAS systems for public safety purposes; however, given the recent Part 108 notice of public rule-making, this will hopefully change in the near term. The generated results and identified gaps can help inform the design, evaluation, and regulation of these future *m:N* public safety relevant systems.

1 Introduction and Background

Many potential uncrewed aircraft applications for public safety exist (e.g., crowd monitoring, monitoring earthquake damage or for new wildland fires, dousing wildland fires), however, at the time that this project commenced, public safety personnel were typically functioning under the Federal Aviation Administration (FAA) 14 Code of Federal Regulations (CFR) Part 107 rules [1]. These regulations limit a person responsible for the flight of uncrewed aircraft systems (UAS) to line-of-sight operations of a single UAS.

This purpose of this task was to investigate how one or a small number (m) of public safety personnel can deploy multiple UAS (N) for various operations. This problem is known as the *m:N* operational problem, which is more commonly known as the human-to-robot ratio [2–4]. Solving the *m:N* problem is not as simple as identifying an appropriate number of N UAS that can apply generically for all public safety operations. Instead, this problem is in fact exceptionally complex given the large set of potential factors that influence task performance across the multitude of public safety domains. The human-robot interaction community has sought a generalized solution, which remains unsolved after 25+ years.

This research task aligns well with the Oregon State University (OrSU) led FAA ASSURE Center of Excellence project focused on *m:N* pilot proficiency requirements. That project conducted a literature review focused on human performance factors for *m:N* operations, and identified *m:N* operational human performance limitations and research gaps, as well as modeled use cases and human performance tradeoffs. This prior project identified the need to down select to specific multi-UAS mission scenarios, since the very large variability in the factors that impact *m:N* operations made quantification or assessment in a general manner unlikely during this task's performance period. Thus, the current effort focused on:

- Sub-Task 3.1: Identifying mission specific criteria and associated use cases.
- Sub-Task 3.2: Assessing available (or in development) state-of-the-art industry offerings.
- Sub-Task 3.3: Conducting flight evaluations of selected solution(s).

This task as written in the original proposal (not by Adams and Sanchez) aimed to focus on human-in-the-loop multiple UAS flight tests to help identify requirements for public safety operations. At the time this effort commenced, as noted earlier, public safety organizations were not using multiple-UAS systems. Thus, there were no such opportunities available, and even today the availability of such systems remains very limited. After the proposal was funded and Adams and Sanchez became the leads of Task 3, they worked with the project manager to redefine Sub-Task 3.3 to focus on human-in-the-loop (HITL) evaluations with relevant simulated multiple UAS systems.

The FAA ASSURE Center of Excellence A-26 project [5–8] conducted an extensive literature review of *m:N* system evaluations, of which the majority used simulated systems lacking ecological validity and/or conducted HITL evaluations with convenience participants; most of whom had no crewed or uncrewed aircraft piloting experience. Thus, the majority of the existing literature does not translate well to real-world *m:N* systems. A-26 developed use cases and conducted modeling of two *m:N* system operations: homogeneous small delivery drones and heterogeneous multiple UAS collaboratively conducting a wildland fire ridgeline ignition and surveillance task. The FAA ASSURE Center of Excellence A-28 and A-52 projects [9,10] focused specifically on disaster response preparedness. OrSU's efforts in relation to these projects focused on wildland fire fighting and response to earthquakes/landslides. Specifically, OrSU collected relevant information and challenges from local, state and federal subject matter experts, developed use cases, and contributed to developing relevant Concept of Operations (CONOPS). The associated results from these projects (i.e., A-26, A-28 & A-52) were leveraged to accelerate the current effort.

Adams was also a member of an integrator team for the Defense Advanced Research Projects Agency's (DARPA) Offensive Swarm-Enabled Tactics (OFFSET) program [11–15]. This program conducted field exercises over five years in increasing complex urban environments with an increasingly larger swarm of ground and aerial (i.e., UAS) robots. The program culminated with the team deploying 144 heterogeneous robots, predominately UAS. Adams' practical experience provided insights into the potential applications of m:N systems for public safety including: large fire suppression, surveillance and reconnaissance, search and rescue, managing traffic and crowds, supply delivery, etc.

2 Task 3.1: Identify Mission Specific Criteria and Use Cases

This task focused on answering the question of what mission specific criteria and use cases needed to be considered related to *m:N* operations specific to public safety. The preliminary answers to these questions were informed by prior work the team had completed for FAA ASSURE Center of Excellence projects A-26, A-28, and A-52 [5, 9, 10]. These projects investigated a number of public safety relevant use cases across a large number of potential disasters. The A-26 effort completed as this task's research began, while the disaster response efforts had continuous overlap with this task through October 2024. While these FAA funded efforts investigated use cases for multiple UAS public safety applications, no actual systems were available when this project commenced. The prominent multiple UAS systems deployed with FAA approvals were delivery drones, which were investigated as part of the A-26 effort. Adams and Sanchez had existing relationships with United States-based delivery drone companies that enabled HITL evaluations; thus, the team initially pursued public safety scenarios that shared strong conceptual similarities to delivery drone operations. This approach enabled the identification of corporate partners for later tasks, and permitted leveraging key takeaways from the prior efforts. As such, the team began investigating public safety use cases that leveraged the team's strong background in wildland fire response and also provided parallels to delivery drone use cases.

Throughout the development of the use case, data gathering was conducted by interviewing industrial, and governmental, subject matter experts. Additionally, information was gathered from the FAA ASSURE Center of Excellence A-52 workshops on using satellites and prescribed burns in relation to wildland fires. The industrial engagement efforts were conducted with DroneUp, Matternet, Parallel Flight, Sierra Nevada Corporation, Wing, and Zipline. Additionally, the national UAS program manager for the United States Forest Service and other Forest Service personal responsible for wildland fire management were interviewed.

The majority of wildland fires historically are started by lightning. For example, on August 9, 2022, 5,743 lightning strikes occurred in Oregon, resulting in 92 fires of roughly 1 acre each. A review of historical lightning strike and wildland fire data informed the development of an *m:N* use case focused on the United States Pacific Northwest. The frequency of lightning flashes occur during the summer months from June through August [16], with the most frequent strikes occurring during the afternoon/early evening between 12:00 and 20:00 [17, 18]. Further, within the state of Oregon, historically high risk areas for wildland fires are in predominately rural unpopulated areas, usually located along the eastern side of the cascade mountains, as well as in the southwestern and northeastern portions of the state. Thus, the initial use case focused on deploying *m:N* teams to locations (e.g., snow parks) on a daily basis to monitor for lightning strikes and new wildland fires.

2.1 Lightning Strike/Fire Surveillance Use Case

The use case incorporates a nominal use case as well as a number of unexpected events and human distraction events, please see the detailed use case description in Appendix A.1. The physical aspects for this use case were inspired by Wing's distributed deployment system and the Sentien Hive-XL systems. In the current use case, lightning strike monitoring teams are distributed throughout the region, operating predominantly in rural or remote areas with rough terrain (though operations may extend to rural/urban interfaces). The deployment environment is characterized by limited or non-existent cellular and long-range communications. Teams instead rely on local radio communications and possibly satellite phones, though real-time contact with incident command may not be available. The operation utilizes small UAVs that meet Industry Consensus Standards and hold FAA Airworthiness Certificates. The deployment team consists of four specialized roles: a UAS Supervisor, a Team/Communication lead, a Logistics coordinator, and a Utility Specialist cross-trained in all positions. Teams operate from vehicles with limited cargo capacity, navigating potentially challenging terrain to reach deployment areas. The deployment team has an assigned location at which a shipping container containing the UAS and the team/communication lead's and UAS Supervisor command and control (C2) workstation are stored. The logistics coordinator manages the UAS hardware during deployments. A Utility Specialist can substitute for any of the primary m roles. Each team is assigned an operational sector, whose size varies based on environmental conditions such as terrain and other priority considerations.

The primary nominal task involves rapid response missions where UASs are dispatched directly to lightning strike locations to assess potential fire ignition. The secondary task requires systematic broad-area surveillance of designated sectors to monitor for potential fire activity. Multiple aircraft (4-20) equipped with various sensors are monitored by the UAS Supervisor, while the Team/Communications lead monitors the associated sensor feeds. Thirty-one unexpected event use cases were developed, but are not an exhaustive delineation of all possible unexpected events. These events are organized into seven categories: Supervisor failures, Mission changes, Intentional interference, UAS hardware failures, UAS software failures, Flight path and mission obstructions, and Collisions. Six human distraction event use cases were also developed. The nominal, five unexpected events, and two distraction events were modeled using IMPRINT Pro to understand the impacts on human performance (details provided in Appendix A). The nominal, unexpected events, and distraction events use cases were leveraged to help identify parallels to delivery drone use case.

The comparison between the wildland fire lightning strike and delivery drone use cases focused on the human factors aspects of the respective use cases. Note, the delivery drone use case was developed for the FAA ASSURE Center of Excellence A-26 program [5]. The specific human factors elements analyzed were: contingency planning, distractions, environmental factors, fatigue, frustration, perceptual errors, situation awareness, stimulus detection, stress, task switching, vigilance, working memory capacity, and workload. Each factor was systematically analyzed for each use case, Table 1 provides an example summary for two human factors elements, please see Table A.6 for the full set of analyzed elements. The human factors elements were further analyzed to fully understand the impacts on these considerations, as shown in Figure 1, generally the factors are similar, but in some cases there is a wider variance for the lightning strike use case.

Table 1: Example analysis for two human factors elements for the lighting strike (LS) and package delivery (PD) use cases.

Human Factors	Notes	Differences
Stress Level	Over time individuals get used to performing the respective job so stress levels stabilize. However, the stressors are different for each use case. Stress may change due to task requirements or unexpected events. Both use cases have some amount of stress, but not zero stress; thus, the value 25 was chosen.	**LS**: Same (Relatively low stress environment) **PD**: Same (Relatively low stress environment)
Contingency Planning	If there are any major unexpected events there is little a supervisor can do outside of reporting it; thus, a value of 5 was chosen.	**LS**: Same **PD**: Same

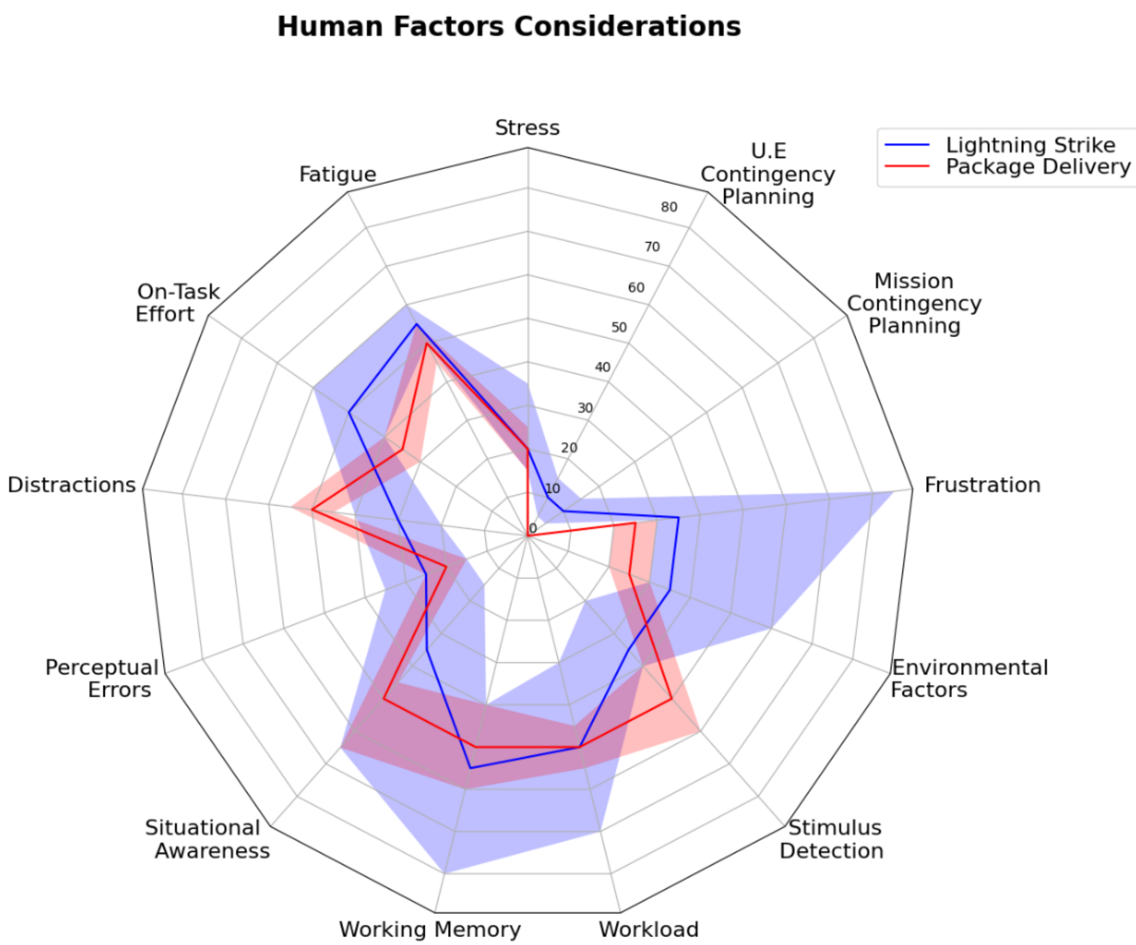


Figure 1: The comparison of the human factors elements between the two use cases.

A similar analysis was conducted comparing the lightning strike and delivery drone use cases across multiple factors. The role of the human supervisor (i.e., pilot-in-command) encompasses all tasks for which the supervisor was responsible. Nine elements were considered, but the delivery scenario required few demands of the supervisor. A full analysis is provided in Table A.7. Physical UAS differences were considered across eight factors, including considerations such as payloads or power consumption. The full analysis is provided in Table A.8. The mission characteristics analysis considered fourteen elements ranging from the mission objective to environmental complexity, with the full analysis provided in Table A.9.

2.2 Large UAS Wildland Firefighting Use Case

The second use case focuses on large UAS being deployed for mitigating a wildland fire. This use case was inspired by an independent Master's thesis project in which large UAS are used for commercial freight delivery (e.g., FedEx) between hub airports and spoke airports [19]. The Master's thesis assumed an Instrument Flight Rules (IFR) environment that required the remote pilot to monitor air traffic control channels, active weather conditions, and take appropriate action and communicate the expected information for N UAS.

The wildland firefighting use case assumes that the UAS are staged at an untowered airport, meaning no air traffic control. As such, each UAS is flown under visual flight rules (VFR), and the remote pilot is responsible for monitoring all communications with other aircraft in the area, and ensuring that normal crewed aircraft operation rules (CFR Part 91) are followed (e.g., the lower aircraft takes evasive action when necessary). This use case's operations may fall under the UAS beyond visual line-of-sight rules (14 CFR Part 108) in the future, but these rules are not formalized at this time. The use case assumes that the remote pilot is responsible for deploying four UAS while also addressing airspace incursions by non-cooperative or otherwise unresponsive intruder aircraft.

The public untowered airport is located in a common area for wildland fires (e.g., Sisters Eagle Airport, Oregon). The airport was selected given its spatially proximity to several towered airports, including hub airports (e.g., Portland International) and spoke airports (e.g., Redmond Municipal), and a busy business and general aviation airport (e.g., Bend Municipal), which ensure there is realistic commercial, business, and private crewed aircraft traffic near and above the operational area. Further, the general aviation airport serves as a staging area for wildland fire response crewed aircraft. The additional air traffic is necessary to ensure that the remote pilot, when flying under VFR communicates necessary information and takes necessary actions to safely manage their UAS. Further, the use case assumes there are other large UAS being flown in the operational area. Some large UAS are unrelated (e.g., freight delivery), but there is also another remote wildland fire pilot operating out of the same untowered airport with responsibility for N UAS.

The pre-mission deployment briefing provides the preplanned flight routes for dropping water or fire retardant on the wildland fire. Each flight route has a specified take-off departure waypoint and landing approach waypoint that is the same for all aircraft staged at the untowered airport. Multiple flight routes can be specified, with all waypoints being derived from commonly defined aviation waypoints. The Airboss approves the flight paths, which the remote pilot-in-command (PIC) reviews prior to commencing their deployment shift.

The remote pilot receives instructions from the Air Boss regarding when to perform a takeoff for each UAS during their shift. The remote pilot is responsible for monitoring all communications across multiple channels related to the PIC's aircraft, as well as the ADS-B data for all other crewed and uncrewed aircraft within the operational area. The remote pilot is also responsible for monitoring relevant weather conditions affecting the operational area.

Under nominal conditions, the remote pilot monitors the UAS(s) that are deployed, and also monitors ADS-B traffic, with intermittent communications with the Air Boss. Air Boss communications may change flight paths, for example cutting the flight path short by selecting a different waypoint later in the flight path to go to directly, thereby skipping the scheduled waypoints between the current position and the selected waypoint. The remote pilot is also responsible for ensuring that their own aircraft will not conflict with one another.

The off-nominal condition occurs when another aircraft, either crewed or uncrewed, may result in an incursion with one of the remote pilot's aircraft. The separation values were roughly based on the traffic alerting system for the Garmin G1000 avionics line, as shown in Table 2. The remote pilot is responsible for contacting the pilot of the incursion aircraft and/or taking evasive actions when the remote pilot's aircraft has a higher altitude than the incursion aircraft. If the remote pilot's aircraft is the lower aircraft, then the remote pilot expects to receive communications from the incursion aircraft's pilot about the actions that pilot is taking to avert an incident. If the incursion aircraft's pilot does not take necessary action to avoid an incident, then the remote pilot must do so. The remote pilot can change the UAS's heading, altitude and airspeed as needed.

Table 2: Flight separation categories.

Separation Category	**Horizontal (Nautical Miles)**	**Vertical (Feet)**
Distant	> 10	$> 5,000$
Proximal	< 10	$< 5,000$
Caution	< 5	< 1.000
Warning	< 2	< 600

3 Task 3.2: Assess Available Relevant State of the Art Systems

This sub-task focused on assessing the state-of-the-art industry *m:N* UAS disaster response offerings that are available or in-development when this effort began. The considerations for this task included:

- Use case and CONOPs, since mission/task requirements directly impact the *m:N* ratio and operation capabilities.
- The impact of flight phases on crew roles and allocations.
- Multi-UAS composition – homogeneous vs. heterogeneous UAS.
- Number of UAS supported.
- Embedded UAS mission capabilities, such as autonomy levels to support inspection, delivery, etc.
- Crew training requirements and assessment of competency.
- Delay-Tolerant-Network infrastructure dependencies.
- Standardized command and control system requirements vs. mission specific custom requirements, including interaction modalities to support system inputs (e.g., mouse and keyboard vs. haptic) and outputs (e.g., flight path plan vs. current position).
- UAS interoperability.
- Impact of contingency scenarios on command and control.
- Human performance metrics (e.g., workload, fatigue, vigilance).

This sub-task was completed in conjunction with the early efforts to support sub-task 3.1 (see Section 2), and leveraged results from ASSURE Center of Excellence efforts that were recently completed or on-going [5,9,10]. Those efforts determined that while relevant UAS hardware existed (e.g., Drone Amplified's aerial ignition UAS), there were no plans to use these systems in a 1:*N* manner due to flight regulations. The team interviewed various industry and wildland fire subject matter experts to understand existing UAS usage, and to identify how a potential *m:N* system may be used in the future. The team interviewed relevant United States Department of Agriculture personnel, and participated in two FAA ASSURE Center of Excellence A-52 disaster preparation workshops for wildland fire: New fires in Satellite data and Prescribed burns. The team also interviewed industry experts to understand *m:N* operations by DroneUp, Matternet, Parallel Flight, Sierra Nevada Company (Volansi), Wing, and Zipline. Other industry teams, include BETA Technologies, Duece Drones, Phoenix UAS and Skydio were investigated, but not interviewed, due to lack of direct relevance to this effort. Adams also attended or participated as a speaker in multiple NASA *m:N* workshops throughout the performance period.

The data collection from these sources included how the industry flight operations were conducted, and details about what the relevant crew roles were for each of the respective systems, some of which were deployed commercially outside of the United States. All such systems used homogeneous UAS, and the number of UAS deployed varied based on regulatory approvals and domain application, with the fewest being 1 human to 2 UAS. It is noted that the team's primary partner, Wing, continually received new approvals for an increased number of *N* vehicles throughout this grant's performance period. The majority of the commercial systems, all of which were Group 1 UAS, were designed to be highly autonomous with minimal human control responsibilities, but required FAA certified remote human pilots. The organizations and companies that the team interviewed had anecdotal information regarding the remote human pilot's performance metrics, and were eager to have actual data that captured such performance information.

The assessment determined that there were no relevant public safety $m{:}N$ systems that were being actively used, either developed or planned. Ultimately, the team devised a relevant wildland fire use case that can be implemented on existing $m{:}N$ systems, in this case delivery drone services. The subsequent lightning strike use case (see Section 2.1) aligned well with the commercially available delivery drone services, which allowed the team to leverage their relationship with Wing to conduct a HITL with Wing's operational system's simulator and their certified pilots. The large UAS wildland fire use case (see Section 2.2) was developed later to investigate and conduct a HITL for a different, but still relevant, scenario.

4 Task 3.3: Human-in-the-Loop Evaluations

The HITL evaluations were designed to conduct flight evaluations of selected solution(s), either that can be acquired by the research team or the research team is provided access to by external sources. This sub-task required:

- Define operational evaluation scenarios for the selected use case.
- Develop the experimental design and methodology in accordance with human subjects evaluation requirements, including determining the appropriate independent and dependent measures, with a focus on objective metrics (e.g., workload) while also assessing overall system performance.
- Summary report providing quantitative results and qualitative assessment of efficacy, gaps identified, and product maturity roadmap.
- Provide *m:N* operability recommendations, targeting industrial and consumer levels of gradation.

Two HITL evaluations were conducted during this effort. Both evaluations focused on understanding the factors that do indeed impact *m:N*. Much of the previous work on the *m:N* ratio has directly focused on the number N of UAS allocated to each pilot. This focus is not necessarily the correct focus. Both prior work [5, 11], and industry partner subject matter expert feedback, have identified several factors that do have an impact on the *m:N* ratio. Adams has presented these factors in various venues including the spring 2024 and summer 2025 NASA Multi-Vehicle *m:N* Working Group meetings. The factors are:

- The **Human-Robot Interaction Role** factor defines the interactive relationship between humans and robots (i.e., UASs). The roles range from a bystander with limited interaction with a robot to the common supervisor role [14, 20–22]. All use cases analyzed for the reported research assumed the human had a Supervisor role.
- The **robot heterogeneity** factor represents whether the UASs represented are all identical (i.e., homogeneous) in terms of form factor, behaviors and payloads, or have some level of heterogeneity.
- The **reliable and validated autonomy** factor represents whether or not the UAS are able to fully autonomously handle nominal and off-nominal (i.e., unexpected events) conditions, or whether the human has some level of responsibility to verify UASs capabilities and responses, which is typically reflective of a lower level of autonomy.
- The **environmental complexity** factor captures how complex the mission deployment environment is and the potential impact on *m:N*. For example, an urban area with many tall structures, high civilian populations, and multiple commercial airports has higher complexity than a larger rural area composed of flat plains, low civilian population, and no commercial airports.
- The **spatial operational area** factor is highly relevant to remote pilot (i.e., Supervisor) missions, as a larger area will require more visual scanning and thus workload.
- The **environmental conditions** factor focuses on aspects such as weather that can vary on a daily or hourly basis. For example, heavy weather (e.g., thunderstorms) can ground Group 1 UAS.

- The **communication requirements** factor reflects the amount and type of communications, as well as the party that is being communicated with. For example, a large UAS must communicate within the air traffic control system.

As stated, no *m:N* public safety UASs existed that were able to be used in this work. An analysis comparing the lightning strike use case system to a commercially active delivery drone systems (see Section A.3) determined that a delivery drone system was a viable alternative. The team worked with various industry partners, and ultimately Wing teamed with OrSU. The intention was to conduct two evaluations with Wing's pilots. The first evaluation focused on assessing baseline pilot performance by manipulating the (1) number of nests (i.e., launch and recovery areas), and (2) UASs deployed. The second evaluation was intended to incorporate UAS with fully autonomous DAA capabilities, and to manipulate the listed factors that impact the *m:N* ratio. This second evaluation was expected to occur before the completion of this project; however, the OrSU effort was dependent on Wing rolling out updates to their operational system, procedures, and simulator. Unfortunately, these updates were not completed in time to support a second evaluation within the project duration. The Large Wildland Fire Response use case and evaluation were developed and conducted as a replacement to the second planned Wing evaluation. Necessary Institutional Review Board (IRB) approvals were obtained for both evaluations.

4.1 Small UAS Delivery Evaluation

The within-subjects small UAS delivery evaluation was designed in collaboration with Wing personnel, and was conducted at Wing's operational facility located in Dallas, Texas. Wing's trained and FAA certified pilots participated in two one-hour trials. The trials established baseline results with a maximum number of launch/landing areas and the maximum number of UASs (approximately 100) capable of being simulated, which is significantly more than the numbers Wing's pilots were actually operating with in March 2024. A link to the full evaluation report is available in Appendix B. The evaluation relied on Wing's custom flight simulator, custom pilot-in-command user interface, public ADS-B flight data, and weather information. During each trial, each of the seven pilots completed three nominal task periods, two detect and avoid events periods, and one weather event period, while objective and subjective performance metrics were collected. All task periods were 10 minutes in length to ensure that the physiological performance metrics were able to collect sufficient data to estimate performance. The trials' first DAA event involved a single crewed aircraft, while the second DAA event involved two crewed aircraft. The weather event occurred during the last ten minute task period, as Wing shuts down operations for the rest of the day when severe weather occurs. During each trial, the ADS-B data was for live crewed aircraft and the incursion crewed aircraft were injected into the ADS-B display. The subjective metrics included in-situ workload probes and situation awareness probes that occurred during each ten minute inter-trial period.

The evaluation hypothesis was that manipulating the number of active UAS, the number of UAS launch/landing areas, and the unexpected conditions will not impact operator performance, where performance is measured by workload, situation awareness and focus of attention. The results showed that the pilots actively engaged in the tasks and had good to very good situational awareness across all conditions. Manipulation of the conditions did not result in any large changes in overall workload, which always remained in the normal range. The pilots visually focused the most on the ADS-B display, followed by the Wing user interface. The Weather display received increased attention during the adverse Weather task. Pilots also interacted with the ADS-B display and Wing interface nearly exclusively, and in ways that demonstrated they were gathering pertinent information relevant to their job duties. These interactions were largely consistent across tasks and trials, although the interaction rate was naturally affected by the nature of unexpected events.

There is no evidence that the typical *m:N* factors impacted pilot performance. The Wing pilots act in a supervisory human-robot interaction role, with system level control, meaning that the pilot issues system level commands. Wing's validated and reliable fully-autonomous UASs relieve the pilots from managing or commanding individual UAS. Further, the Wing system also removes the need for the pilot to communicate with other humans in relation to delivery activities on a regular basis. Each of these factors enable a higher N UASs. Weather, an Environment Condition, was expected to impact pilot performance, but since Wing grounds the system for the rest of the day when severe weather occurs, this factor does not impact pilot performance or N. The Dallas-Fort Worth, Texas urban area is quite complex, including two commercial airports and a high amount of helicopter traffic; however, the high environmental complexity did not negatively impact pilot performance. The one factor that had a minor impact, a small increase in workload, but still within the normal workload range, was a DAA event with two crewed aircraft that were spatially distant from one another over the operational area. This increased visual workload as the PIC needed to scan a larger visual area of the display during the event. The Spatial Operational Area factor was only present for this one DAA instance, and not in any of the other events that the pilot's encountered.

Importantly, none of the experimental conditions had a negative impact on the pilots' performance. Generally, the pilots performed their job duties successfully, and generally in the same manner when the number of nests and number of active UAS increased, as well as during the DAA encounters and adverse weather conditions. These results debunk the traditional theory that increasing the number of UAS is detrimental to a pilot's performance.

4.2 Large UAS Wildland Fire Response Evaluation

The within-subjects large UAS wildland fire response evaluation was designed to have some characteristics in common with a large UAS delivery drone evaluation [19] when it became apparent in February 2025 that the second planned Wing evaluation was infeasible within the period of performance for this research effort. The wildland fire response evaluation assessed pilot workload and airspace deconfliction under varying levels of operational complexity, please see full details in Appendix C. The simulated wildfire response operations at an untowered airport required FAA certified pilots to supervise four UAS using visual flight rules (VFR), while responding to scripted non-cooperative intruder aircraft and managing associated communications with the Air Boss. The number and composition of non-cooperative intruder aircraft were manipulated. The pilots completed two 30-minute trials that each contained three DAA events and four nominal condition tasks, in addition to monitoring communications traffic and responding to Air Boss communications/requests. The counter-balanced trials represented low and high workload. Both trials began with a nominal operations period, followed by a DAA event, another nominal period, a second DAA event, a third nominal period, a third DAA event, and a final nominal period. The low workload trial's first and second DAA events involved one intruder aircraft each, and the third DAA in this condition involved two separate intruder aircraft that were spatially distributed. The high workload trial's first two DAA events involved two separate, but spatially distributed, intruder aircraft and the third DAA event involved a single intruder aircraft. In all DAA events, the pilots were to take appropriate evasive actions if necessary to deconflict with the intruder aircraft, and then report the situation to the Air Boss. Throughout each trial subjective and objective performance metrics were collected. Physiological sensors were used to gather information to estimate objective pilot workload, and in situ workload probes were collected immediately after each DAA event. Additional objective metrics included pilots' focus of attention, actions with the user interface and communications hardware, task performance efficiency and accuracy, and communication efficiency and accuracy.

The *general research question* was whether the remote pilot's performance were impacted by the operational complexity of airspace incursions when supervising a constant fleet of UAS using VFR in a temporary flight restriction operational area, under standardized environmental and communication conditions. Overall, the remote pilots were generally successful at their tasks. The DAA events did indeed negatively impact their performance, with the double intruder aircraft situations resulting in worse performance. The high workload's second double DAA event was particularly challenging, resulting in the worst performance. The remote pilot's subjective workload increased with these DAA:Double events, and the visual fixations increased for both events, with the double DAA events being higher. The participants were engaged with the tasks, and focused primarily on the Map display in terms of both where they fixated their eyes and their interaction with the system. The remote pilots responded to Air Boss communications, and initiated a very large number of their own communications to the Air Boss. There is no established readback latency for this situation, but many readbacks exceeded the preferred five second latency for crewed aircraft pilots to ATC [23].

While this evaluation did not modulate the number of UAS that the remote pilot was responsible for, the other *m:N* factors were considered. The remote pilots served as supervisor who were also responsible for providing commands to individual UAS, as well as monitoring of and responding to communications. The UAS were assumed to have reliable and validated autonomy, but were unable to autonomously detect and avoid intruder aircraft. The operational area represented quite a large spatial deployment, and there were a reasonable number of Air Boss (as well as background crewed aircraft) communications that the remote pilots had to monitor. The ADS-B traffic was representative of the crewed aircraft traffic in the operational area. The communication requirements did not negatively impact the remote pilots, but the spatially distributed double DAA event did decrease overall performance, and increase pilot workload. While the environmental complexity may be considered high due to the mountainous terrain on which the wildland fired burned, the large UAS flew at altitudes high enough that the actual complexity was quite low and did not impact the *m:N* ratio. Further, since the use case assumed a typical summer month Oregon Cascades Mountain wildland fire, there was no extreme weather. Further, the micro-environmental conditions were not considered given the large UAS flight altitudes. Thus, it can be concluded that only the spatial operational area during the most complex double intruder DAA event slightly impacted the factors related to the *m:N* ratio.

5 Findings and Gaps

A number of important research findings and gaps were identified throughout the entire research project. The identified **findings** include:

- Two different sets of wildland fire response use cases were developed and were computationally modeled. The lightning strike mission assumed Group 1 UAS, and the wildland fire monitoring mission assumed large UAS. The use cases included unexpected events.

- An analysis of the human factors, UAS, Supervisory role, and mission characteristics of the lightning strike use case determined that this mission was very similar to small delivery drone operations (e.g., Wing, Zipline).

- The definition and investigation of factors that were shown to impact the *m:N* ratio, which included: human-robot (UAS) interaction role, robot heterogeneity, reliable validated autonomy, environmental complexity, environmental conditions, spatial operational area, and communication requirements.

- The Wing pilot-in-command and the large UAS wildland fire mitigation HITLs demonstrated that remote pilots serving as supervisors, even when there is a need to interact with an UAS and communicate with an Air Boss, enables *1:N* systems. System level supervision supports larger *N* than systems that require remote pilot interactions with the aircraft.

- Reliable, validated autonomy enabled delivery drone remote pilots-in-command to be responsible for a larger number of *N* UAS with no detriment in performance.

- Environmental complexity and environmental conditions were anticipated to impact *m:N* operations, but were not a factor for Wing's remote pilots-in-command. These aspects were not investigated in the large UAS wildland fire mitigation.

- Incursion events were expected to impact remote pilots in both the Wing small delivery drone and large UAS wildland fire HITLs. The results found that the spatial distance and distribution of multiple near simultaneous incursions had a mild impact on performance, but that performance remained well within acceptable ranges.

- Developed a comprehensive package delivery use case that identified relevant factors, decision points, and potential unexpected events.

- The large UAS wildland fire mitigation HITL required the remote pilots to respond to Air Boss commands and to initiate communication as needed, which was hypothesized to impact performance. The HITL, as designed, did not find any significant impacts on performance as a result of requiring communication by remote pilots.

- The Wing Group 1 delivery drone and the large UAS wildland fire mitigation HITLs determined that both these tasks contain high levels of visual and cognitive workload. The wildland fire mitigation HITL also had fairly high levels of auditory, speech, fine motor, and tactile workload.

- The small delivery drone HITL, in collaboration with Wing as an industry partner, developed a comprehensive evaluation of an autonomous *m:N* system that included several unexpected event conditions, and found that the number of UAS or launch/landing areas did not noticeably impact remote pilot-in-command workload. This evaluation provided a baseline for consideration of autonomous *m:N* operations.

- All HITLs involved human subjects who had at least a private pilot certificate, resulting in objective datasets with representative users, something that has been highly missing in the literature.

- The HITL results and the associated use cases can enable and support the operation of future multiple UAS; consistent with the proposed Part 108 beyond visual-line-of-sight recommendations.

- Primary investigator Adams has been invited to many meetings, including the NASA *m:N* working group meetings, to present the outcomes of this research. It is noted that within the last year, the NASA *m:N* Working Group has incorporated the identified factors into their reporting and outcomes.

The identified **gaps** include:

- Interviewed several Wildland fire response subject matter experts, and determined that there were no *m:N* UAS systems in usage or planned to be used in the near future.

- There are no deployed public safety *m:N* systems, which is primarily due to FAA regulations. The newly proposed FAA Part 108 regulations will expand complex operations to permit beyond visual line-of-sight operations, which may result in the viability of *m:N* systems to support public safety.

- Prior work conducted a comprehensive literature review and concluded that there were no relevant *m:N* datasets for highly autonomous systems [5]. While recent work [11] created the first objective dataset, there are no such hardware multiple UAS objective datasets for public safety systems.

- Existing human performance modeling tools overestimate observed workload (IMPRINT vs. HITL) because of their inability to properly model the workload associated with *m:N* systems.

- There is a lack of understanding of what mitigation strategies will enhance management of *m:N* systems (i.e., training, user interface design, hand-offs, task characteristics like no UAS displayed on the screen).

- There are assumptions that handling *N* UAS must be done in a manner similar to how air traffic controllers handle crewed aircraft. There is a need to more accurately understand the true factors that influence how remote pilots manage *N* UAS for public safety situations, as many such situations will have differing mission objectives and operational environments (e.g., urban building fire vs. wildland fire in a remote mountainous area).

- Little research has focused on the *m:N* human factors requirements for large UAS that must use towered or untowered airports, including the implications of managing ATC and Air Boss communications.

- While there is a known five second latency preference for crewed aircraft pilot readback to ATC, no such guidance exists for uncrewed aircraft pilot readback latency to the Air Boss. Differences between, and complexities of, public safety domains may impact that threshold.

- There remains too much focus on the *m:N* ratio, specifically the number of UAS to remote pilot. This ratio is too simplistic for understanding how many UAS a single human can be responsible for.

- There remains a lack of understanding of how different components of overall workload (i.e., cognitive, auditory, speech, visual, gross motor, fine motor and tactile) impact a human's ability to be responsible for N UAS.

- There remains a lack of datasets that exercise the full set of factors that truly impact the *m:N* ratio.

6 Conclusions

This research effort focused on the human factors requirements associated with a single human supervising–and having responsibility for–multiple UASs in public safety situations. This research leveraged prior results from several FAA ASSURE Center of Excellence projects efforts, which provided baseline knowledge and enabled a deeper analysis of the factors that influence the *m:N* ratio. This facilitated the establishment of objective HITL datasets composed of participants with at least an FAA private pilot certification. The HITLs included both crewed and uncrewed aircraft pilots with a broad range of flight hours, experience, and ages. The derived wildland fire-focused use cases spanned small and large UAS operations, and were computationally modeled and evaluated. The research effort identified and analyzed multiple factors that impact the *m:N* ratio, which have subsequently been adopted by the NASA *m:N* working group. The research effort addressed gaps in knowledge that are currently a barrier to the safe, efficient, and timely usage of multiple UAS systems for public safety operations, but also identified a number of key gaps that must be addressed to enable the future usage of multiple UAS systems in public safety.

7 Acknowledgments

The reported research was supported through University Space Research Association award #904186092. The contents are those of the authors and do not represent the official views of, nor an endorsement, by the National Aeronautics and Space Administration or the U.S. Government. The authors thank Wing, their Wing collaborators, and Wing's pilots for supporting the small delivery drone human-in-the-loop evaluation. The authors also thank all the subject matter experts who informed the overall research directions and outcomes.

Bibliography

[1] "FAA Code of Federal Regulations (14 CFR) Part 107-Small Unmanned Aircraft System," 2016, https://www.ecfr.gov/cgi-bin/text-idx?node=pt14.2.107&rgn=div5.

[2] M. Goodrich and D. Olsen, "Seven principles of efficient human robot interaction," in *IEEE International Conference on Systems, Man and Cybernetics*, vol. 4, 2003, pp. 3942–3948 vol.4.

[3] M. Lewis, "Human interaction with multiple remote robots," *Reviews of Human Factors and Ergonomics*, vol. 9, no. 1, pp. 131–174, 2013.

[4] H. Yanco and J. Drury, "Classifying human-robot interaction: An updated taxonomy," in *IEEE International Conference on Systems, Man and Cybernetics*, vol. 3, 2004, pp. 2841–2846.

[5] J. A. Adams, P. Uriarte, C. A. Sanchez, T. Read, J. Glavan, E. J. Bass, T. Haritos, and K. Silas, "A26 A11L.UAV.74 : Establish pilot proficiency requirements multi-UAS components, final report," FAA's ASSURE Center of Excellence, Tech. Rep. A26 A11L.UAV.74, November 2022.

[6] E. Bass, J. A. Adams, C. A. Sanchez, and T. Haritos, "A26: Establish pilot proficiency requirements multi-uas components, literature review," FAA's ASSURE Center of Excellence, Tech. Rep., February 2021".

[7] E. J. Bass, R. Amey, J. Glavan, T. Read, N. Raghunath, C. A. Sanchez, K. Silas, T. Haritos, and J. A. Adams, "Participant characteristics in human-in-the-loop studies with multiple unmanned vehicles including aircraft," in *Human Factors and Ergonomics Annual Meeting*, 2022.

[8] J. J. Glavan, E. J. Bass, C. A. Sanchez, T. Read, and J. A. Adams, "Measures of attention in autonomous and semi-autonomous multi-vehicle supervision," in *IEEE International Conference on Human-Machine Systems*, 2022.

[9] J. Hendrix, R. M. Mead, S. Warr, J. P. O'Neil-Dunne, P. Webley, H. C. Jr., C. Cahill, J. A. Adams, M. Olsen, E. Arnold, A. Zylka, D. Findlay, R. Garcia, and J. Ma, "A28_A11L.UAS.68 : Disaster preparedness and response using uas, final report," FAA's ASSURE Center of Excellence, Tech. Rep. A28_A11L.UAS.68, June 2022.

[10] C. Calama and Others, "A52_A11L.UAS.68 : Disaster preparedness & recovery for UAS phase II, final report," FAA's ASSURE Center of Excellence, Tech. Rep. A52_A11L.UAS.68, October 2024.

[11] J. A. Adams, J. Hamell, and P. Walker, "Can a single human supervise a swarm of 100 heterogeneous robots?" *IEEE Transactions on Field Robotics*, vol. 2, pp. 46–80, 2025.

[12] R. Brown and J. A. Adams, "Congestion analysis for the darpa offset ccast swarm," *IEEE Transactions on Field Robotics*, vol. 2, pp. 21–45, 2025.

[13] S. Clark, K. Usbeck, D. Diller, and R. E. Schantz, "CCAST: A framework and practical deployment of heterogeneous unmanned system swarms," *GetMobile: Mobile Comp. and Comm.*, vol. 24, no. 4, p. 17–26, mar 2021. [Online]. Available: https://doi.org/10.1145/3457356.3457362

[14] J. B. Lyons, A. Capiola, J. A. Adams, J. D. Mator, E. Cherry, and K. Barrera, "Examining the human-centred challenges of human–swarm interaction," *Philosophical Transactins of The Royal Society A*, vol. 383, no. 2289, p. 38320240140, 2025.

[15] P. Walker, J. Hamell, C. A. Miller, J. Ladwig, H. Wauck, and P. K. Keller, "Immersive interaction interface (i3): A virtual reality swarm control interface," *IEEE Transactions on Field Robotics*, vol. 1, pp. 424–445, 2024.

[16] R. L. Holle, K. L. Cummins, and W. A. Brooks, "Seasonal, monthly, and weekly distributions of NLDN and GLD360 Cloud-to-Ground Lightning," *Monthly Weather Review*, vol. 144, no. 8, pp. 2855 – 2870, 2016.

[17] T. L. Koehler, "Cloud-to-ground lightning flash density and thunderstorm day distributions over the contiguous united states derived from nldn measurements: 1993–2018," *Monthly Weather Review*, vol. 148, no. 1, pp. 313 – 332, 2020.

[18] M. L. Rorig and S. A. Ferguson, "Characteristics of lightning and wildland fire ignition in the Pacific Northwest," *Journal of Applied Meteorology*, vol. 38, no. 11, pp. 1565 – 1575, 1999.

[19] A. M. Dassonville, "Limitations of pilot-ATC communication in multi-uas operations," Master's thesis, Oregon State University, 2025.

[20] J. A. Adams, J. Scholtz, and A. Sciarretta, "Human-robot teaming challenges for the military and first response," *Annual Review of Control, Robotics, and Autonomous Systems*, vol. 7, pp. 149–173, 2024.

[21] M. A. Goodrich and A. C. Schultz, "Human-robot interaction: A survey," *Foundations and Trends in Human-Computer Interaction*, vol. 1, no. 3, pp. 203–275, 2007.

[22] J. Scholtz, "Theory and evaluation of human robot interactions," in *Annual Hawaii International Conference on System Sciences*, 2003.

[23] C. A. Wolter, K. Davikoff, and R. Rorie, "Pathfinding for airspace with autonomous vehicles (PAAV) tabletop 4 final report," Available at https://ntrs.nasa.gov/citations/20230006884, NASA, Tech. Rep. Tech. Rep. 20230006884, 2023.

[24] J. Flynn, "15+ average commute time statistics [2023]: How long is the average American commute?" 2023, https://www.zippia.com/advice/average-commute-time-statistics/.

[25] G. A. Miller, "The magical number seven, plus or minus two: Some limits on our capacity for processing information," *Psychological Review*, vol. 63, no. 8, pp. 81–97, 1956.

[26] C. Miller, H. Funk, P. Wu, R. Goldman, J. Meisner, and M. Chapman, "The playbook™approach to adaptive automation," in *Human Factors and Ergonomics Society Annual Meeting*, 2005, pp. 15–19.

[27] Zipline, "Zipline website," Accessed 07-11-2023, https://www.flyzipline.com/technology.

[28] N. L. Schomer and J. A. Adams, "Mountain search and recovery: An unmanned aerial vehicle deployment case study and analysis," *Journal of Field Robotics*, vol. 41, no. 8, pp. 2583–2596, 2024.

[29] J. Zhang, J. F. Campbell, D. C. Sweeney, and A. C. Hupman, "Energy consumption models for delivery drones: A comparison and assessment," *Transportation Research Part D: Transport and Environment*, vol. 190, p. 102668, 2021.

[30] J. K. C. S. Stolaroff, E. R. O'Niell, A. S. Mitchell, and D. Ceperley, "Energy use and life cycle greenhouse gas emissions of drones for commercial package delivery," *Nature Communications*, vol. 9, p. 409, 2018.

[31] J. A. Paredes, C. Saito, M. Abarca, and F. Cuellar, "Study of effects of high-altitude environments on multicopter and fixed-wing UAVs' energy consumption and flight time," in *IEEE Conference on Automation Science and Engineering*, 2017, pp. 1645–1650.

[32] G. Diehl and J. A. Adams, "Battery variability management for swarms," in *Distributed Autonomous Robotic Systems*, F. Matsuno, S.-i. Azuma, and M. Yamamoto, Eds. Springer International Publishing, 2022, pp. 214–226.

[33] J. Steenhuisen, M. M. De Weerdt, and C. Witteveen, "Enabling agility through coordinating temporally constrained planning agents," in *International Conference on Information Systems for Crisis Response and Management,*, 2007, p. 457–466.

[34] R. Parasuraman, T. B. Sheridan, and C. D. Wickens, "A model for types and levels of human interaction with automation," *IEEE Transactions on Systems, Man, and Cybernetics - Part A: Systems and Humans*, vol. 30, no. 3, pp. 286–297, 2000.

[35] B. T. Baxley, M. T. Palmer, and K. A. Swieringa, "Cockpit interfaces, displays, and alerting messages for the interval management alternative clearances (IMAC) experiment," National Aeronautics and Space Administration, Tech. Rep. 20150014350, Jul. 2015. [Online]. Available: https://ntrs.nasa.gov/citations/20150014350

[36] K. Y. Hui, C. H. Nguyen, G. N. Lui, and R. P. Liem, "AirTrafficSim: An open-source web-based air traffic simulation platform," *Journal of Open Source Software*, vol. 8, no. 86, p. 4916, Jun. 2023.

[37] J. Heard and J. A. Adams, "Multi-dimensional human workload assessment for supervisory human–machine teams," *Journal of Cognitive Engineering and Decision Making*, vol. 13, no. 3, pp. 146–170, 2019. [Online]. Available: https://doi.org/10.1177/1555343419847906

[38] J. Hendrix, Personal Communication, Aug.. 2025.

A Lightning Strike Wildland Fire Monitoring

The lightning strike wildland fire monitoring mission was identified as a task that requires multiple UAS to conduct. Overall the task considers deploying multiple UAS to investigate wildland areas where lightning strikes have occurred to identify any indicators of the start of a wildland fire. This appendix presents the nominal and unexpected event use cases, the IMPRINT Pro modeling that was conducted, and a comparison between this use case and delivery drone systems. Since no actual multiple UAS systems were available for the lightning strike, or any other public safety application, the first HITL was conducted for the delivery drone scenario (see Appendix B).

A.1 Use Cases

This use case was developed based on two existing use cases developed for the FAA ASSURE Center of Excellence project A-26 Pilot Proficiency Requirements [5]. The two previously developed use cases were delivery drones and ridgeline aerial ignition. Understanding the use case requires first defining the human roles and component taxonomy and providing any necessary assumptions. The key human and system roles, terms, and information objects used throughout the use case and system design are provided in the following taxonomy.

Taxonomy

- **Supervisor**: Human operator monitoring the UASs controlled by the UAS autonomy (Pilot Flying).
- **Pilot Flying (PF)**: The autonomy controlling the UAS during the mission.
- **Team Lead**: The human deployment team member who oversees the entire team, is responsible for communicating with Incident Command and other responder teams in the deployment area, and is responsible for authorizing deployment initiation. The Team lead also serves as the primary Communications lead.
- **Communication Lead**: The human deployment team member who during the deployment is the central point of communication within the deployment team and with external organizations. This individual also is responsible for monitoring the sensor information provided by deployed UASs and working with the Supervisor to plan additional UAS deployments. The Communications lead is not necessarily a Team lead.
- **Logistics Coordinator**: The human deployment team member responsible for setting, maintaining and breaking down the launch/landing zone, pre-deployment/flight readiness, battery swaps, etc.
- **Utility Specialist**: The human deployment team member that is cross trained to assume the Supervisor, Communication Lead, and Logistics Coordinator team roles.
- **Command and Control (C2)**: system enabling human interaction with UASs.
- **Mission-Flight-Info**:
  - Regional Weather(i.e., wind speeds, precipitation)
  - Generated Flight Path

  - Lightning strike and fire detection related Information (i.e., historical lightning strike locations, recent lightning strike locations, coverage area and path)
  - Energy Parameters (i.e., battery levels)
  - Propulsion Parameters
  - Flight and Navigation information (i.e., airspeed, altitude, location)
  - C2 Workstation and UAS communication link signal strength, quality, or status.
- **Available Capacity**: Value reflective of the current workload of a Supervisor.
- **Route Planner**: A subcomponent of the C2 System, in charge of generating deconflicted UAS flight paths.
- **Uncrewed Aircraft System Traffic Management (UTM)**: Manages airspace and deconfliction for UASs.

A number of general assumptions that inform the nominal use case are presented in Table A.1. These assumptions were formulated based on interviews with industry subject matter experts, or were basic assumptions associated with the research proposal.

Table A.1: The use case assumptions.

General Assumptions
Operations can occur at any time of day, including at night, but are more likely to occur between 1200 and 2000, when dry lightning strikes are most likely.
Deployment teams will be distributed throughout the region/state. Teams may remain in a single location throughout the May to October months or may move on a regular basis to a new location based on the weather forecast.
UAS operations will usually be conducted over areas that are not densely populated, predominantly in rural or remote areas (e.g., state/national forest), and possibly remote with rough terrain wilderness. However, it is possible that operations can occur at the rural/urban interface.
UASs will not be operated close to airports or heliports. 'Close' is initially defined as within 3 miles of an airport, unless permission is granted from air traffic control or the airport authority. A distance of greater than 5 miles will be examined if needed to support an appropriate level of safety.
There is no, or exceptionally limited, cellular or other long range (e.g., radio frequency) communications available at the deployment area. Humans can use radios for local communications. Crews may have satellite communications (i.e., phones). The crew may not have real-time communications with the incident command center.
A small UAS that is potentially designed to an Industry Consensus Standard and has been issued an FAA Airworthiness Certificate or other FAA approval.
All necessary maps are generated prior to departing the mission preparation center, or if reliable communications are available, can be downloaded. If the deployment team remains in the same location each shift, the maps may not change on a daily basis.
Deployment teams are self-sufficient, all necessary equipment is deployed with the team.

Table A.1: Use case assumptions continued.

Multiple deployment teams may share a home base (e.g., snow park), and deconflict the home base area appropriately. The deployment environment conditions (e.g., fire behavior, terrain) may differ from those anticipated prior to mission deployment.
Depending on the actual environmental conditions, the developed mission plan may require modification (e.g., launch/landing area, coverage area).
The multiple UASs may be operating in scenarios that include N UASs with $\leq N$ unique paths distributed over the assigned deployment. The N is limited by the number of UASs that can fit into the deployment team's vehicle (e.g., Conex box on a truck, Conex box "parked" at the deployment location), and may vary depending on the sector size and presence of high priority considerations.
Deployment Team Assumptions
Four-person team: The UAS Supervisor, the Team/Communication Lead who is on the radio communicating with other responders and serves as the sensor/information feed monitor,, the Logistics Coordinator who prepares and manages the physical UASs during the mission, and the Utility Specialist who is trained as the UAS Supervisor, Communications lead and Logistics Coordinator.
The team coordinates with incident command to establish a mission plan prior to departing to conduct the mission. Any human driven vehicles have limited cargo capacity and must accommodate safety gear, UASs, UAS batteries, one or two small generators, etc.
The small (i.e., four person) team is transported via truck with a trailer or some similar type of vehicle. Reaching the deployment area may require driving on poorly maintained rutty dirt roads.
There must be two trained personnel (i.e., one Supervisor and one Communication Lead) in the C2 area at all times during UAS deployments. The Utility Specialist can substitute for either the Supervisor or the Communication Lead as needed.
Mission Assumptions
UAS deployment operations are expected to occur between 1200 and 2000 (12:00 PM and 8 PM) local time.
Total team deployment time, not including driving time, is expected to total 10 hours, with one hour for pre-deployment site setup, and one hour for post-deployment site teardown.
During fire season, it is possible that the deployment vehicle and equipment can be pre-positioned and remain in that location, assuming no impending evacuation is needed.
During fire season, deployments are expected to occur on a regular basis, possibly daily.
Each deployment team is assigned an operational sector within which they are to conduct their operations.
A deployment sector can vary in size depending on environmental conditions and other high priority considerations. A sector in a rural area may be larger than a sector at the rural/urban interface. A sector in an area with complex terrain may be smaller than a sector in other terrain.
Historical cloud-to-ground, in particular dry lightning, strike data can be used to define relevant deployment sector sizes and priorities.
Historical results demonstrate that strikes increase with elevation.

Table A.1: Use case assumptions continued.

Modifiable deployment coverage areas can be pre-defined to reduce Supervisor workload, based on historical cloud-to-ground, in particular dry lightning, strike data, prior wildland fire characteristics, ground fuel data, terrain characteristics, other prioritized characteristics (e.g., urban/rural interface), etc.
UAS Specific Assumptions
Multiple UASs (i.e., 4-20) are required to complete these missions.
Mission UASs will provide sensor feedback of the fire status, deployment area, and the other mission UASs.
Mission UASs permit monitoring where humans and other UASs are located, gathering information to update (off-line) the fire map, etc.
Each UAS has a maximum safe flight time between fifteen and twenty-minutes, not inclusive of the required power level to return to the launch/landing area.
A low power supply UAS replacement (Swap) behavior, when a UAS's battery is depleted prior to mission completion the UAS returns to the launch area and is replaced by another UAS with a fresh battery, is used to provide continuous mission execution.
All UASs fly at least 100 ft above ground.
All UASs can operate up to 15 km from the Supervisor in nominal conditions.
All UASs have a typical flight speed of 5 meters per second, with a maximum speed of 15 meters per second (approximately 35 mph).
Typical UAS sensors include a long-wavelength infrared camera, a visual camera, array of thermal cameras, thermistors, and global positioning system (GPS). Wind speed, both vertical and horizontal, sensors are usually incorporated as well.
While real-time communication of sensor information is possible, it is bandwidth limited beyond 1 km. On-board UAS processing determines in real-time what information (e.g., images, video, other sensor data) to send to the Supervisor and all data is stored for post-deployment download and post-mission analysis.
All UASs have on-board real-time autonomous DAA capabilities.
Supervisor Specific Assumptions
A human Supervisor uses a Command-and-Control (C2) station that permits monitoring and modifying UAS operations as needed.
The Supervisor has been trained, but may only have a high school diploma or equivalent.
A Supervisor has a maximum limit of UASs to supervise simultaneously.
Each deployment team Supervisor is responsible for a sector of the operational area that is deconflicted from other deployment team Supervisors and is based on the physical location of the deployment and the terrain.
The UASs are highly autonomous, and the Supervisor is generally monitoring progress with very little interaction.
Each UAS is assigned a separate and independent goal location that does not overlap with other goal locations, or each UAS is assigned a coverage area, possibly as part of a UAS team.
Situation awareness is generally related to what is transpiring with the overall system, meaning all monitored UASs are healthy and completing their task without issue.

Table A.1: Use case assumptions continued.

At a minimum, a portion of the C2 interface display contains a map of the Supervisor's area of responsibility (i.e., sector) that includes individual glyphs for each deployed UAS for which the Supervisor is responsible.
At a minimum, the C2 interface provides an ability to display a map-centric interface with UAS paths and coverage areas, as well as the ability to specify coverage areas or waypoints.
At a minimum, a portion of the C2 interface display will provide the Supervisor with critical deployed UAS specific mission information (i.e., mission status, vehicle health status, airspeed, navigation path, communication connectivity).
At a minimum, the C2 interface provides the ability to access relevant mission information (i.e., coverage area, sensory information to confirm fire).
The Supervisor is not directly responsible for monitoring sensor feeds (e.g., cameras), but does have the ability to view the sensor feeds directly on the C2 interface.
The Supervisor is only permitted to deploy and operate UASs in the deployment team's assigned sector.
If the Supervisor requires a break, the current Communications lead replaces the Supervisor. If something precludes the Communications lead from serving as the Supervisor, the Utility Specialist replaces the Supervisor.
Communication Lead Specific Assumptions
The Communications lead is responsible for communicating with other responders in the area, and if reachable, with incident command.
The Communications lead is responsible for monitoring the sensor feeds (e.g., camera) and notifying the Supervisor of any pertinent information or needed mission changes.
During the mission deployment, the Communication Lead is positioned near the Supervisor to facilitate direct verbal communication (i.e., no radio communication required).
If the Communications lead requires a break, the Utility Specialist replaces the Communications Lead.
Logistics Coordinator Specific Assumptions
The Logistics Coordinator is responsible for all UAS hardware specific tasks, including verifying launch zone spacing, hardware readiness, battery swaps, etc.
The Logistics Coordinator has a deployment system, likely handheld, that indicates the home locations for each UAS, facilitates pre-flight checks, and can be used to monitor impending launches/landings.
It is feasible, if there is sufficient time, that the Logistic coordinator can leave the area for a biological break that will not exceed the time between UAS launches and landings.
If the Logistics Coordinator requires a longer break, then the Utility Specialist replaces the Logistics Coordinator.
Utility Specialist Specific Assumptions
The Utility Specialist is cross trained as a Supervisor, Communication Lead, and Logistics Coordinator. The Utility Specialist is intended to be an individual who can substitute for any team role when needed.

Table A.1: Use case assumptions continued.

During pre-deployment set up, the Utility Specialist can assist in any activity. If there is a larger number of UASs (e.g., 20), then the Utility Specialist is likely assisting the Logistics Coordinator in the launch/landing area with hardware preparations.
During the deployment, the Utility Specialist is located in C2, unless needed to replace the Logistics Coordinator, in order to ensure the Utility Specialist is aware of the current activities and can quickly take over as either the Supervisor or Communication Lead.
Unexpected Event Assumptions
If a UAS crashes, the practice is to leave it in place.
Unexpected events (UE) can, and will, happen when a UAS is out of communications with the deployment team. The UAS must be able to handle the UE autonomously and there is nothing that the deployment team can do to mitigate the situation.
The UASs must be able to handle UEs autonomously.

A.1.1 Nominal Use Case

An overview of the nominal lightning strike wildland fire detection scenario. The use case is divided by flight phase.

Pre-deployment Activities

Since the mission deployment occurs in a remote area, potentially without communications with incident command, a number of pre-deployment activities are necessary in order to enable mission readiness upon arrival at the mission deployment site. These activities are conducted at the mission preparation center with the knowledge that access to communications is likely to be limited at the mission deployment site.

The information required to conduct the mission includes:

- Known wildland fire hazards.
- Current and predicted known wildland fire behavior and weather (wind is an important factor for the fire behavior).
- Current fire activities and progress of known wildland fires.
- Ground cover fuel type, density in the assigned mission deployment sector.
- Topography and other necessary maps for the assigned mission deployment sector.
- Ingress and Egress routes for the team (options).

This information is used to develop a safe mission plan that incorporates all the above with the expected weather conditions, number of UASs, designation of the flight region and geofence, deconfliction plan, flight plan - including potential UAS navigation plans-, and expected mission duration for anticipated deployment areas.

The UASs' navigation path plans either include specified lightning strike locations (e.g., waypoints), or a coverage area that automatically determines the coverage pattern and sensor collection points. If the Supervisor provides a coverage pattern (e.g., a pattern with points at which lightning strikes have occurred or are anticipated), the system automatically generates navigation paths and monitoring locations for all UASs. The mission plan is reviewed with the relevant personnel and approved to ensure sector deconfliction across lightning strike crews as well as deconfliction with other uncrewed and crewed aircraft in the sector's area.

Deployment Location Arrival and Preparation

1. The team of four individuals (i.e., UAS Supervisor, Communications Lead, Logistics Coordinator, Utility Specialist) deploys with four to twenty UASs.
   (a) The team may drive to the location with their equipment.
   (b) The team may drive to a location with prepositioned equipment.
2. If driving to a new deployment zone, then while the team drives, the Supervisor reviews the assigned sector, historical information related to wildland fires, lightning strikes, etc. including:
   (a) Deconfliction
   (b) Weather
   (c) Known fires in the area and their behavior
   (d) Known ground fuel level
   (e) Assigned sector, geofence and potential flight plans
   (f) Topography
   (g) Known hazards
   (h) Logistics
   (i) Safety plan
   (j) Historical lightning strike locations.
3. If the team is assigned to a single deployment location for an extended time period (e.g., each day they deploy from the same location), then the Supervisor reviews the information listed in item 2 either before departure or upon arrival.
4. Upon arrival at the deployment location,
   (a) If communications are available with the incident command center, the Communication Lead communicates the team's arrival at the deployment location.
   (b) The Communication Lead communicates to other responders, if any, within radio range the intent to launch the mission.
   (c) The deployment team assesses the local conditions for safely deploying the UASs and conducting the mission. The location has to be inspected to ensure that it is safe for the team to set up and deploy the UASs from this location. The deployment team must consider the listed factors. If dangers are identified in the specified launch/landing area, the team must identify a new safe launch/landing location at which they will set up and from which they will launch the UASs. The team may also update the overall mission plan.
      i. Known fire behavior
      ii. Assigned sector
      iii. Terrain
      iv. Weather
      v. Known hazards
      vi. Other deployment teams working from the same area.

(d) The team identifies a launch/landing area and a location for the communications equipment (e.g., open terrain with no tree coverage, no dangerous obstacles). The communications equipment allows the UASs to communicate locally with the team.
(e) The team sets up the UASs and communications equipment, prepares extra UASs to be used later in the mission as replacement UASs when power sources are depleted on deployed UASs.
(f) The team completes safety checks on the UASs and communications equipment.

Pre-Launch Preparation

1. If communications are available with the incident command center, the Supervisor via the Communications lead verifies:
   (a) Assigned sector and mission plan, including navigation routes.
   (b) Known fire behavior
   (c) Weather
   (d) Sector
   (e) Deconfliction.
2. The team
   (a) Reviews the high-level mission and each individuals' role.
   (b) Places prepared UASs in the launch/landing area.
   (c) Completes final safety checks on all systems: Supervisor controller, communications, and UASs.
3. If communications are available with the incident command center, the Communication Lead communicates intent to commence the mission.
4. The Communication Lead communicates to others in radio range the intent to commence the mission.

A.1.2 Human Team Roles by Flight Phase

The human team roles are presented by role and flight phase.

A.1.2.1 UAS Supervisor

Pre-deployment

1. The Supervisor plans the deployment based on either:
   (a) Coverage of known areas with high lightning strike histories.
   (b) Receives notification of a lightning strike to investigate.
2. The Supervisor reviews how many UASs are recommended to address the new strikes or the coverage areas. The Supervisor verifies that the required number of UASs are available for deployment.
   (a) If the required number of UASs are available, then the Supervisor notifies the Logistics Specialist who begins the Pre-Flight Phase preparations.
   (b) If there are not enough UASs,

i. The system can generate a deployment plan with only the available UASs.
ii. The Supervisor can instruct the system to generate a deployment plan with only the available UASs.

3. The Supervisor validates that the deployment plan is ready for launch, which requires:
   (a) Loading the plan into the Supervisor's interface.
   (b) Opening the plan nodes (nodes in a graph) and visually reviewing the node elements.
4. The Supervisor validates team readiness for imminent deployment.
   (a) The Supervisor asks the Communications lead if the team is ready (does not require a radio to do so).
   (b) The Communications lead provides a verbal response. The Supervisor does not have permission to launch the mission until the Communications lead indicates mission readiness. Mission readiness requires verifying with the Logistics Coordinator that all UASs are mission ready and it is safe to begin.
5. If communications are available with the incident command center, the Communication Lead communicates imminent deployment launch.
6. The Communication Lead communicates to others in radio range imminent launch.

Launch, Ascent to Altitude

7. The Supervisor launches the deployment plan. The plan may launch the UAS(s) in different configurations, represented by "Variants".
   (a) **Variant 1**: All UASs launch simultaneously
      i. The UASs launch and begin executing the deployment plan.
      ii. *Note:* This approach may result in congestion if there are multiple vehicles launching simultaneously.
         a. To navigate to multiple strike independent strike locations that are in the same general direction.
         b. To navigate to a coverage area.
   (b) **Variant 2**: The UASs launch in sequence to ensure all UASs avoid congestion. *Note:* This variant is likely to be the most common.
      i. A subset of UASs launch and begin executing the mission. This pattern repeats until all UASs are launched. The UASs with the furthest deployment goals (e.g., strike zone or coverage area) may launch first. This ordered launch sequence sends the UASs to strike locations or coverage areas based on factors like route length and proximity.
         a. There may be multiple deployment plan launch nodes representing sub-missions.
         b. First launch node command is sent.
         c. UASs for that node take off and begin moving to their designated locations.
         d. Once the UASs clear out of the airspace above the launch zone, repeat steps 7.b until all mission plan launch nodes are completed.

ii. The UASs fly to their designated strike locations or start point of their coverage area.

Enroute, Area Coverage

8. The UAS(s) autonomously navigate to their goal locations.
9. Upon arrival at the strike location or the start locations for a coverage area, all UASs autonomously begin the search of the area.
   (a) If only a strike location was provided, then the search is composed of covering the location $+X$ diameter around the location, depending on terrain and fuel type.
   (b) If a coverage area has been defined, then the search paths have been planned for and are conducted.
10. As the deployment plans execute, the UASs execute their planned search paths. Note: this step can occur simultaneously and interchangeably with Supervisor steps 7–13.
    (a) As the UASs execute the search, the Supervisor visually monitors their mission progress and ensures the mission objectives are achieved.
        i. During the monitoring task the Supervisor discusses with the Communications lead the:
            a. Resulting fire identification to determine if the deployed UAS(s) need modified deployment plans to capture additional information.
            b. Strike locations to determine
                - For which to develop deployment plans or prioritize higher.
                - for which may no longer require investigation.
                - for which may require a follow-up visit after a period of time.
                - If the deployment plan's default area around a strike location requires modification to gather either a broader area or additional information.
            c. Coverage areas to determine
                - for which to develop deployment plans or prioritize higher.
                - for which may no longer require investigation.
                - for which may require a follow-up visit after a period of time.
                - If the deployment's coverage navigation plan requires modification to Assign or accommodate more UASs, De-assign or remove UASs from the area, and Modify the coverage area size or coverage navigation paths.
        ii. Once the plan(s) are adjusted, the Supervisor reviews them and makes any necessary further adjustments. UASs in the air will automatically begin executing a new navigation plan once it is generated on-board. If no new plan is needed, the Supervisor resumes visual monitoring of the overall mission. If further adjustments are required, return to the top of Supervisor step 10.
        iii. Modify the UAS(s) deployment plan, generally means modifying:
            A. The strike locations.
                - The Supervisor selects the coverage area.
                - The Supervisor specifies:
                    – New strike locations by selecting strikes, such as clicking on strikes displayed on the map.

- Points on the map that represent a modified or new coverage area.

- The Supervisor sends the new strike locations or relevant coverage area to the UAS.
- The UAS receives the information and automatically replans the navigation path.

B. The coverage area

- The Supervisor selects the UAS.
- The Supervisor can modify the existing coverage area by
  - Modifying the shape of the area object by selecting and dragging the outline of the area or selecting a segment of the area outline for removal and potentially replacement.
  - Modifying "drag points" on the area object by selecting and dragging the drag point or adding a new drag point and integrating it into the area or by removing and potentially adding a new drag point.

C. How a UAS is conducting the coverage search.

(b) If a UAS, or any number of UASs, is no longer needed, the Supervisor can initiate the return to launch (RTL) behavior to land the UAS(s).

i. The Supervisor selects the UAS(s) and issues an RTL command.

11. The Communications lead, possibly the Supervisor, monitors the deployed UASs' sensor feeds relative to their positions. Note: this step can occur simultaneously and interchangeably with Supervisor steps 7-13.

(a) Note: It is unlikely the Supervisor is viewing raw sensor feeds, especially cameras. This job typically falls to the Communication Lead.

(b) The individual monitoring the UAS sensor information communicates important mission relevant information to the Supervisor. This communication may be verbal (e.g., "Can you have UAS 10 hover at the specified location?" - where the location appears on the Supervisor's control system, "Please look at the thermal feed from UAS 10" – This case requires the Supervisor to open UAS 10's thermal camera feed on the Supervisor's control system), or verbal and visual (e.g., "Please look at the video feed from UAS 10" – This case requires the Supervisor to look at the Communication Lead's sensor monitoring system screen).

i. The Communication Lead is monitoring the sensor feeds. Most of the communication between the Supervisor and the Communication Lead is verbal, but the Communication Lead can ask the Supervisor to view particular information (e.g., Surveillance UAS sensor feed). The Communication Lead may also add a point of interest on the sensor monitoring system that when specified can also appear on the Supervisor's control system display. A conversation may occur between that Supervisor and the Communication Lead.

12. If a UAS has an unexpected event (UE) safety issue, the UAS responds autonomously. If the UAS is within communication range, the UAS's visual representation is updated, but the Supervisor really cannot do anything. Note: this step can occur simultaneously and interchangeably with Supervisor steps 7-13.

13. As the deployed UASs' power levels are depleted, they will automatically request a replacement UAS (a lower power swap behavior). Note: this step can occur simultaneously and interchangeably with Supervisor steps 7-13.
    (a) Note: A deployed UAS with a low battery will, depending on the criteria below, automatically execute a Return to Launch (RTL) behavior when a replacement UAS is available.
        i. The RTL behavior requires the UAS with a low battery to navigate a path to its home position and land.
    (b) Note: The time at which the replacement UAS swap is requested depends on how far away the UAS is from the launch/landing zone. UASs that are spatially further from the launch zone will request a replacement UAS earlier than those located spatially closer to the launch zone.
    (c) Note: The Swap behavior is automatic and the Supervisor is not required to do anything on the control interface to verify that a UAS is conducting the Swap behavior, other than visual monitoring.
    (d) Any UAS conducting a non-persistent mission will request a UAS replacement and immediately begin the RTL behavior. Once the returning UAS's request is received, a replacement UAS will launch and navigate to the location at which the returning UAS left off. Upon reaching the returning UAS's last position, the replacement UAS begins completion of the remaining plan.
    (e) Any UAS conducting a persistent deployment (e.g., continuous monitoring is required, which is expected to be rare) will request a UAS replacement when the battery level is higher than in 13.d, will wait until the replacement UAS is within range and then the UAS with a low battery will begin the RTL behavior. If a second critical battery level (i.e., the level required to ensure safe return to the launch/landing zone) is reached, the deployed UAS will automatically RTL.
        i. A UAS conducting persistent deployment will request a replacement UAS earlier than the other cases, as the replacement UAS must arrive at the returning UAS's location at approximately the same time the returning UAS begins navigating to the launch/landing zone.
            a. Upon receiving a replacement request from the deployed UAS, the replacement UAS launches and navigates to the location of the deployed UAS to be replaced.
            b. Once the replacement UAS is within range of the deployed UAS with low power, the low power deployed UAS begins the RTL behavior.
        ii. If the replacement UAS has not arrived within range of the deployed UAS being replaced and the deployed UAS's battery has reached the critical level
            a. The deployed UAS automatically begins to RTL.
            b. The replacement UAS continues to the last position of the deployed UAS before it began to RTL.
    (f) Note: All navigation path planning is done automatically on-board the UASs and is automatically deconflicted with the in-air UASs.
    (g) The Supervisor monitors any activities.

(h) As UASs land with low batteries and it is safe to do so, the Logistics Coordinator
    i. Powers down the UASs.
    ii. Visually inspects the UASs and makes any necessary adjustments.
    iii. Swaps out the depleted battery for a fresh battery.
    iv. Powers on the UASs so that they are ready to be replacement UASs.

Return, Descent from Cruising Altitude, Landing

14. As a UAS completes the deployment plan
    (a) The UAS can Return to launch (RTL).
    (b) If the UAS has sufficient power
        i. The Supervisor can extend the UAS's mission.
        ii. The UAS's on-board planner develops the navigation path, automatically deconflicting with the other UASs.
        iii. The UAS continues the deployment.
15. Once all UASs have landed and the mission is complete
    (a) If communications are available with the incident command center, the Communication Lead communicates the mission has completed.
    (b) The Communication Lead communicates to others in radio range the mission has completed.

Post-Mission

16. The Logistics Coordinator inspects all UASs prior to breakdown and putting away or packing.
17. The team breaks down and packs all equipment.

A.1.2.2 Logistics Specialist

The Logistics specialist has a monitoring device that receives information from C2 regarding which UASs with their corresponding homebase in the launch/landing area will be launched. As well, this device is updated with information from UASs that are RTLing for any reason (e.g., deployment completed, low battery) and can communicate with the overall C2 system to which homebase location a UAS is returning. Further, this device also reports the communication status and battery level of each UAS that is in the launch/landing area and is powered on.

Pre-Flight

A centralized system assigns lightning strike locations (Sites) to deployment teams, assuming communications are possible with the deployed team (e.g., satellite communications).

A designated safe launch/landing area (UAS homebase) has been chosen by the deployment team. The Logistics specialist unpacks all UASs upon arrival. As each UAS is unpacked, it is visually inspected for damage. All UASs with no physical damage are placed in appropriate deployment positions on the launch/landing area.

Once all UASs are in position, including UASs to be used for the Swap behaviors and backup UASs, the Logistics specialist first ensures that all UASs are able to communicate with all necessary systems, including C2.

After the communications check, the Logistics specialist verifies that all UASs have a GPS lock and that the home position is set to the local GPS-based location.

The Logistics specialist performs a preflight verification to ensure the UASs' sensors are working properly and verify their airworthiness.

Any UASs that are problematic can receive active troubleshooting, if time allows, or are put aside for later troubleshooting.

Once the logistics specialist has verified the fleet, a "ready for deployment" message is communicated verbally (e.g., in person or over the radio or via text) to the communications lead.

The Communication Lead will notify the Logistics Coordinator when the mission will commence and UASs are to begin launching.

Launch

A single UAS or multiple UASs are requested for a lightning strike, Site-$ or coverage area, Area-@. The Supervisor creates a mission for the request (Site-$/Area-@) and the Route Planner generates an optimized flight path for Site-$/Area-@, which is deconflicted using the UTM or by segmentation of the airspace if UTM is unavailable.

Meanwhile, at deployment Unit-A's homebase, the UAS(s) is/are selected for Site-$/Area-@ by the deployment system automatically based on available UASs and their battery levels. The Logistics specialist receives updates on a monitoring device as to which UAS homebase locations in the launch/landing area are being launched, and which homebase locations have UASs RTLing for any reason. Site-$/Area-@'s deployment data is uploaded to the UAS(s). The Logistics specialist visually monitors all actual UASs launching and landing.

The UAS(s) will attempt to complete the investigation of Site-$/Area-@ autonomously. The UAS(s) begins an autonomous take-off procedure. The UAS(s)' flight phase status automatically updates on the Supervisor's C2 workstation at the start of seven flight phases: Take-off, Ascent to Cruising Altitude, Enroute, Coverage Search Data Collection, Return, Descent from Cruising Altitude, Landing. The Supervisor monitors all of the team's deployed UASs, which includes the newly deployed UAS(s).

Ascent to Cruising Altitude

The UAS(s) ascend to the designated cruise altitude, assuming vertical take-off and lift. During ascent, the UAS(s) adhere to the deconfliction requirements. The UAS(s)' flight phase status is updated on the Supervisor's C2 workstation, who monitors all assigned UASs.

Enroute

Once at cruise altitude, the UAS(s) follow the generated flight path to Site-$/Area-@ and adhere to the UTM's deconfliction requirements. The UAS(s)' flight phase status is updated on the Supervisor C2 workstation, who continues to monitor all assigned UASs.

Area Coverage

The UAS(s) arrives at Site-$/Area-@. The Site-$/Area-@'s status is updated on the Supervisor's C2 workstation. The UAS(s) begin an autonomous area coverage search looking for fires. If the deployment is for a Site, then the area covered is smaller and for a single UAS. If the deployment is for an Area, then the area covered is in all likelihood larger and can require from 1 to N UAS. The UAS(s) inspection status is updated on Supervisor's C2 workstation, who continues to monitor all assigned UASs.

Return

After UAS-1 completes the area coverage search and assessment, UAS-1 follows an on-board generated flight path back to Unit-A's launch area. UAS-1's flight phase is updated on Supervisor's C2 workstation. Supervisor-X continues monitoring all assigned UASs.

Descent from Cruising Altitude

UAS-1 descends from cruising altitude as it approaches the deployment unit's launch area following the generated flight path. The UAS continues adhering to the deconfliction requirements. UAS-1's flight phase status is updated on the Supervisor's C2 workstation. Supervisor continues to monitor all assigned UASs.

Landing

UAS-1 arrives near the deployment unit's launch area and travels to the designated landing home position. UAS-1's flight phase status is updated on Supervisor's C2 workstation.

UAS-1 begins an autonomous landing procedure. First, UAS-1 searches for its designated landing home position, after which the UAS-1 begins descending. While descending, UAS-1 constantly scans its surroundings. UAS-1 lands and the UAS's mission status is updated to "Complete" on Supervisor's C2 workstation. Supervisor continues to monitor remaining actively assigned UASs.

A.1.3 Unexpected Events

Potential example Unexpected Events were developed and validated as part of the A26 project and were modified for this effort; however, the provided UEs do not represent a complete and detailed analysis of all potential unexpected events. A number of assumptions were derived, as listed in Table A.2. The UEs were organized into the following categories: Supervisor failures, Mission changes, Intentional interference, UAS hardware failures, UAS software failures, Flight path and mission obstructions, and Collisions.

Based on the A26 project results, many UEs will be handled by the UAS's on-board autonomy and; thus, will not add to the Supervisor's workload. The expected frequency of UEs, one (1) or fewer UEs are anticipated per week of operations per vehicle. Generally, as the number of UASs deployed increases, the overall total number of UEs will also increase.

Thirty example UEs were developed and were categorized. Some of these example UEs have a common high-level event, but represent unique variants that impact human

Table A.2: Unexpected Event use case modeling assumptions.

The UAS's autonomy will handle a majority of UEs and not require Supervisor intervention.
The human Supervisor generally does not need to be notified of UEs that are common (e.g., avoiding collisions with stationary or moving obstacles).
It is assumed that the system design is sufficiently mature so that safety critical UEs across the entire operation in which neither the system nor the human can reduce or prevent harm will be extremely rare.
It is assumed that a UAS handles the vast majority of UEs, particularly since a UAS may be out of communications range with C2 and UTM.
If communications are available, then the uncrewed aircraft traffic management system will handle UAS deconfliction; otherwise, airspace segmentation is used for deconfliction. If the UAS is to avoid a collision with an obstacle, then obstacle detection and avoidance automation will handle the situation. Detection and avoidance technology will be used for crewed aircraft.
It is assumed that if a UAS crashes, the UAS remains in the wilderness and is not retrieved.
There is a lower likelihood of danger in a wildland area; thus, there is a higher tolerance for allowing UASs to handle UEs.
All UEs are applicable to multiple UASs.
The UAS autonomy is aware of UEs and classifies the specific type of UE, but the system requirements to support this awareness are beyond the scope of this project.

performance and may do so differently depending on the Supervisor's required response. As well, a single UE may affect multiple UASs simultaneously, or multiple different UEs can occur for either a single UAS or multiple UASs simultaneously.

Each UE was analyzed within the taxonomy and was described using the same format. Prior to providing the format, it is important to define terms that are used throughout each UE description:

- *Nominal Monitoring*: Supervision of UAS(s) that are not experiencing issues completing the assigned delivery mission.
- *Post-Response Monitoring*: Continuous supervision of UAS(s) after the UAS(s) have a command in response to a UE.
- *Periodic Check-ins*: Supervision of UAS(s) for multiple short durations after the UAS(s) have a command in response to a UE.
- *Direct Monitoring:* Direct supervision of a specific UAS with less focus on other UASs.
- *Affected UAS(s)*: The UAS(s) that experienced the UE.

Each UE description includes the following fields:

- *Description*: A brief statement describing what the particular UE represents.
- *Event Severity*: The UE's potential danger or damage to the UAS, civilians or property [1 (low), 10 (high)].
- *Supervisor Notification Need*: Describes how crucial it is to have the Supervisor notified about the UE [1 (low), 10 (high)].

- *Supervisor Response Need:* Describes how crucial it is to have the Supervisor respond to the UE [1 (low), 10 (high)]
- *Autonomy Aware:* Describes whether the UAS's Autonomy is cognizant of the UE's occurrence [Yes, No].
- *Responder*: Describes the party responsible for initially and directly addressing the UE, typically the UAS itself or the Supervisor, although others may also respond.
- *Supervisor Aware*: Describes whether the Supervisor is cognizant of the UE's occurrence.
- *Supervisor Notified*: Describes whether the Supervisor is made cognizant of the UE's occurrence by either being notified by the C2 station, or an external communication source.
- *Additional Supervisor Monitoring Required*: Describes whether the autonomy's or Supervisor's response to the UE requires the Supervisor to either post response monitor, direct monitor, or periodically check in on affected UAS(s).
- *Supervisor Perception Possibilities*: Lists potential methods, without focusing on specific user interface designs, by which the Supervisor can be notified of and made cognizant of the UE's occurrence.
- *Notes*: Contains general comments about the UE and details on the expected autonomy or Supervisor response to the UE.

A.1.3.1 Supervisor Failures

Supervisor C^2 Station Failure

Description: The Supervisor's C^2 station crashes, freezes, is affected by communication outages, or experiences input or output device failure.
Event Severity: 10
Supervisor Notification Need: 10
Supervisor Response Need: 10
Autonomy Aware: Yes, if in communication range
Responder: Supervisor
Supervisor Aware: Yes
Supervisor Notified: Yes
Additional Supervisor Monitoring Required: No
Supervisor Perception Possibilities: Self
Notes: Supervisor Responses to Variations of C^2 Station Failures

- Crash or Freeze
  - The Supervisor C^2 Station is unresponsive due to a system crash or freeze.
  - The Supervisor will attempt to restart the C^2 Station. Simultaneously, the backup C^2 Station is started up.
  - If the main C^2 Station does not restart, the Supervisor will attempt to use the backup C^2 Station.
    * If the backup C^2 Station is viable, then the mission continues as planned. The Utility Specialist will continue to attempt to revive the main C^2 Station.
    * If the backup C^2 Station is also non-functional, then the Communications lead attempts to contact any other deployment teams in the area to have the

team's sector reassigned so that they have control of the UASs. All UASs will RTL to their original launch zone home positions.
    * If the backup C^2 Station is also non-functional, and there are no other deployment teams within communications range and broader communications (e.g., cellular) are unavailable, then the deployment team will wait for the UASs to RTL to their launch zone home positions.

- Output Device Failure (i.e., Monitor failure) or Input Device Failure (i.e., Mouse, Keyboard failure)
  - The Supervisor will first troubleshoot the issue themselves.
  - If unable to successfully troubleshoot the output/input device, the Supervisor will start up the backup C^2 Station to use as a replacement for the main C^2 Station.
  - If the backup C^2 Station is viable, then the mission continues as planned. The Utility Specialist will continue to attempt to revive the main C^2 Station.
  - If the backup C^2 Station is also non-functional, then the Communications lead attempts to contact any other deployment teams in the area to have the team's sector reassigned so that they have control of the UASs. All UASs will RTL to their original launch zone home positions.
  - If the backup C^2 Station is also non-functional, and there are no other deployment teams within communications range and broader communications (e.g., cellular) are unavailable, then the deployment team will wait for the UASs to RTL to their launch zone home positions.

A.1.3.2 Mission Changes

Strike Location/Coverage Area Canceled

Description: The strike location/coverage area assignment is canceled while the UAS is en-route. The Supervisor cancels the assignment.
Event Severity: 1
Supervisor Notification Need: 0
Supervisor Response Need: 0
Autonomy Aware: Yes, if in communications range
Responder: Autonomy
Supervisor Aware: Since the Supervisor has canceled the assignment, the Supervisor is aware and created the response.
Supervisor Notified: No
Additional Supervisor Monitoring Required: No
Supervisor Perception Possibilities: Information about the UE is accessible for the Supervisor via the C2 station within the UAS's mission details.
Notes:

- The Autonomy will update the affected UAS's flight plan or it will RTL.
- The Supervisor does not stop Nominally Monitoring the UAS after the UE occurs. The Supervisor will continue monitoring the UAS until RTL is completed or a new deployment plan is completed.

Strike Location/Coverage Area Updated

Description: Information is received that updates the strike location/coverage area while the UAS is en-route.
Event Severity: 1
Supervisor Notification Need: 0
Supervisor Response Need: 0
Autonomy Aware: Yes, if in communications range
Responder: Autonomy
Supervisor Aware: Since the Supervisor has updated the assignment, the Supervisor is aware and created the response.
Supervisor Notified: No
Additional Supervisor Monitoring Required: No
Supervisor Perception Possibilities: Information about the UE is accessible for the Supervisor via the C2 station within the UAS's mission details.
Notes:

- The UAS has enough fuel to navigate to and from the updated strike location/coverage area. Therefore, the Autonomy updates the UAS's flight plan, and the Supervisor continues to Nominally Monitor the UAS.
- The UAS does not have enough fuel to navigate to and from the updated strike location/coverage area. Therefore, the Autonomy commands the UAS to RTL. The Supervisor continues Nominally Monitoring the UAS until it RTLs.
- The updated strike location is outside of the Supervisor's sector. The update does not occur, and the strike location/coverage area is assigned to another deployment team.

A.1.3.3 Intentional Interference

UAS Experiences Global Position System (GPS) Spoofing

Description: The UAS is GPS spoofed by a malicious actor, and the Supervisor is notified of the GPS inconsistencies reported by the UAS.
Event Severity: 7
Supervisor Notification Need: 5
Supervisor Response Need: 3
Autonomy Aware: Yes. Although the specifics are beyond the scope of the current effort, the Autonomy can become aware of inconsistencies with GPS data, but not that it is being spoofed. The UAS's Autonomy can become aware of the GPS inconsistencies using the following methods:

- comparing the UAS's current reported spoofed position with locations on the originally planned route.
- comparing observed environmental landmarks with known terrain-based landmarks/features distinct to the area in which the UAS is currently.

Responder: Supervisor
Supervisor Aware: Yes. Aware of GPS inconsistency.
Supervisor Notified: Yes. Notified about GPS inconsistencies.

Additional Supervisor Monitoring Required: Yes, as Periodic Check-ins
Supervisor Perception Possibilities: Notified by C2 station

- Text Log without Audible Alert
- Text Log with Audible Alert
- Glyph Change with Audible Alert
- Glyph Change without Audible Alert

Notes:

- Multiple UASs can experience spoofing simultaneously.
- The Autonomy becomes aware of the inconsistencies with its GPS data.
- The Supervisor acknowledges the notification about the GPS inconsistencies.
- The Supervisor periodically checks in to see if the UAS GPS issue has been resolved.
- At any point, if the severity of GPS inconsistencies surpasses a threshold:
  - The Autonomy commands the UAS to attempt to RTL, or land in place. The UAS cannot be permitted to continue to fly its planned path if it is believed to be controlled via GPS spoofing.
  - The Supervisor is notified about the Autonomy's commands and post-response Monitors the affected UAS.

UAS Experiences Radio Frequency Jamming

Description: The UAS is subjected to radio frequency jamming, mid-flight, by a malicious actor.
Event Severity: 7
Supervisor Notification Need: 3
Supervisor Response Need: 3
Autonomy Aware: Possibly. UASs may have the capacity to surmise that it is being radio frequency jammed.
Responder: Autonomy
Supervisor Aware: Possibly. The Supervisor will only be able to know about the UE if the UAS reestablishes the C2 link and the UAS's Autonomy notifies the Supervisor. Otherwise, the Supervisor will perceive the radio frequency jamming of the UAS as a C2 link loss.
Supervisor Notified: Yes. The Supervisor is notified about the C2 link loss of the UAS by the C2 station, but is not notified about radio frequency jamming.
Additional Supervisor Monitoring Required: Yes, as Periodic Check-ins
Supervisor Perception Possibilities: Notified by C2 station

- Text Log w/ Audible Alert
- Visual Glyph Change w/ Audible Alert

Notes:

- Multiple UASs can experience jamming simultaneously.
- Technologies capable of radio frequency Jamming UASs are illegal in the United States.
- Sequence of events:

    - The UAS's Autonomy perceives the radio frequency jamming.
    - Autonomy determines if UAS is capable of continuing the mission:
        * If capable, the UAS continues and reports back to the Supervisor when possible.
        * If not, the Autonomy commands the UAS to land in place or RTL.
    - Meanwhile, the C2 station notices a drop in communication with the affected UAS, but is only able to perceive the event as a C2 link loss.
    - The Supervisor receives a notification from the C2 station about the C2 link loss between the C2 station and UAS.
    - The Supervisor periodically checks in on the UAS to see if communication has been reestablished.
        * If the UAS does not reestablish communication with the Supervisor's C2 station by the expected mission end, the "UAS Experiences Unusual C2 Link Loss" UE is considered.

A.1.3.4 UAS Hardware Failures and Difficulties

UAS Experiences Extended GPS Signal Loss

Description: UAS experiences severe GPS signal loss for an extended period of time making it impossible for the UAS to safely continue with the mission.
Event Severity: 6
Supervisor Notification Need: 6
Supervisor Response Need: Varies
Autonomy Aware: Yes
Responder: Autonomy
Supervisor Aware: Yes
Supervisor Notified: Yes
Additional Supervisor Monitoring Required: Yes
Supervisor Perception Possibilities: Notified by C2 station

- Text Log without Audible Alert
- Visual Glyph Change without Audible Alert

Notes: Sequence of events:

- Upon sensing the GPS signal loss, the Autonomy commands the UAS to return towards the location of the last GPS connection.
    - UAS arrives in the area of the last GPS location. If the GPS dead zone is on the en-route path, the Autonomy reroutes to avoid the dead zone:
        * If the UAS has rerouted multiple times and is still unable to find a path with an adequate GPS signal, the UAS is commanded to return to launch. The Supervisor is notified after the first reroute attempt.
        * The Supervisor Post-Response Monitors the UAS as it attempts to reroute.
        * The Supervisor returns to Nominally Monitoring the UAS if it is capable of finding a path with an adequate GPS signal.

    - After rerouting X number of times or after Y seconds, the Supervisor is notified. The Supervisor decides whether the UAS continues or aborts the mission.
  - UAS arrives in the area of the last GPS location, and the GPS dead zone is near the lightning strike/coverage area location:
    - The Autonomy chooses to either find an inspection location, coverage area, or RTLs without completing its mission objectives. The Supervisor is not notified about this event.
  - If the UAS is unable to regain GPS signal and it is out of communication range, it flies in a heading towards the last known location or the landing zone, in order to regain communication.
    - If the UAS is unable to regain GPS signal, it will be unable to find the launch/landing zone and eventually will run low on battery, it will then land in place.
  - The Supervisor is notified, if there are communications with the UAS, about the UE and Autonomy's command and then monitors the UAS while it lands.

UAS Experiences Temporary GPS Signal Loss

Description: UAS experiences short GPS signal loss during the mission. The UAS is still capable of making mission progress despite occasional GPS loss.
Event Severity: 3
Supervisor Notification Need: 1
Supervisor Response Need: 1
Autonomy Aware: Yes
Responder: Autonomy
Supervisor Aware: No
Supervisor Notified: No
Additional Supervisor Monitoring Required: No, the Supervisor will be unaware of the UE because temporary GPS signal loss is an expected occurrence for the UAS's Autonomy to handle. The Supervisor will not stop Nominally Monitoring the UAS.
Supervisor Perception Possibilities: Not Notified
Notes: This UE can impact multiple UASs simultaneously.
The affected UAS experiencing temporary GPS loss will attempt to navigate by other means without GPS. If a GPS link is reestablished the event will be logged and the UAS will continue with the deployment plan. The Supervisor is never notified of the event, but is capable of seeing its occurrence in the log.

UAS Experiences Unusual C2 Link Loss (DSS Available)

Description: A UAS's Autonomy has not communicated with the Supervisor's C2 station for an extended period of time; the Supervisor is unsure about the whereabouts of the UAS or its mission status. The C2 station has a decision support system implemented to assist with information gathering and analysis.
Event Severity: 5

Supervisor Notification: 5
Supervisor Response Need: 5
Autonomy Aware: Yes
Responder: Supervisor
Supervisor Aware: Yes
Supervisor Notified: Yes
Additional Supervisor Monitoring Required: No. The Supervisor will be Nominally Monitoring the UAS and does not engage in any other form of monitoring.
Supervisor Perception Possibilities: Notified by C2 station

- Visual Glyph Change w/ Audible Alert
  - Glyph saliency increased

Notes:

- This UE will occur due to the UAS navigating in terrain that blocks line of sight with the communications technology.
- This UE can occur for a single UAS, or multiple UASs simultaneously.
- Sequence of events:
  - The affected UAS enters an out of communication state. After a short period of time (1 minute), the UAS glyph is changed (i.e., color change) to represent the UAS's prolonged out of communications state. After X minutes the UAS passes the notification threshold and the Supervisor is formally notified to investigate.
  - The Communications lead contacts the Logistics Coordinator to determine if the UAS has returned.
    * If Yes: The Supervisor can remove the UAS's assignment.
    * If No: The Supervisor interacts with the decision support system, inputting information about the affected UAS. The DSS predicts the potential current locations of the UAS. Then, the DSS communicates its analysis, about the UAS's predicted current location and updates the UAS's Glyph.

C2 Link Loss (Decision Support System Unavailable)

Description: A UAS's Autonomy has not communicated with the Supervisor's C2 for an extended period of time; the Supervisor is unsure about the whereabouts of the UAS or its mission status. The C2 station does not have a decision support system implemented to assist the Supervisor with information gathering and analysis.
Event Severity: 5
Supervisor Notification: 5
Supervisor Response Need: 5
Autonomy Aware: Yes
Responder: Supervisor
Supervisor Aware: Yes
Supervisor Notified: Yes
Additional Supervisor Monitoring Required: No. The Supervisor will continue Nominally Monitoring the UAS and does not engage in any other form of monitoring.
Supervisor Perception Possibilities: Notified by C2 station

- Visual Glyph Change w/ Audible Alert
  - Glyph saliency increased

Notes:

- This UE will occur due to the UAS navigating in terrain that blocks line of sight with the communications technology.
- This UE can occur for a single UAS, or multiple UASs simultaneously.
- The affected UAS is nominally monitored, while in the initial out of communications event.
- The Supervisor waits to determine if the UAS can reestablish communications as it nears or lands at the launch site. During this waiting period, the Supervisor returns to Nominally Monitoring the other UASs. Once the waiting period completes, the Supervisor switches back to addressing the UE.
- Sequence of Events Overview:
  - The affected UAS enters an out of communication state. After a short period of time (1 minute), a visual change occurs (i.e., UAS glyph color change) to represent the UAS's prolonged out of communications state. After 7 minutes the UAS passes a notification threshold and the UAS's visual representation on the C2 station is updated to indicate a prolonged link loss state.
  - The Supervisor manually gathers information about the affected UAS, such as the UAS's last known location, how long it has been out of communication, last known speed and direction, and last known flight phase. An analysis of the gathered data results in a prediction of the UAS's current whereabouts as well as the UAS's expected RTL time.
  - If the expected RTL time arrives and the UAS has not reestablished contact, the Supervisor proceeds to contact the Logistics Coordinator to determine if the UAS has returned.
    - If Yes: The Supervisor requests the removal of the UAS's assignment.
    - If No: The Supervisor reports the situation analysis to the Communication Lead who has responsibility for recording the event and reporting the lost UAS to the Logistics Coordinator and other responsible parties.

Unexpected Battery Depletion

Description: UAS loses charge faster than expected mid-deployment.
Event Severity: 7
Supervisor Notification Need: 3
Supervisor Response Need: 3
Autonomy Aware: Yes
Responder: Autonomy
Supervisor Aware: Yes
Supervisor Notified: Yes
Additional Supervisor Monitoring Required: Yes
Supervisor Perception Possibilities: Notified by C2 station

- Visual Glyph Change with Audible Alert
- Visual Glyph Change without Audible Alert

Notes: Sequence of events:

- The UAS's glyph updates on the C2 station.
- Supervisor may or may not notice the glyph change related to the UE.
- The Autonomy is capable of commanding the UAS to land in place or to RTL.
- The Supervisor is notified of Autonomy's actions after the Autonomy's commands have been received by the UAS.
- The Logistics Coordinator receives a notification about a faulty battery if the UAS RTLs.

UAS Detect and Avoid Sensor Failure

Description: UAS's DAA sensors fail mid-flight.
Event Severity: 5
Supervisor Notification Need: 1
Supervisor Response Need: 1
Autonomy Aware: Yes
Responder: Autonomy
Supervisor Aware: No
Supervisor Notified: No
Additional Supervisor Monitoring Required: No
Supervisor Perception Possibilities: Not Notified
Notes:

- Sequence of events:
  - Autonomy commands RTL.
  - The Supervisor will remain unaware of the UE's occurrence, especially if the UAS is out of communication range, and continues to Nominally Monitor the UAS regardless of the Autonomy's response.
- The Supervisor can look within the UAS's mission details to identify information about the UE's occurrence.

UAS Partial Motor Failure

Description: A UAS experiences partial motor failure but is still capable of flying.
Event Severity: 7
Supervisor Notification: 7
Supervisor Response Need: 1
Autonomy Aware: Yes
Responder: Autonomy
Supervisor Aware: Yes
Supervisor Notified: Yes
Additional Supervisor Monitoring Required: No
Supervisor Perception Possibilities: Notified by C2

- Visual Glyph Change with Audible Alert
- Saliency increased

Notes: Sequence of events:

- The Autonomy becomes aware of the partial motor failure.
- The Autonomy commands the UAS to RTL or land in place.
- If the UAS is within communications range, the C2 station is updated about the UE and the Supervisor may or may notice the change related to the UE's occurrence.
- The Supervisor continues to Nominally Monitor the UAS as it RTLs.

UAS Experiences Unexpected Flight Dynamics

Description: UAS suddenly experiences difficulty maintaining stability and control of pitch, yaw, or roll.
Event Severity: 7
Supervisor Notification Need: 5
Supervisor Response Need: 1
Autonomy Aware: Yes
Responder: Autonomy
Supervisor Aware: Yes
Supervisor Notified: Yes
Additional Supervisor Monitoring Required: No
Supervisor Perception Possibilities: Notified by C2 station

- Visual Glyph Change with or without Audible Alert
- Popup attached to Glyph

Notes:

- This UE can impact multiple UASs simultaneously.
- The instant the Autonomy becomes aware of the continual unusual flight dynamics, the UAS's goal is changed to land in place or RTL.
- After the Autonomy makes a response and if the UAS is within communications range, the C2 interface is updated and the Supervisor may notice the Autonomy's actions.

UAS Experiences Adverse Wind Conditions and Unable to Progress

Description: UAS experiences strong constant winds, turbulent winds, propeller vortices, up/down drafts, or wind shear and is unable to progress safely.
Event Severity: 7
Supervisor Notification Need: 6
Supervisor Response Need: 1
Autonomy Aware: Yes
Responder: Autonomy
Supervisor Aware: Yes
Supervisor Notified: Maybe, if the UAS is within communication range
Additional Supervisor Monitoring Required: Yes
Supervisor Perception Possibilities: Yes

- Text with Audible Alert
- Visual Glyph Change with Audible Alert
  - Glyph highlighted or circled
  - Glyph color change

Notes: This UE can impact multiple UASs simultaneously.
Initially, the Autonomy will focus on keeping the UAS stable while progressing, but if the UAS continuously experiences adverse conditions and is unable to safely make progress, the Autonomy decides to either have the UAS reroute, RTL, or land in place.

- Land in place site triggers a notification on the C2 station, if the UAS is within communications range.
- Reroutes or RTL do not trigger notifications, but the UAS's representation updates.
  - Information about the UE and Autonomy's commands are logged in the mission details and are accessible by the Supervisor if necessary.

UAS Detect and Avoid Sensors Impeded in Low Visibility Conditions

Description: UAS is unable to utilize on-board detect and avoid sensors that are impeded by low visibility conditions caused by: heavy rain, fog, smoke, falling leaves, etc.
Event Severity: 7
Supervisor Notification: 1
Supervisor Response Need: 1
Autonomy Aware: Yes
Responder: Autonomy
Supervisor Aware: No
Supervisor Notified: No
Additional Supervisor Monitoring Required: No
Supervisor Perception Possibilities: Not Notified
Notes:

- This UE can impact multiple UASs simultaneously.
- The Autonomy will command the UAS to reroute (i.e., raise or lower in altitude) to try and regain vision.

A.1.3.5 UAS Software Failure

UAS Flyaway

Description: UAS has significantly diverged from its flight path and is not attempting to correct back to the planned course.
Event Severity: 7
Supervisor Notification Need: 10
Supervisor Response Need: 10
Autonomy Aware: No
Responder: Supervisor
Supervisor Aware: Maybe, if the UAS is within communication range

Supervisor Notified: Maybe, if the UAS is within communication range
Additional Supervisor Monitoring Required: Maybe, if the UAS is within communication range
Supervisor Perception Possibilities:

- Notified by C2 station
  - Visual glyph change
  - Visual popup attached to glyph
  - A notification window appears in the center of the C2 station interface.
- Supervisor interprets Flyaway from UAS glyph and Mission Information.
  - The Supervisor visually perceives UAS deviating from the flight path.

Notes:

- This UE can impact multiple UASs simultaneously.
- If the Supervisor was notified by the C2 station, the Supervisor first acknowledges the C2 station's notification.
- Upon UE perception, and if the UAS is within communications range, the Supervisor will send a command and monitor if the UAS responds to the command. The command can either land in place, or RTL.
  - If the UAS is commanded to Land in Place and is responsive, the Supervisor will Post-Response Monitor the UAS as it lands.
  - If the UAS is commanded to RTL then the Supervisor will Post-Response Monitor the UAS for a portion of the return flight. The Supervisor will return to Nominal Monitoring until the UAS Lands.
  - If the UAS is not responsive:
    * If there is a deployment team servicing a sector adjacent to the team's sector and the UAS is flying towards that sector, the Supervisor will notify the Communications lead who takes the responsibility of notifying the deployment team servicing the sector towards which the UAS was flying.
    * If there is no adjacent sector, the team just has to let the UAS fly away.
      - It may RTL due to low battery.
      - It may crash due to obstacles in the environment or low battery.

UAS Unresponsive During Unexpected Event

Description: UAS is unresponsive to Supervisor's commands intended to address an ongoing Unexpected event affecting the UAS.
Event Severity: 8
Supervisor Notification Need: Notification not possible. The C2 is assumed to be unable of determining whether the UASs are correctly responding to the Supervisor's command; therefore, the C2 is unable to notify the Supervisor about the occurrence of this UE.
Supervisor Response Need: 10
Autonomy Aware: No
Responder: Supervisor

Supervisor Aware: Yes
Supervisor Notified: No
Additional Supervisor Monitoring Required: Yes
Supervisor Perception Possibilities: Perceived during Post-Response Monitoring
Notes:

- This UE is more of a UE "extension" than a standalone UE. For example, a Supervisor commanded UASs to RTL because of an Emergency in the Airspace and some of the UAS's are not reacting to the command.
- This UE may occur after any instance of a Supervisor Response.
- This UE has been included for the sake of completeness.

A.1.3.6 Flight Path and Mission Obstructions

Emergency in Airspace (UAS unaware)

Description: The Communication Lead notifies the Supervisor of the emergency and all aircraft in the designated airspace need to exit the designated airspace. The autonomy is unaware of the emergency.
Event Severity: 10
Supervisor Notification Need: 10
Supervisor Response Need: 10
Autonomy Aware: No
Responder: Supervisor
Supervisor Aware: Yes
Supervisor Notified: Yes
Additional Supervisor Monitoring Required: Yes
Supervisor Perception Possibilities: Notified by Outside Source

- Audibly
  - Informed by the Communications Lead.
  - If communications are available, an Emergency Broadcast Notification System on C2 station.
- Text
  - Informed by the Communications Lead.
  - If communications are available, an Emergency Broadcast Notification System on C2 station.
- Audibly and Text
  - If communications are available, an Emergency Broadcast Notification System on C2 station.

Notes: This UE can impact multiple UASs simultaneously.
Upon perception, the Supervisor has several options:

- Command UAS(s) into Holding Pattern
- Command UAS(s) to Return to Launch
- Reroute UAS(s)

Emergency in Airspace, Autonomy Aware

Description: UAS(s) Autonomy is aware of an emergency in the airspace and is responsible for clearing the affected airspace of UAS.
Event Severity: 10
Supervisor Notification Need: 8
Supervisor Response Need: 1
Autonomy Aware: No
Responder: Autonomy
Supervisor Aware: Yes
Supervisor Notified: Yes
Additional Supervisor Monitoring Required: Yes
Supervisor Perception Possibilities: Notified by C2 Station

- Affected areas of operations are made visually salient on the interface's sector map. An audible alert is played and the glyphs of affected UASs are made visually salient. A notification window, describing the emergency, appears in the center of the affected area.

Notes:

- This UE can impact multiple UASs simultaneously.
- The Autonomy is aware of the Emergency in Airspace and is capable of responding. After the Autonomy commands the affected UAS(s), the Supervisor is notified to acknowledge and assess the Autonomy's action.
- Next, the Supervisor Post-Response Monitors the affected UASs to ensure they are reacting accordingly to the Autonomy's command.

UAS Flight Path Obstructed (Autonomy addresses)

Description: The UAS is unable to temporarily progress in the mission because its flight path is being obstructed by objects like another UAS, crewed aircraft, or terrain-based features.
Event Severity: 3 (advisory)
Supervisor Notification Need: 1
Supervisor Response Need: 1
Autonomy Aware: Yes
Responder: Autonomy
Supervisor Aware: No
Supervisor Notified: No
Additional Supervisor Monitoring Required: No
Supervisor Perception Possibilities: Not Notified
Notes:

- Regardless of the type of obstruction encountered, the Autonomy will command the UAS to either reroute, adjust its velocity, or hold in place.
- The Autonomy logs the UE occurrence and the Autonomy's actions within the mission flight log. The information is retrievable by the Supervisor if necessary; however, the Supervisor is not notified of the UE's occurrence.

UAS Path Obstructed A. (Autonomy Unable to Address Obstruction, communications with C2)

Description: UAS's planned path is obstructed for an extended time period and UAS is unable to make mission progress.
Event Severity: 4 (caution)
Supervisor Notification Need: 7
Supervisor Response Need: 8
Autonomy Aware: Yes
Responder: Supervisor
Supervisor Aware: Yes
Supervisor Notified: Yes
Additional Supervisor Monitoring Required: Yes
Supervisor Perception Possibilities: Notified from Outside Source

- Audibly
  - Informed by the Communications lead.
  - If communications are available, an Emergency Broadcast Notification System on C2 station.
- Text
  - Informed by the Communications lead.
  - If communications are available, an Emergency Broadcast Notification System on C2 station.
- Audibly and Text
  - If communications are available, an Emergency Broadcast Notification System on C2 station.

Notes:

- The Supervisor issues a new routing command or a nudge command.
- If the UAS responds properly, the UE is concluded.
- If no clear path is possible, then the Supervisor attempts to RTL or land the UAS in place.
- If the Supervisor cannot resolve the issue, the UAS continues to hover until it either battery RTLs or crashes.

UAS Path Obstructed B. (Autonomy Unable to Address Obstruction, communications with C2)

Description: UAS's planned path is obstructed for an extended time period and UAS is unable to make mission progress.
Event Severity: 4 (caution)
Supervisor Notification Need: 7
Supervisor Response Need: 8
Autonomy Aware: Yes

Responder: Autonomy
Supervisor Aware: No
Supervisor Notified: No
Additional Supervisor Monitoring Required: No
Supervisor Perception Possibilities: Not Notified
Notes:

- If the Autonomy has failed to handle this situation as discussed in B.2.6.4, then the UAS continues to hover until it either battery RTLs or crashes.
- If the UAS is within communication range with C2, then it may send a message that makes the Supervisor aware of the situation. The Supervisor can decide what action to take (e.g., assign a new mission, RTL).

Adverse Weather, *Autonomy Aware*

Description: The Autonomy is aware that the UAS's ability to fly safely is at risk due to imminent adverse weather conditions (i.e., thunderstorms, low visibility conditions, or hail).
Event Severity: 10
Supervisor Notification Need: 5
Supervisor Response Need: 1
Autonomy Aware: Yes
Responder: Autonomy
Supervisor Aware: Maybe, if UAS is in communication
Supervisor Notified: Maybe, if UAS is in communication
Additional Supervisor Monitoring Required: Maybe, if UAS is in communication
Supervisor Perception Possibilities: Notified by C2 Station

- Affected areas of operations are made visually salient on the interface's sector map. An audible alert is played and the glyphs of affected UASs are made visually salient. A notification window, describing the adverse weather, appears in the center of the affected area.

Notes: This UE can impact multiple UASs simultaneously.

- This instance assumes adverse weather information is digitized and available to the Autonomy, which may not be the case.
- The Autonomy is capable of taking appropriate actions. The Supervisor is notified of Autonomy's actions and acknowledges the Autonomy's action.

Adverse Weather, Autonomy Unaware

Description: The Autonomy is unaware that the UAS's ability to fly safely is at risk due to imminent adverse weather conditions (i.e., thunderstorms, low visibility conditions, or hail).
Event Severity: 10
Supervisor Notification Need: 10
Supervisor Response Need: 10
Autonomy Aware: No

Responder: Supervisor
Supervisor Aware: Yes
Supervisor Notified: Yes
Additional Supervisor Monitoring Required: Yes
Supervisor Perception Possibilities: Notified from Outside Source

- Audibly
  - Informed by the Communications lead.
  - If communications are available, an Emergency Broadcast Notification System on C2 station.
- Text
  - Informed by the Communications lead.
  - If communications are available, an Emergency Broadcast Notification System on C2 station.
- Audibly and Text
  - If communications are available, an Emergency Broadcast Notification System on C2 station.

Notes:

- This UE can impact multiple UASs simultaneously.
- Adverse Weather and "Emergency in Airspace" share a lot in common. The same Supervisor responses for an "Emergency in the Airspace" can be used for "Adverse Weather".
- Upon perception of the UE, the Supervisor has several response options:
  - Command UAS(s) to Holding Pattern
  - Command UAS(s) to Return to Launch
  - Reroute UAS(s)
  - Do Nothing

A.1.3.7 Collisions

Mid-Air Collision (Crash), Autonomy Online

Description: UAS has crashed and is unable to fly, but the UAS's Autonomy is still capable of communicating.
Event Severity: 10 (warning)
Supervisor Notification Need: 10
Supervisor Response Need: 1
Autonomy Aware: Yes
Responder: Autonomy
Supervisor Aware: Yes
Supervisor Notified: Yes
Additional Supervisor Monitoring Required: Yes
Supervisor Perception Possibilities: Notified by C2 station

- Visual Glyph Change with Audible Alert
  - Glyph highlighted or circled
  - Glyph changes color
- Visual Popup
  - Popup graphic attached to affected UAS's glyph appears
  - A notification window appears in the center of the C2 station interface.

Notes:

- This instance of the UE assumes the Autonomy is capable of communicating with the deployment team.
- The Supervisor receives a notification about the UE.
- The recording and safeguarding of the event, data, etc. logs, if available, will be the responsibility of the Communications lead or the Utility Specialist, not the Supervisor.

Mid Air Collision (Crash), Autonomy Offline

Description: UAS has crashed, is unable to fly, and the UAS's Autonomy is offline or incapable of communicating with the Supervisor due to the sustained damage.
Event Severity: 10 (warning)
Supervisor Notification Need: 10
Supervisor Response Need: 10
Autonomy Aware: Yes
Responder: Supervisor
Supervisor Aware: No
Supervisor Notified: No
Additional Supervisor Monitoring Required: No
Supervisor Perception Possibilities: Not Applicable
Notes: This instance of the UE assumes the Autonomy is incapable of communicating with the deployment team, there is nothing that the Supervisor or deployment team can do. System logging is expected to have recorded any available information prior to the collision.

Mid Air Collision

Description: UAS collided with an object while flying and is still airworthy and capable of completing the mission.
Event Severity: 8 (warning)
Supervisor Notification Need: 5
Supervisor Response Need: 5
Autonomy Aware: Yes
Responder: Autonomy
Supervisor Aware: Maybe, if the UAS is in communications
Supervisor Notified: Maybe, if the UAS is in communications
Additional Supervisor Monitoring Required: Maybe, if the UAS is in communications
Supervisor Perception Possibilities: Notified by C2 station

- Text Log without Audible Alert
- Text Log with Audible Alert
- Visual Glyph Change with Audible Alert
- Visual Glyph Change without Audible Alert

Notes: Assuming communications with the UAS, the Supervisor is notified of the UAS's collision. Autonomy has commanded the UAS to continue flying. The Supervisor Post-Response Monitors the UAS for z secs until the Supervisor considers the UAS to be functioning normally. The Supervisor then returns to Nominally Monitoring the UAS.

- The recording and safeguarding of event data is handled by the Communications lead or Utility Specialist.

Mid-Air Collision (UAS can fly, but is damaged. Cannot complete the mission)

Description: UAS sustains damage from a collision with an object while airborne, maintains flight capabilities, but loses airworthiness.
Event Severity: 9 (warning)
Supervisor Notification Need: 5
Supervisor Response Need: 5
Autonomy Aware: Yes
Responder: Autonomy
Supervisor Aware: Maybe, if the UAS is in communications
Supervisor Notified: Maybe, if the UAS is in communications
Additional Supervisor Monitoring Required: Maybe, if the UAS is in communications
Supervisor Perception Possibilities: Notified by C2 station

- Text Log without Audible Alert
- Text Log with Audible Alert
- Visual Glyph Change with Audible Alert
- Visual Glyph Change without Audible Alert

Notes:

- The autonomy acts as the primary responder and attempts to address the event by commanding the UAS to RTL. Meanwhile, the Supervisor may be notified of the UE if there is communication with the UAS. The Communications lead or Utility Specialist proceeds to gather relevant information related to the event in order to report the incident to airspace officials.
- Once all Autonomous options for grounding the UAS have been exhausted, the Supervisor becomes responsible for landing the UAS. The Supervisor is alerted and begins identifying a method to ground the UAS. After addressing the UE, the Supervisor returns to nominal monitoring of the unaffected UASs.
- The recording and safeguarding of the event, data, etc. logs, if available, will be the responsibility of the Communications Lead or the Utility Specialist, not the Supervisor.

UAS Losses Flight Capabilities and Crashes

Description: UAS experiences a full loss of flight and crashes into the ground due to adverse weather conditions, or hardware failure; the Autonomy is incapable of communicating with the deployment team.
Event Severity: 9
Supervisor Notification Need: 5
Supervisor Response Need: 5
Autonomy Aware: Yes
Responder: Supervisor
Supervisor Aware: Maybe, if UAS is in communications
Supervisor Notified: Maybe, if UAS is in communications
Additional Supervisor Monitoring Required: No
Supervisor Perception Possibilities: Notified by C2 station

- Text Log without Audible Alert
- Text Log with Audible Alert
- Visual Glyph Change with Audible Alert
- Visual Glyph Change without Audible Alert

Notes:

- This UE covers all the possible instances where a UAS crashes into the ground not due to a mid-air collision.
- The recording and safeguarding of the event, data, etc. logs, if available, will be the responsibility of the Communications Lead or the Utility Specialist, not the Supervisor.
- Sequence of events:
  - The Supervisor may be notified about the crashed UAS.
  - The UAS is left in place and is not retrieved.

UAS Physically Damaged Mid Flight and Maintains Flight

Description: UAS sustains damage while flying, not due to a collision (i.e., hit by a projectile), and remains operational.
Event Severity: 6 (warning)
Supervisor Notification Need: Varies
Supervisor Response Need: Varies
Autonomy Aware: Yes
Responder: Autonomy
Supervisor Aware: Maybe, if in communication
Supervisor Notified: Maybe, if in communication
Additional Supervisor Monitoring Required: Maybe, if in communication
Supervisor Perception Possibilities: Notified by C2 station

- Text Log without Audible Alert
- Text Log with Audible Alert
- Glyph Change with Audible Alert

- Glyph Change without Audible Alert

Notes: If operational, then the Autonomy commands the UAS to continue with the Mission. The Supervisor post response monitors the UAS before considering the UAS stable and returns to Nominally Monitoring the UAS.

UAS Damaged Mid Flight and Maintains Limited Flight Capabilities

Description: UAS sustains damage while flying, not due to a collision (i.e., hit by a projectile) and remains operational, but with limited flight capabilities.
Event Severity: 9 (warning)
Supervisor Notification Need: 5
Supervisor Response Need: 5
Autonomy Aware: Yes
Responder: Autonomy
Supervisor Aware: Maybe, if in communication
Supervisor Notified: Maybe, if in communication
Additional Supervisor Monitoring Required: Maybe, if in communication
Supervisor Perception Possibilities: Notified by C2 station

- Text Log without Audible Alert
- Text Log with Audible Alert
- Glyph Change with Audible Alert
- Glyph Change without Audible Alert

Notes: If operational, but with some limitations, the Autonomy determines that UAS can continue with the mission, RTL, or land in place. If the UAS is in communications range, then the Supervisor reviews the situation and decides whether or not to permit the UAS to continue with the mission, RTL, or land either in place. The Supervisor post response monitors the UAS for a period of time before Nominally Monitoring it again.

- The recording and safeguarding of the event, data, etc. logs, if available, will be the responsibility of the Communications Lead or the Utility Specialist, not the Supervisor.

A.1.4 Distraction Events

Exemplar potential distraction events are modified from those developed for the A26 project. A number of assumptions were derived, as listed in Table A.3. Six potential distractions were identified based on consideration of both internal and external distractions. The distraction events were organized into the following categories based on their predicted impact on workload and task performance: high and low severity.

Table A.3: Distraction Event use case modeling assumptions.

Subject Matter Expert-Based Assumptions:
Supervisors manage UAS systems in a shared work environment, simultaneously occupied by the Communications lead and the Utility Specialist.
Distractions derive from the external or internal work environment, or from within the Supervisor.
Supervisors have some limited access to personal devices and may receive communications.
Distractions are composed of various components, and can be auditory, speech-based, visual, cognitive, or haptic in nature.

Distractions represent demands that impact the Supervisor's workload and exist outside the UAS control system, and as such, they must be handled solely by a human Supervisor, and not the autonomy. Each distraction description contains the following fields:

- *Description*: A brief statement describing what the particular distraction represents.
- *Event Severity*: The distraction's potential danger or damage to UAS operations [1 (low), 10 (high)].
- *Supervisor Response Need*: Describes how crucial it is to have the Supervisor respond to the distraction [1 (low), 10 (high)].
- *Responder*: Describes the party responsible for initially and directly addressing the distraction, although others may also respond.
- *Type of Distraction*: Lists ways in which the Supervisor's performance is affected by the distraction.
- *Duration of Distraction*: Describes how long a given distraction may be expected to persist normally [1 (short – 30 secs), 2 (long – 120 secs)].
- *Leave Workstation*: Identifies whether the distraction requires the Supervisor to leave the C2 workstation
- *Notes*: Contains general comments about the distraction, details on the distraction or Supervisor response to the distraction.

Auditory Distraction (e.g., Environmental, Conversations)

Description: Supervisor experiences some auditory interference (e.g., conversation, thunderclap).
Event severity: 3
Supervisor response need: 1
Responder: Supervisor
Type of distraction: Audio, Speech, Haptic
Duration of distraction: Short
Leave workstation: No
Notes:

- Assumes Supervisor is working in a shared environment that is not sound isolated.
- Sequence of events:

  - Supervisor perceptually experiences a loud noise at their workstation, that is unrelated to their workstation. This event may be speech related or not (e.g., thunderclap).
  - Supervisor immediately returns to monitoring task.

Biological Need

Description: Supervisor must address a biological need (i.e., hunger, bathroom, sickness) and based on type of need may need to immediately leave the C2 station to address the personal biological need.
Event severity: 3–8
Supervisor response need: 3–8
Responder: Supervisor or Utility Specialist
Type of distraction: Cognitive, Visual
Duration of distraction: Short or Long
Leave workstation: Yes or No
Notes:

- May require the Utility Specialist to take over as Supervisor.
- Sequence of events:
  - Supervisor perceives a biological need and depending on its severity may have to leave their workstation.
    * If need can be addressed at the workstation (i.e., eating a snack) or can wait until a scheduled break, normal monitoring continues.
  - If the Supervisor needs to leave the workstation to address a need, the Supervisor hands-off all UASs to the Utility Specialist, who becomes the Supervisor, and attends to the need.
  - Supervisor recovers and returns, based on need, the time away from the workstation may be short (i.e., bathroom break) or long (i.e., food poisoning) in duration, after which normal monitoring resumes.

Supervisor Fatigue

Description: Supervisor is experiencing a form of fatigue (perceptual or cognitive).
Event Severity: 8
Supervisor Response Need: 8
Responder: Utility Specialist
Type of distraction: Cognitive, Visual
Duration of distraction: Short or Long
Leave workstation: Yes
Notes:

- Sequence of events:
  - The Supervisor experiences noticeable cognitive or perceptual fatigue.
  - The Supervisor hands off the tasks to the Utility Specialist, who continues as the Supervisor.

- The Supervisor recovers and returns after taking a break or at the next shift based on severity, after which normal monitoring resumes.

IM/SMS/Notification Received

Description: Supervisor receives a personal communication or non-task related notification, and attends to notification.
Event severity: 2
Supervisor response need: 2
Responder: Supervisor
Type of distraction: Audio, Visual, Haptic
Duration of distraction: Short
Leave workstation: No
Notes:

- Assumes Supervisor has access to their functioning personal devices or communications (e.g., email client), including wearable devices (e.g., smart watches).
- Sequence of events:
  - Supervisor receives a notification aurally or through vibration.
  - Supervisor views the notification message, ignoring their C2 station for a moment, and then continues normal monitoring.

Interaction with Teammates

Description: Failures or difficulties in team communication or job duties may lead to frustration in the Supervisor.
Event severity: 5
Supervisor response need: 2
Responder: Supervisor
Type of distraction: Audio, Visual, Haptic
Duration of distraction: Long
Leave workstation: No
Notes:

- Can compound and increase over shift.
- Sequence of events:
  - Failures to effectively communicate with teammates requires the Supervisor to manage/repeat/verify communications.
  - Supervisor ignores the C2 station momentarily while reiterating/clarifying communication.

Task/Time Pressure

Description: Given the dynamic nature of task and unpredictable nature of lightning strikes, racing to beat constraints (e.g., time on site, advancing fire lines on residential areas, requests from ground support staff) can stress and preoccupy the Supervisor.
Event severity: 8

Supervisor response need: 8
Responder: Supervisor
Type of distraction: Audio, Visual, Haptic
Duration of distraction: Long
Leave workstation: No
Notes:

- Assumes Supervisor has situational awareness outside of task.
- Sequence of events:
  - Supervisor becomes aware of external factors that introduce time/task pressure.
  - Out of abundance of caution, Supervisor double checks or repeats work efforts, or processes information out of sequence to address pressures, in addition to managing the stress of such time pressure.

A.2 IMPRINT Pro Modeling

Improved Performance Research Integration Tool (IMPRINT) Pro was used to model the monitoring task. IMPRINT Pro, developed by the United States Army Research Laboratory Human Research and Engineering Directorate, supports manpower as well as personnel and human systems integration. IMPRINT Pro incorporates network modeling and accommodates dynamic, stochastic, discrete events. The models represent the interactions between humans and systems. IMPRINT Pro can inform system requirements; identify human performance driven system design constraints; and evaluate the potential personnel training capabilities and manpower requirements to effectively operate and maintain a system under environmental stressors. A number of plugins can provide additional capabilities, including unmanned systems, fatigue, and training effects. IMPRINT Pro has been used to model human interaction with uncrewed aircraft and robotic systems. The nominal use case, five unexpected event use cases and two distraction use cases were modeled.

A.2.1 Model Design

A.2.1.1 Nominal Use Case

The nominal use case assumes deployments occur between 12:00 and 20:00 when dry lightning strikes are most prevalent. Teams are distributed throughout the region, operating predominantly in rural or remote areas with rough terrain, though operations may extend to rural/urban interfaces. Operations maintain a safe distance from airports and heliports, defined as beyond three miles. The deployment environment is characterized by limited or no cellular and long-range communications. Teams rely on local radio communications and possibly satellite, though real-time contact with incident command may be unavailable. The operation utilizes small UASs that meet Industry Consensus Standards and hold FAA Airworthiness Certificates. Teams are self-sufficient, carrying all necessary equipment and pre-generated maps, though mission plans may require modification based on actual environmental conditions. The deployment team consists of four specialized roles: UAS Supervisor, Team/Communication Lead, Logistics Coordinator, and Utility Specialist cross-trained in all positions. Teams operate from vehicles with limited cargo capacity, navigating potentially challenging terrain to reach deployment areas. Two trained personnel must maintain presence in the C2 area during all UAS operations.

Mission deployments typically span ten hours, including setup and teardown time, with regular operations lasting eight hours during fire season. Each team has an assigned operational sector, whose size varies based on environmental conditions and priority considerations. Historical data, particularly regarding cloud-to-ground lightning strikes, influences the deployment sectors and coverage areas. Analysis of historical strike data reveals that the temporal distribution of lightning strikes follows a Gaussian distribution throughout the day.

The nominal use case model was designed based on historical lightning strike data for the Deschutes National Forest in Oregon, which serves as a representative case study for forest fire prevention operations. The number of lightning strikes during a typical operational shift were determined based on historical information [16–18], providing crucial insights into the temporal patterns and strike intensity activities that teams may encounter. The modeled lighting strike frequency was modeled using Gaussian distributions for the historical data, as shown in Figure A.1), as it helps optimize deployment strategies and resource allocation during high-risk periods.

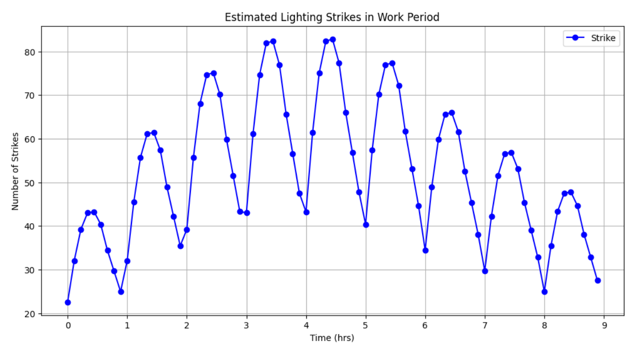


Figure A.1: The distribution of lightning strikes used in the model.

The UAS deployment system is designed to handle two distinct types of operational tasks. The primary task involves rapid response missions where UASs are dispatched directly to lightning strike locations to assess potential fire ignition. The secondary task consists of systematic coverage operations where UASs conduct broad-area surveillance of designated sectors to monitor for fire activity. These coverage patterns are pre-planned based on historical data and risk assessments, but can be dynamically adjusted when strike response missions take priority. The system must balance resources between these two mission types, often running them concurrently with different UASs assigned to each task type.

The multiple UASs are equipped with various sensors including infrared cameras, visual cameras, thermal arrays, and environmental sensors. Each UAS has a flight time of 15-20 minutes, operates at least 100 ft above ground, and can function up to 15 km from the Supervisor under nominal conditions. The UAS possess autonomous DAA capabilities and can process sensor data onboard to manage bandwidth-limited communications.

The Supervisor operates from a C2 station that enables monitoring and modification of UAS operations. While the system is highly autonomous, the Supervisor maintains situation awareness through map displays, UAS status information, and access to sensor feeds. The

Communication Lead monitors sensor feeds and maintains contact with other responders, while the Logistics Coordinator manages hardware-related tasks. The Utility Specialist provides operational flexibility by being able to fill any role as needed.

A.2.1.2 Unexpected Events

Thirty UE use cases were defined and an analysis determined that the most important UEs to model were those that required Supervisor responses. The UEs were grouped into five categories based on specific criteria, from which one UE was selected to be modeled.

Internal Critical System Failures Unrelated to Autonomy and Environmental Challenges

These events require the Supervisor to engage primarily in high amounts of visual monitoring, with some motor interaction and decision making, while verbal communication is minimal or not required. Typically, these events are driven by significant system malfunctions or challenging external conditions. While the Supervisor is tasked with monitoring the situation, the majority of the response is autonomously handled by the UAS, which reduces the need for intensive decision-making and verbal communication. Events in this category include Unexpected Battery Depletion, UAS Partial Motor Failure, and Adverse Weather, Autonomy Aware. Adverse Weather, Autonomy Aware was modeled, where the UAS's autonomy detects that its ability to operate safely is compromised due to imminent adverse weather conditions, such as thunderstorms, low visibility, or hail.

Navigation Challenges and (External) System Disruptions

The Supervisor engages in high amounts of visual monitoring and intensive decision making, with some motor interaction and minimal or no verbal communication. The Supervisor must assess the UAS's condition and make decisions based on external system disruptions or navigation issues, although autonomy plays a significant role in executing operational commands. The Supervisor's primary task is to evaluate the situation and determine the appropriate response. Events include: C2 Link Loss (Decision Support System Unavailable), UAS Experiences Global Position System Spoofing, and Mid-Air Collision. Mid-Air Collision was selected for modeling, where the UAS collides with an object during flight but remains airworthy and capable of completing the mission, requiring the Supervisor to assess the damage and make critical decisions regarding the UAS's continued operation.

Real-Time Coordination and Command Challenges (Internal System Failure Including Autonomy)

These events require substantial engagement across all action areas: visual monitoring, motor interaction, decision-making, and verbal communication. These UEs typically involve significant system failures or external threats, necessitating real-time responses and communication from the Supervisor. These events demand a high level of active oversight, coordination, and decision making. Some events include: UAS Experiences Unusual C2 Link Loss (Decision Support System Available), UAS Flyaway, and Supervisor C2 Station Failure. UAS Path Obstructed (Autonomy Unable to Address Obstruction) was modeled, where the

UAS's planned path is blocked for an extended period, preventing mission progress and requiring the Supervisor to assess and determine the appropriate response.

Externally Driven Command-Intensive Events Without Communication

These events require high visual monitoring, moderate motor interaction, and intensive decision making, but no verbal communication. While similar to Critical System Failures and Environmental Challenges, these events demand higher levels of engagement. The Supervisor must manage the situation with minimal communication, relying on autonomous systems to execute certain responses. Events include: UAS Unresponsive During Unexpected Event, Mid-Air Collision (UAS Can Fly, but is Damaged and Cannot Complete the Mission), and Task/Time Pressure. The Mid-Air Collision (UAS can fly, but is damaged. The UAS cannot complete the mission) UE was modeled, where the UAS has crashed, is unable to fly, and its autonomy is offline or incapable of communicating due to sustained damage.

Minimal Engagement Mission Updates

These events require minimal visual monitoring, with no motor interaction, decision making, or verbal communication. The Supervisor's role is limited to acknowledging updates, which are autonomously managed by the UAS. Events in this category include: Strike Location/Coverage Area Canceled and Strike Location/Coverage Area Updated. The Strike Location/Coverage Area Updated UE was modeled, where new information is received that updates the strike location while the UAS is en-route.

A.2.1.3 Distraction Events

The six distraction event user cases were categorized into two groups. One distraction event from each category was modeled.

Interference and Personal Limitation

The Supervisor engages in minimal visual monitoring and motor interaction, with moderate decision making and occasional verbal communication. The Supervisor manages personal limitations or external interferences, such as fatigue or distractions, while maintaining UAS oversight. The events include: Biological Need, Supervisor Fatigue, and UAS Experiences Radio Frequency Jamming. The Supervisor Fatigue event was modeled, where the Supervisor is experiencing perceptual or cognitive fatigue, impacting their ability to effectively monitor and make decisions during the UAS operation.

Distraction Management and Brief Interactions

These events involve low to moderate motor interaction and decision making, with some verbal communication and minimal visual monitoring. The Supervisor is distracted by external factors, such as communications or environmental influences, requiring brief interactions or quick decisions to regain focus on the primary tasks. The events include: Interaction with Teammates, IM/SMS/Notification Received, and Auditory Distraction (e.g., Environmental, Conversations). The Interaction with Teammates event was modeled, where failures or difficulties in team communication or job duties lead to frustration in the Supervisor.

A.2.2 Model Development

IMPRINT Pro tool was developed for purposes different from supervising multiple UAS and uses a linear model of overall workload. This linear model results in the same workload being added for each new UAS the Supervisor is assigned, irrespective of the mission domain and UAS capabilities. However, based on field work [11] this linear overall workload model is not representative of the expected actual workload for the wildland fire monitoring use case. Insights from results developed for the FAA's ASSURE Center of Excellence project A-26 [5] were leveraged to derive a relevant workload model.

UAS with reliable high autonomy levels (e.g. Wing's delivery UAS) transform the Supervisor's task from managing and interacting with each individual UAS to one focused on visually monitoring the UASs' actions and the airspace. IMPRINT Pro's limitations related to modeling and assessing human performance for such systems are not unique when the number of UASs increases. Workload (w) in scenarios involving the supervision of multiple UAS can be modeled using a logarithmic function, reflecting the efficiency of human visual scanning across increasing numbers of UAS. This approach acknowledges that as the number of UAS (N) increases, the workload grows at a rate less than linear due to the nature of visual search efficiencies. Assuming that workload varies linearly in relation to visual search time, a logarithmic function may be appropriate for modeling workload given:

$$w = a + b \ln N, \tag{1}$$

where w is associated with the workload from monitoring a single UAS, and b is the rate workload grows as additional UAS are incorporated. The workload for a single UAS, a, can be estimated using IMPRINT Pro's existing workload rubrics. The rate parameter, b, needs to be estimated using another method, such as rescaling a logarithmic visual search time function of set-size, which can be achieved by factoring Equation 1:

$$w = a(1 + \frac{b}{a} \ln N), \tag{2}$$

and substituting a new parameter r, the logarithmic rate, for the quantity $\frac{b}{a}$ resulting in:

$$w = a(1 + r \ln N). \tag{3}$$

The difference between Equations 1 and 3 is that b in Equation 1 has dimensions $[workloaditems - 1]$, whereas r in Equation 3 has dimensions $[items - 1]$. This difference allows estimating the logarithmic rate directly from set-size gradients measured in units other than workload (e.g. search time). However, it is necessary to fit r to the use case.

It is necessary to define a more appropriate workload model than the one provided by IMPRINT Pro, as most alternative workload models do not appear to accurately represent workload for 1:N UAS scenarios [5,11]. The approach for the developed IMPRINT Pro model, as represented in Equation 3 requires choosing an appropriate log rate. Various log rates were analyzed for the nominal use case, as shown in Figure A.2. Based on Adams' prior efforts with the DARPA OFFSET program [11] and the FAA's ASSURE Center of Excellence project A-26 [5], the logarithmic rate (r) for the Wildland Fire Monitoring IMPRINT Pro workload model was set to 0.5.

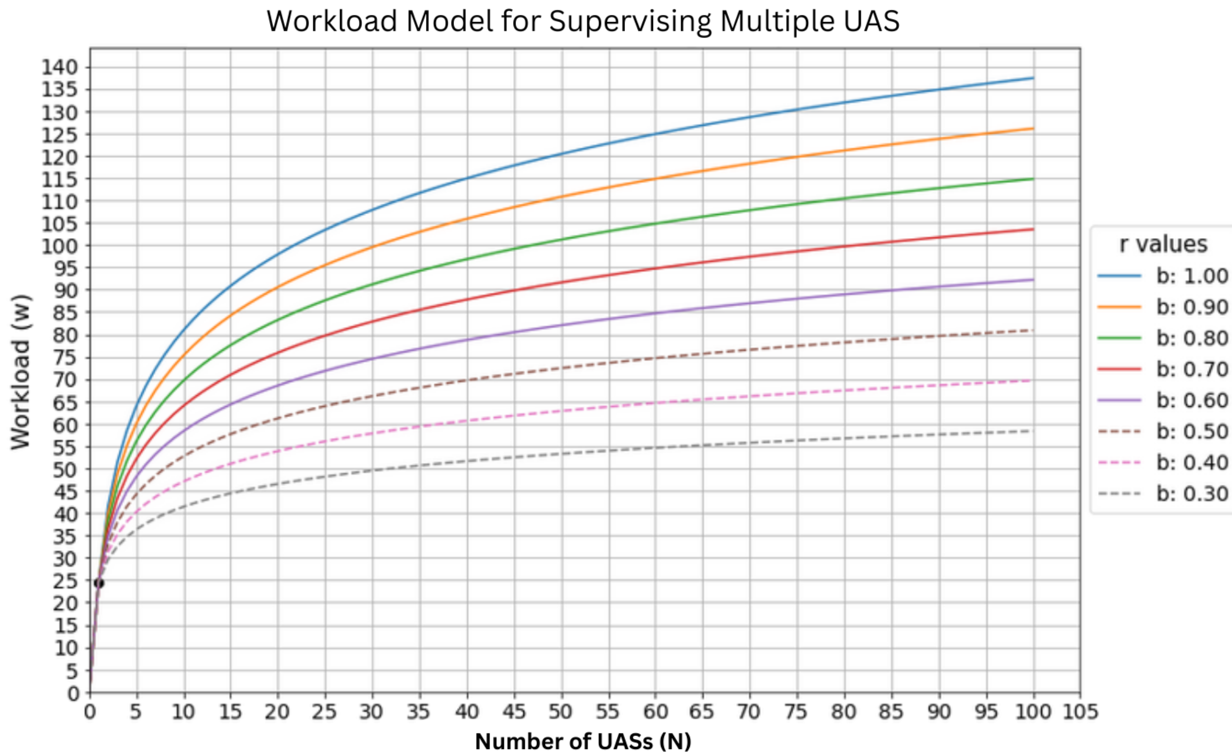


Figure A.2: The r value analysis by the number of UAS for the nominal delivery use case.

The nominal use case model represents Supervisor's workload based on normal activities only. The workload from monitoring multiple UAS follows the logarithmic function. This modeling allows for a representation of how workload increases with the number of UAS when considering the efficiency of human visual scanning. The IMPRINT Pro model must also consider UEs, which incorporates the additional workload due to those UEs. The UE scenarios require the Supervisor to use more visual and cognitive resources to successfully complete the task, increasing the overall workload. Similarly, the distraction events are modeled. IMPRINT Pro incorporates a fatigue model directly, which was leveraged. All models began with 15 UAS ready to be deployed and 5 UAS were in reserve.

The holistic workload model is intended to provide a more accurate estimation of a Supervisor's workload for 20 UASs. This overall approach seeks to address the limitations of linear workload models and acknowledges the complexities and efficiencies of human visual scanning and cognitive processing in dynamic and challenging scenarios. A total of 25 simulation trials were conducted per condition to evaluate the model's effectiveness across all conditions. The mean and standard deviation (SD) of Supervisor workload were computed across these 25 trials to assess consistency and variability in workload estimation.

A.2.3 Modeling Results

Multiple sets of IMPRINT Pro model simulation results for the wildfire monitoring supervisory task were produced. IMPRINT Pro runs the simulations in real-time; thus, requiring 8-hours for each simulated deployment shift. Twenty-five trials were run for each model, which is 200 hours per model. Given that the UEs and the Teammate Interaction distraction event do not occur continuously throughout the deployment period, the modeling approach integrated the UEs and the Team Interaction distraction event into two models. One model included a sequence of the high-impact UEs Mid-Air Collision (Returns), UAS Path Obstructed, and Mid-Air Collision (No Return). The second model integrated the lower-intensity UEs Lightning Strike Location/Coverage Area Updated events and one Adverse Weather event, along with the Teammate Interaction distraction event to simulate more routine supervisory disruptions. Additionally, the nominal model and the nominal with enabled IMPRINT Pro Fatigue feature model represented the final two models. Each model variant estimated overall workload on a continuous basis. All simulation results are recorded at 1-minute across an 8-hour work shift (480 minutes). Each simulation includes ramp-up, steady-state, and ramp-down periods.

The IMPRINT workload threshold for operator overload is defined as a workload value ≥ 60 and underload is defined as a workload value ≤ 20. Values exceeding overload threshold may indicate unacceptable levels of operator strain. Values below underload threshold may indicate operator boredom. Even though the logarithmic model better represents workload compared to the embedded IMPRINT Pro model, the model appears to over estimate the workload levels in the following results, based on prior UAS field trials [11].

A.2.3.1 Nominal Use Case

Under nominal operating conditions, the Supervisor monitors UASs conducting both strike response and area surveillance missions. No unexpected events or distractions occurred in this model. During the ramp up period (0–30 minutes) workload increased steadily as UASs are gradually launched and assigned, as shown in Figure A.3. The steady-state period (40 - 460 minutes) results in the Supervisor's workload fluctuating with the dynamic allocation and return of UASs, with workload consistently hovering near the overload threshold. The ramp down period (460 - 480 minutes) results in a steady decline in workload as no new UAS launch and the current UASs complete the mission and return to the launch area. It is further noted that the number of deployed UASs is dependent on the distribution of the modeled lightning strikes (see Figure A.1), which also impacts the workload results. The results indicate that the Supervisor is operating slightly above the overload threshold, even in the absence of unexpected or distraction events.

A.2.3.2 Unexpected Events

The first set of UEs model results, shown in Figure A.4 are for the following UEs:

- Five Mid-Air Collision (UAS can fly but is damaged, Cannot complete the mission) events [Collision (Returns) in the Figure].
- Eight UAS Path Obstructed (Autonomy Unable to Address Obstruction, communications with C2) events [Obstructed Path in the Figure]
- Three Mid-Air Collision (UAS cannot fly) [Collision (No Return) in the Figure].

The events were integrated at different time points and the periods of time for the events are represented by the corresponding UE color. Note that each time the Mid-Air Collision (UAS cannot fly) event occurred, the total number of UAS was reduced by one UAS.

Figure A.3: The nominal use case continuous workload per minute over the 8-hour shift.

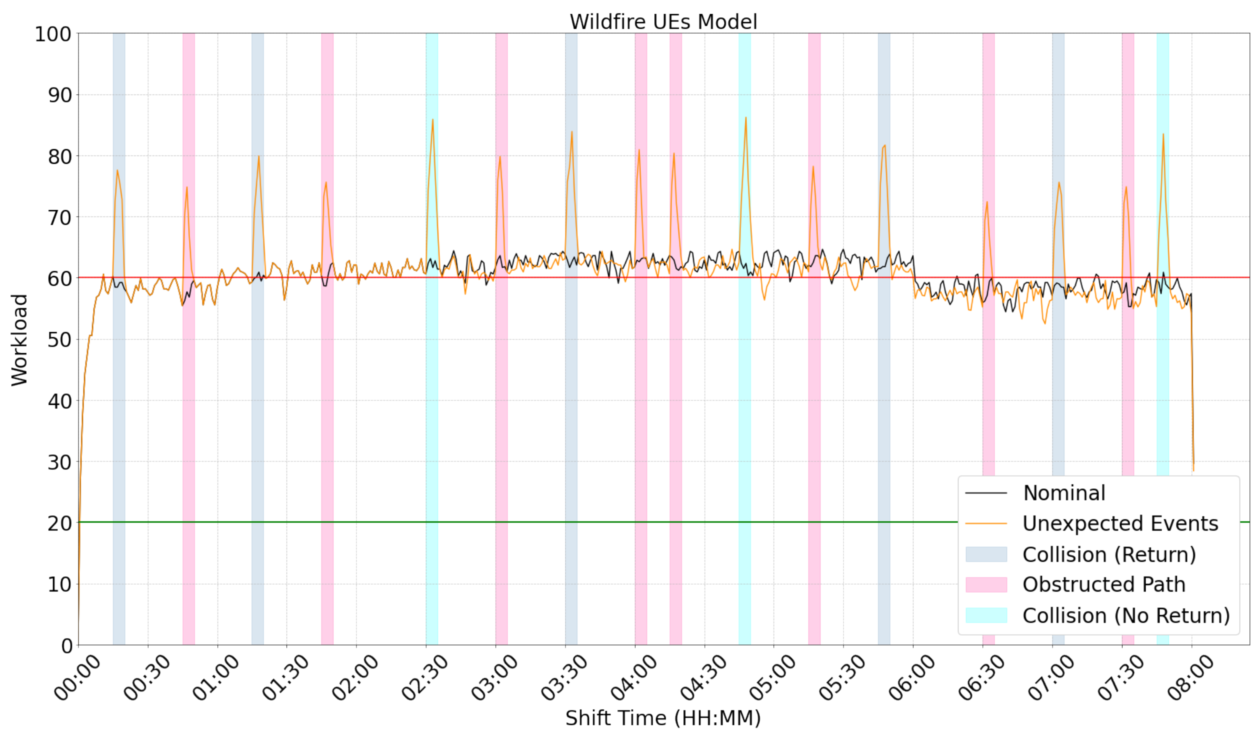


Figure A.4: The collision and DAA UEs model compared to the nominal use case results. The individual UE events appear with a corresponding color for each event type.

This model's ramp up and ramp down periods demonstrated a similar pattern to the nominal use case model. Further, the general workload results also reflect the number of UASs deployed based on the lightning strikes modeled (see Figure A.1). The periods during which no UEs occurred resulted in similar workload as the nominal use case. Generally, the Supervisor's workload spiked during each UE. The Obstructed Path events resulted in the smallest workload spike, followed by the Collision (Returns) events. The Collision (No Return) event resulted in the highest workload spike. It is also noted that nominal workload decreased each time a Collision (No Return) event occurred because the UAS was no longer functional.

The second set of UEs modeled included:

- Seven lightning Strike Location/Coverage Area Updated events (Strike Location Update in the Figure A.5]).
- One Adverse Weather, Autonomy Aware event (Weather in the Figure).

The Strike Location Update event required the Supervisor to update the UAS's plan. The Adverse Weather event occurred at the end of the shift, because all UASs return to the launch area and if there is adverse weather, the system was shut down for the rest of the shift.

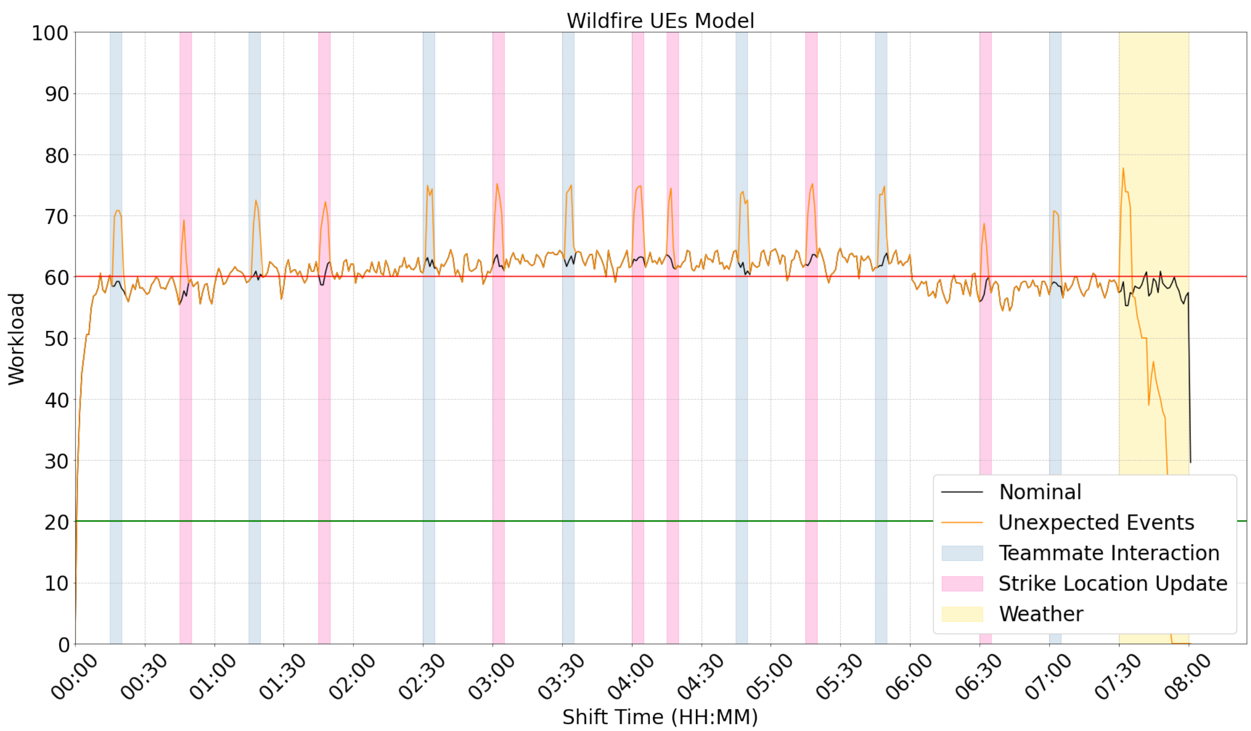


Figure A.5: The adverse weather and strike location update UEs model that also incorporated the Interaction with Teammates distraction event. Each individual event type appears with a corresponding color.

Throughout this modeled shift, the nominal use case periods corresponded to the nominal use case results. This model's ramp up period demonstrated a similar pattern to the nominal use case model. The differences appear due to the UEs. The Strike Location Update events result in higher workload, but not as high as the UEs in Figure A.4. The Adverse Weather event results in an immediate workload spike that quickly reverses as the UASs return to the launch area and land, which results in a very different workload pattern than the nominal use case's ramp down period.

A.2.3.3 Distraction Event

Interaction with Teammates

The Interaction with Teammates distraction event was incorporated into the second UE Model. Seven interaction distraction events were modeled, as shown in Figure A.5 as Teammate Interaction. This distraction event generally had a larger impact on workload than the Strike Location Update UE, but the distraction results were lower than the workload increases due to the collision and DAA UEs.

Fatigue

The Fatigue event simulates degrees of sleep deprivation and the associated effects on performance. The IMPRINT Pro fatigue tool was used to model 1, 4, 6, and 8 hours of sleep the prior night, as shown in Figure A.6. IMPRINT Pro classifies the sleep conditions along with expected situation awareness integrity and risk level, as shown in Table A.4.

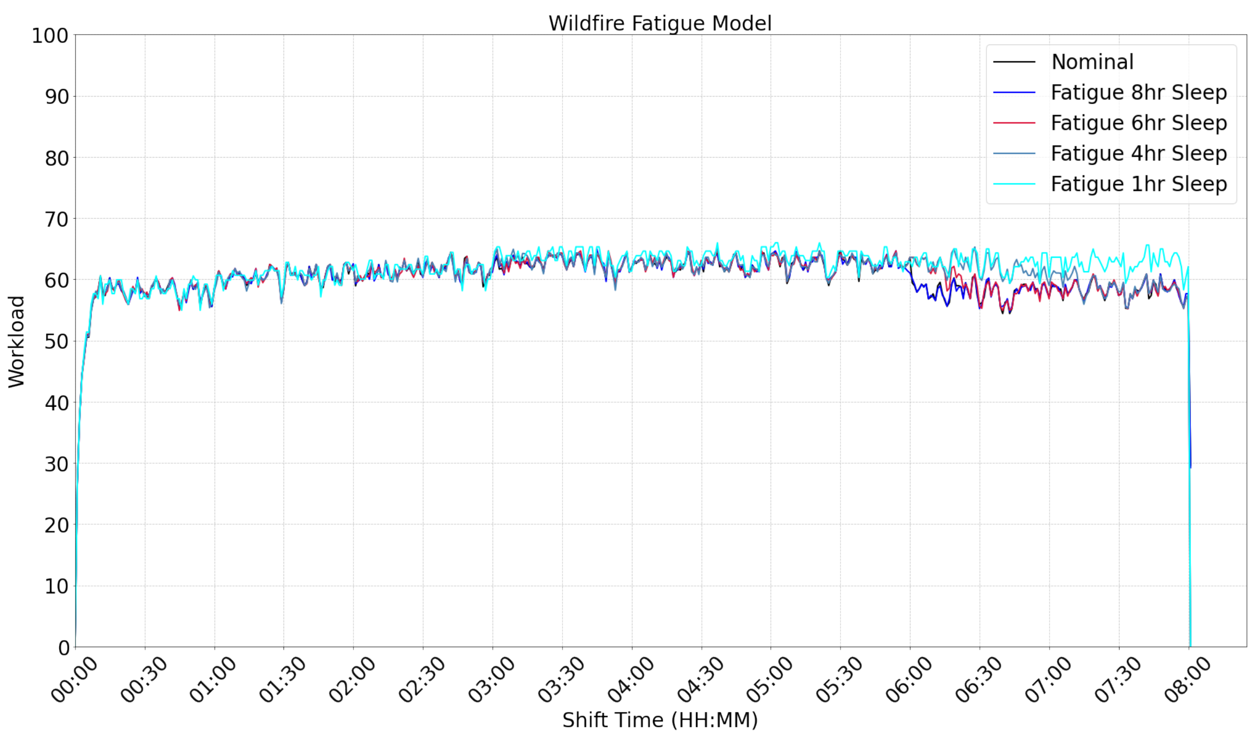


Figure A.6: Workload under fatigue conditions.

Overall, the 8-hours of sleep is the nominal use case workload. Fatigue introduced a nonlinear decay in the Supervisor's performance, as shown in Table A.4. As sleep deprivation

Table A.4: Cross-Scenario Fatigue Comparison Summary by hours slept.

Sleep Condition	**Hours Slept**	**Situation Awareness Integrity**	**Risk Level**
Well-Rested	8	High	Safe
Moderate	6	Degrading	Moderate Risk
Severe	4	Fragile	High Risk
Critical	1	Collapsed	Not Acceptable

increased, the Supervisor became less resilient to interruptions and errors. Visible differences begin at thrree hours into the shift for the one hour of sleep data, as shown in Figure A.6, with differences for the 4 and 6 hours slept appearing around six hours into the shift before returning to the same levels as the nominal use case later in the shift.

Fatigue had a clearly negative impact on the amount of visual scans. As sleep duration decreased, the number of base linear scans dropped substantially, while the time required to scan the UASs increased substantially, as shown in Table A.5. The mean and maximum times to scan a UAS were equivalent across all conditions. However, individuals with only 1 hour of sleep performed roughly 73% fewer scans than those with 8 hours of rest and required more than three times as long to complete a scan. These results underscore the critical importance of adequate rest for mission effectiveness in high-stakes operational environments.

Table A.5: The number and time to complete visual scans by the number of hours slept.

Metrics\Conditions	**8 Hours**	**6 Hours**	**4 Hours**	**1 Hour**
Number of Base Linear Scans	1357	1254	1084	372
Time to Scan 1 UAS (seconds)	1.40	1.52	1.74	5.04
Time to Scan 10 UASs (seconds)	14.13	15.12	17.50	50.54

A.3 Lightning Strike vs. Delivery Drone Use Case Analyses

A lack of viable deployed *m:N* UAS systems for wildland response in general led to a task of identifying a comparable *m:N* systems for purposes of completing the research. Delivery drone systems met this objective and a comparison across multiple factors were conducted to determine the similarities between the two systems. The factors comparisons, as shown in Tables A.6-A.9, analyzed human factors, mission, Supervisor roles, and UAS capabilities.

Table A.6: The human factors criteria categorized by use case (**LS**: Lightning Strike, **PD**: Package Delivery). Value ranges are provided in parenthesis.

Criteria	***Description***	Differences
Stress level	Over time individuals acclimate to the job and stress levels stabilize, but stressors differ between the use cases. Stress may change due to task requirements, task complexities, or unexpected events that can increase task complexity. The job comes with some, but not zero stress; thus, 20 was chosen.	**LS**: Low **Average**: 20 (15-35) **PD:** Low **Average**: 20 (15-25)
Fatigue	The LS Supervisors work longer days, possibly 10 hours on task plus two hours of set up and tear down, whereas PD Supervisors are expected to work 8 hours. The LS commutes may also be longer. Average city commutes are 27.6 minutes [24]. LS Supervisor's rural locations are distant from population centers. Some sectors may be within 30 minutes of nearby suburbs or rural communities, while others may be 1+ hours away. Therefore, LS commutes may be longer than PD commutes. The LS use case likely also requires more taxing physical setup and tear down after shifts to prepare/store UASs. Fatigue levels of 50 were chosen for PD to indicate average fatigue levels. A value of 55 for the LS use case, as longer days, potentially longer commutes, and setup/tear down will have an impact.	**LS**: Moderate **Average**: 55 (50-60) **PD**: Moderate **Average**: 50 (45-55)

Table A.6: The human factors criteria continued.

Criteria	Description	Differences
On-Task Effort (Sustained Attention)	On-task effort requires maintained task engagement and incorporates stimulus detection; a task is more engaging when it requires less sustained attention to remain engaged. On-task effort and sustained attention tie with stimulus detection; when stimulus detection is higher, the task can be more engaging as visual information facilitates focusing attention. The LS use case has fewer UASs and less frequent interactions with any particular UAS, as they are more likely to lose communication based on topography, distance, etc. When UASs are out of communication, there will be higher monitoring effort and attention demands to track when the UASs come back into communication (likely at a different location than the last telemetry data). PD has more UASs to monitor that may necessitate interacting with an UAS glyph, but generally the Supervisor monitors more UASs. There will exist periods when the UASs lose communication in urban environments, but the environmental consistency allows the centralized system to learn where communication is lost (i.e., urban canyons) and the average time span (e.g., a known delivery location with communications loss). If the UASs are out of communications for too long, this unexpected event is transferred to the Unexpected Event Supervisor.	**LS**: Moderate **Average**: 50 (40-60) **PD**: Low to Moderate **Average**: 35 (30-40)

Table A.6: The human factors criteria continued.

Criteria	Description	Differences
Distractions	Distractions are external to the mission and task. LS efforts occur at remote locations with less opportunity for distractions (e.g., no or limited internet access). There are 2-3 other co-workers who can distract the Supervisor. It is likely that the working environment will keep both the Supervisor and team members engaged in their task. However, close working proximity may foster closer social relationships and increase willingness to interact, which can increase distractions during low workload periods. External distractions are limited for LS. PD occurs in an office environment with internet access, which directly increases opportunities for distractions, but likely internet access will be restricted. PD occurs in urban/suburban environments, so environmental noise levels and interactions with others may be higher. Though task may keep Supervisors occupied most of the time, working near more colleagues can increase external distractions.	**LS**: Low to moderate **Average**: 30 (20-40) **PD**: Moderate **Average**: 50 (45-55)
Perceptual Errors	The command and control (C2) system interfaces will differ substantially. C2 interfaces primarily report tasks' and UASs' status. Supervisors are rarely required to interpret complex information. Assuming the C2 interface(s) accurately report the requisite information, few perceptual errors are anticipated. However, in the LS scenario, the high likelihood of losing communications and needing to track UASs via the interface does cause errors to be slightly more likely, as Supervisors may need to maintain awareness of out of communication UASs.	**LS**: Low **Average**: 25 (15-35) **PD**: Low **Average**: 20 (15-25)

Table A.6: The human factors criteria continued.

Criteria	Description	Differences
Situational Awareness	The LS use case has poorer/unpredictable communication capabilities and is subsequently more likely to have less frequent/reliable UASs status updates. The unreliable communications can reduce the overall amount of available information, which may naturally lower situational awareness. PD has more reliable communications and the environmental context is much more consistent and well-known. Further, the likelihood of redundant tracking/communication systems (e.g., UTM, LTE/WiFi) will ensure reliable tracking of UASs.	**LS**: Low to Moderate **Average**: 35 (15-65) **PD**: Moderate **Average**: 50 (45-65)

Table A.6: The human factors criteria continued.

Criteria	Description	Differences
Working Memory	C2 interfaces for both use cases report all the necessary information a Supervisor needs to perform their job duties; however, interpreting or synthesizing this information varies based upon the nature of the task, training, and number of UASs. Humans maintain 7 ± 2 pieces of information in working memory at any given time [25]. PD consists of a large number of UASs (e.g., 20+) performing very simple tasks. Summarizing information from this many UASs may stress the individual's working memory, as they may need to simultaneously track and integrate information across many UASs. This strain on working memory can be mitigated with a well-designed C2 interface, but that may not eliminate this demand completely. The LS teams have far fewer UASs (e.g., 4-5). which may result in less information to integrate. However, given the unpredictability of the LS environment/communications, other demands (i.e., task switching) may be placed on the working memory system. Task switching is another demand on working memory that will manifest in cases when the Supervisor switches from routine UAS monitoring to another task, be it dealing with unexpected events or distractions. PD companies are adamant that their success is dependent upon the UASs' autonomous ability to handle unexpected events as they occur; thus, it is expected that there is little the Supervisor will do in the event of an unexpected event. There is slightly more task switching in the LS scenario due to the infrequent need to adjust/change the mission plan in response to monitored information, so while on average working memory demands are equivalent between the use cases, there is a greater potential for higher demands in the LS use case.	**LS**: Moderate **Average**: 55 (40-80) **PD**: Moderate **Average**: 50 (40-60)

Table A.6: The human factors criteria continued.

Criteria	Description	Differences
Workload	Workload is an outcome of many factors, including demand on working memory, sustained attention, stimulus detection, fatigue, and frustration. Generally, the overall task demands will dictate perceived workload. For example, more UASs may increase workload, especially in very high numbers; thus, PD produces a higher workload than LS. Similar effects on workload may be observed for increases in other areas (e.g. higher working memory demands may also increase workload). PD Supervisors, given the task's regularity and consistency, will experience moderate levels of workload without much fluctuation. LS Supervisors will also have moderate workload levels, given the various use case demands, but may occasionally be underloaded due to infrequent interactions. However, the LS use case's high likelihood of intermittent communications may also produce workload spikes, as the Supervisor will be monitoring communication status changes and the return of the UASs.	**LS**: Moderate **Average**: 50 (30-70) **PD**: Moderate **Average**: 50 (45-55)

Table A.6: The human factors criteria continued.

Criteria	Description	Differences
Stimulus Detection	Stimulus Detection represents the frequency with which the Supervisor will respond to visual or auditory stimuli that may come from the UAS interface, or other team members. Stimulus detection also incorporates some aspects of perceptual effort. The visual notifications and UAS glyph complexities will be similar between the use cases. All PD UASs perform the same, fairly simplistic task with likely semi-frequent and expected UAS updates. These types of stimuli may be unlikely to occur for an individual UAS, but will probabilistically occur more frequently with a larger fleet. The LS UASs perform multiple functions and may communicate different information to the Supervisor, either through the C2 interface or through other team members. This domain is expected to increase the notification types the Supervisor will receive and process, which are expected to occur less frequently. Further, UASs are deployed for longer mission periods in more remote areas, so LS notifications may be missed due to lack of or poor communications. The PD case produces average stimulus detection levels due to the volume of UASs. The LS use case produces low to average levels of stimulus detection given the lower level of notifications, fewer UASs, and loss of communications.	**LS**: Low/moderate **Average**: 35(20-40) **PD**: Moderate **Average**: 50(40-60)

Table A.6: The human factors criteria continued.

Criteria	Description	Differences
Environ-mental Factors	Environmental factors include temperature, air quality, elevation above sea level, etc. PD Supervisors do their jobs in more controlled environments (e.g., paved roads, buildings). LS Supervisors are more exposed to the elements, given the wilderness environment during fire season (e.g., large elevation changes, dirt roads). The Conex box will mitigate many of these elements; however, it is not the same as working inside an office building. The impact of environmental factors will be low in the PD, but non-zero, as working in office environments is not always ideal. These factors will have a slightly higher impact for the LS strike case, as operating in remote locations presents unique environmental factors that will inevitably play a role.	**LS**: Low to moderate **Average**: 35 (30-60) **PD**: Low **Average**: 25 (20-30)
Frustra-tion	Frustration is low and fairly stable in both use cases, because the Supervisors are primarily working with familiar tools, in a familiar setting. However, unexpected events may significantly increase a Supervisor's frustration in the LS scenario. The PD Teams are expected to be centrally located, where technical support is available. Unexpected events can be allocated to the appropriate support team members (i.e., Unexpected Event Supervisor). LS Teams will be located in remote areas, with very limited technical support that will place the burden of addressing some UEs on the team. For example, a failure of the C2 station will require the Supervisor to address the situation and can lead to increased frustration. Almost all UAS unexpected events will be handled autonomously, however, if human intervention is needed, then the Supervisor's frustration may increase significantly, as the only additional support is their three team members.	**LS**: Low to moderate **Average**: 35 (30-85) **PD**: Low **Average**: 25 (20-30)

Table A.6: The human factors criteria continued.

Criteria	Description	Differences
Mission Contingency Planning	The PD Supervisor does not expend effort for the UAS mission assignment. For example, if a package delivery is canceled by a consumer, the system automatically handles that mission cancellation and the Supervisor has no knowledge of the event. The LS Supervisor may do some mission related contingency planning; however, the amount will be low. For example, some condition requires the Supervisor to define a different coverage area than planned. Another example ensures that alterative landing sites (e.g. parking lot, camp site) are specified. A dynamic plan reconfiguration for new lightning strikes may occur, but that replanning will likely be autonomous, based on the received strike location information, and likely only require Supervisor approval.	**LS**: Low **Average**: 10 (5-15) **PD**: NA **Average**: 0
Unexpected Event Contingency Planning	Any major unexpected events are not handled directly by the PD Supervisor, they are handed off to additional personnel or handled by the autonomy. There are very few unexpected events that require human intervention and those that require Supervisor intervention will use a predefined contingency plan. Failure of the C2 station is an example of an unexpected event that requires the Supervisor to respond, but there exists a pre-defined means of responding to such an event.	**LS**: Low **Average**: 10 (5-15) **PD**: NA **Average**: 0

Table A.7: The Supervisor Tasks for the lightning strike (LS) and package delivery (PD) use cases. Note that the PD use case does not require very many tasks of the Supervisor.

Task	***Description***	**Use Case**
Routine Monitoring	The PD and LS Supervisors monitor the routine operations, including UASs health and status. LS Supervisor monitors for updates of new or existing hotspots, fires, or potential fire locations, which may include hotspots or fires that exist at the start of shift. At shift end, the Supervisor may have to report the status of all known hotspots or fires.	Both
Task Monitoring	The LS Supervisor may need to monitor for fire, hot spots, etc. However, the team lead will have primary responsibility for this task. PD will not require the Supervisor to monitor specific tasks, such as package delivery.	LS
Develop or Modify Mission Plan	The PD Supervisor will not have any control over the pickup/delivery mission plan. The LS Supervisor will develop and verify a mission plan pre-deployment. During the deployment a new plan may be developed, or the existing plan modified. A mission plan is composed of multiple plays [26].	LS
Select or Modify High Level Play	The PD Supervisor will not have this capability. During the LS use case, when action is needed outside of routine operation, the Supervisor will select or modify a high level play for the UAS (e.g., a predefined search pattern or flight path alteration). The highly autonomous UASs do not require frequent play assignment or modification.	LS
Report Findings	The PD Supervisor has no findings to report. The LS Supervisor reports fire outbreaks, hotspot locations, the sector status, UASs fuel levels and possible areas where hotspots or fires may break out. This Supervisor may report the findings to the overall site Supervisor/commander, or the system may upload updates to the appropriate agencies.	LS

Table A.7: The Supervisor Tasks continued.

Task	Description	Use Case
Track Communications Outages	PD will experience infrequent link loss, likely in known locations. The Supervisor cannot take actions during link loss. If extended link loss occurs, the UAS experiencing the unexpected event will be handed off to the Unexpected Event Supervisor. The LS Supervisor will monitor the communication status. There may be known communication dead zones due to topography. The Supervisor may track if the outage is a normal time length or an abnormal amount of time. If a UAS has link loss, the Supervisor is unable to do anything about it.	LS
Assist Hardware and Launch Specialist	The PD Supervisor will not be near or handle any UAS hardware. The LS team members will be cross trained to help each other when necessary with the time consuming tasks. The LS Supervisor may help the Hardware Specialist with the UASs' setup for launching or breakdown at the end of the shift.	LS
Assist Team Lead	The PD Supervisor may interact with the Shift Supervisor, but a formal assistance task does not exist. The LS Team lead may as the Supervisor to provide information (e.g., "did you assign UAS x task i?"), review sensory information (e.g., "please review UAS x's thermal image"), discuss incoming information (e.g., new set of lightning strikes), etc.	LS
Review Sensor information (per Team Lead request)	The PD Supervisor will not view sensor feeds. The LS Supervisor will be primarily responsible for monitoring the UASs' mission plan execution. The Communications Lead has primary responsibility for sensor feed monitoring, but may request the Supervisor review sensor feeds. The Supervisor will display the sensor information on the C2 station.	LS

Table A.8: The UAS subsystem considerations for the (**LS**: Lightning Strike and **PD**: Package Delivery use cases.)

Subsystems	Description	Differences
Sensors	All UASs have some set of the following sensors: • Proprioceptive • Global positioning sensor • Internal measurement unit • Exteroceptive • Lidar • Radar or Sonar • Camera LS UASs will have additional sensors: • Infrared Camera • Air quality sensor	**LS**: More diverse sensors **PD**: Basic sensors (e.g., camera, internal measurement unit, global positioning system)

Table A.8: The UAS subsystem considerations continued.

Subsystems	Description	Differences
Sensor Processing	General use case aspects will require similar data processing, even with slightly different sensors. The processing tasks and the compute levels are similar given that both use cases: • require robust localization. • need object detection, to verify a delivery or pickup location or detect a fire. • must avoid obstacles - DAA. • maintain vehicle control stability by dynamically adjusting to environmental conditions. Both LS and PD UASs will primarily perform onboard sensor processing. LS UASs operate in the wilderness, with limited communications; thus, the majority of the sensor processing and perception will be performed onboard. PD UASs have access to communications networks, but sensor processing must occur onboard because relying on centralized computation can be too slow to allow the UAS to respond to the current situation (e.g., DAA). Both use cases will require continuous onboard DAA. The PD UASs encountering new structures in the environment must report the structures to the UTM to be incorporated into future path planning. These updates are not necessary for the LS UASs, as they are unlikely to rely on the UTM. A key difference in sensor processing is the frequency with which data must be processed; specifically, for object detection. The LS UASs will need continuous infrared imaging object detection to detect early signs of a fire or a lightning strike. The PD UASs may only need to locate a pickup or delivery location, or landing location, which is limited for each deployment.	**LS**: All onboard processing **PD**: Mostly onboard processing & UTM

Table A.8: The UAS subsystem considerations continued.

Subsystems	Description	Differences
Communication	PD UASs can leverage all available terrestrial communication infrastructure (e.g., cellular network, UTM) to communicate with a centralized location. The nature of the LS deployments will mean terrain interference and general limited communication connectivity will exist. Thus, LS UASs will likely rely on peer-to-peer connections, or some form of Ad Hoc network to relay information back to the operations base and C2 station. LS UASs may also need to take advantage of satellite communication. It is important to note that LS UASs may be unable to communicate for periods of time on a regular basis with the operations base and C2.	**LS**: Decentralized Peer-to-peer/Ad Hoc network/ Link loss **PD**: Centralized Traditional network Communications
Autonomy: UAS Health	UAS Health autonomy is the set of algorithms that ensure a UAS can perform basic functions (e.g., flight stabilization, detection and avoidance). Overall, UAS Health requirements are generally the same between the use cases. The primary difference is that PD UASs carry payloads, which may affect flight dynamics. Existing algorithms must account for any potential flight dynamics differences. These differences will vary based upon how the payload is carried (e.g., Zipline UAS designs [27]).	**Autonomy level** (100% = fully autonomous) **LS and PD**: 100% **Computational Requirements:** **LS and PD**: High, depending on onboard fault detection.

Table A.8: The UAS subsystem considerations continued.

Subsystems	Description	Differences
Autonomy: Mission Objective	Mission objective autonomy are the algorithms that ensure a UAS can perform assigned tasks. The PD UASs conduct takeoff, point-to-point navigation (i.e., from launch zone to delivery location and back to landing zone), picking up a package, delivery (i.e., lowering the package), and landing. The UASs need to adjust their flight navigation plans dynamically to allow for delivery cancellations or relocating to different landing zone locations. The UASs must also determine that they have arrived at the pick up or drop off location. The UASs must also autonomously pick up or drop off the packages. The LS UASs perform the similar takeoff, landing, return to base, and navigation functions as the PD UASs. The LS UASs also have a subset of more sophisticated behaviors. These UASs surveil an area by autonomously executing an area coverage algorithm, possibly in coordination with multiple UASs. The UASs must perform ground topology following to maintain a consistent height above the ground, so that sensors collect reliable data [28]. The UASs may replan or adjust their height or flight path based on Supervisor instructions. If sufficient computational capability exists on-board, the UASs may also identify areas of interest (e.g., fire) and conduct a data gathering navigation route to gather additional sensory information, particularly important during link loss situations.	**Autonomy level** (100% = fully autonomous) **LS:** 90% **PD**: 100% **Computational Requirements:** **LS**: High (e.g., terrain following) **PD**: High (e.g., DAA congestion)

Table A.8: The UAS subsystem considerations continued.

Subsystems	Description	Differences
UTM Integration	The PD scenario consists of flight paths for every package to be delivered, which communicated through a centralized service. The UASs need to broadcast remote identifier messages so that personal devices within range that are using UTM-approved applications can receive the broadcast. This broadcast enables the public to reliably identify UASs in their area. The LS UASs use UTM if it is available, but given the remote deployments, UTM is likely unavailable. The only UTM interaction is likely to occur prior to deployment when the Supervisor requests a sector (e.g., the area) for the team to monitor (i.e., max extent of 10 nautical miles) at a time.	**LS**: No real-time UTM communication **PD**: Near real-time UTM communication

Table A.8: The UAS subsystem considerations continued.

Subsystems	Description	Differences
Power Consumption	Power consumption occurs when performing mission tasks. Many factors, categorized by UAS design and dynamics, environmental and delivery operations were identified as the primary factors impacting UAS energy consumption [29]. Consumption factors common to both use cases: • Weather (e.g., high winds increase power consumption during station keeping). • Overall vehicle design (e.g., Fixed wing flight can be more efficient than multi-rotor). Primary PD UAS power consumption factors are payload and weight. A linear correlation between payload weight and additional energy consumed exists. A PD UAS can consume power faster than the LS UAS. However, a UAS's design can significantly mitigate the impact a heavier payload has on power consumption. The PD UASs are expected to be within reasonable proximity of a power source (i.e., landing/launch area) at all times. Prior work demonstrated that a UAS without a payload consumes roughly 30 Joules per meter, and a UAS with a 2 kilograms payload has a range of 40 to 150 Joules consumed per meter [29]. Speed impacts the UAS's energy consumption efficiency [30]. A UAS's optimal speed is platform dependent, but some speeds, both slower and faster, increase power consumption. Prioritizing UAS delivery speed may result in suboptimal power consumption for both loaded and unloaded UASs. The LS UASs may need to prioritize speed, but typically travel at optimal power consumption speeds. The LS power consumption factors are: • High altitude takeoff and landing. • Topology following.	**LS**: 75 **PD**: 50 (Baseline/ Average: Power Consumption)

Table A.8: The UAS subsystem considerations continued.

Subsystems	Description	Differences
Power Consumption Continued	Environmental factors unique to the LS use case will impact power consumption; specifically, higher operating altitudes. Prior work demonstrated that power consumption increases as altitude increases, and can also be influenced by environmental factors (e.g., wind and temperature) [31]. The PD topology (i.e., terrain) following requires precise control over a UAS's height. Hovering requires more precise control over a UAS's motors, and consumes more power. Both the LS and PD UASs will hover during their missions, but the LS use case requires continuous topology following.	
Power Availability	Power availability is the maximum power level available to a UAS. The LS UASs will require higher power availability than the PD UASs because they operate at high altitudes (e.g., > 6000 feet above sea level). Takeoff and landing procedures are more difficult to perform at higher altitudes due to the thinner atmosphere and require a higher maximum power. Power availability is UAS platform specific. The PD UASs are primarily hybrid aircraft (i.e., rotary + fixed wing) can vary in size, whereas the LS UASs are primarily rotary aircraft of a single size. Large PD UASs are designed to carry heavier payloads and conduct long range deliveries, which requires more power. The UASs' hybrid design provides significant flight efficiency improvements. The LS UASs will conduct long distance and duration monitoring tasks at high altitudes that can be achieved with a larger UAS fleet with lower power availability by using task swapping [32]. These tasks can also be achieved with larger rotary aircraft with higher power availability.	**LS**: 70 **PD**: 50 (Baseline/ Average Power Consumption)

Table A.9: Selected mission characteristics categorized by the (**LS**: Lightning Strike and **PD**: Package Delivery use cases.)

Characteristics	***Description***	**Differences**
Mission Objective	A mission objective is the core function or purpose of the human-robot team. The overall objective of each mission is quite different. The PD mission objective is to deliver packages, where a single mission requires delivering one package by flying a specified route to 1) pick up the package, 2) navigate to the delivery location, 3) deliver a package, 4) navigate to either 5a) a landing zone and land, or 5b) pick up a new package. Landing or transitioning to a new package assignment is the end of an individual mission objective. The LS mission objective is to monitor lightning strike locations, either historical or current, for early signs of a fire. This continuous mission involves multiple UASs scanning a sector defined by a specified location or a coverage area.	**LS**: Scan areas **PD**: Delivery
Number of UAS	The PD Supervisor will likely supervise hundreds of in air UASs simultaneously, at least 20-50. The LS Supervisor will supervise 10 - 12 in air UAS simultaneously, sometimes fewer.	**LS**: 10-12 **PD**: 50-100
Mission Coupling [33]	The PD mission has loose coupling, because each UAS has an independent delivery goal. The LS mission requires variable coupling. Some scenarios require monitoring a single large coverage area for which multiple UASs coordinate their scanning paths to ensure all necessary information is gathered, which is a tightly coupled task. Four UASs can conduct area coverage on different directional paths to provide a range of sensor fields of view, as shown in Figure A.7. There are other scenarios that require the team to monitor multiple independent, possibly spatially dispersed locations, where a single UAS is sufficient to monitor each location.	**LS**: Medium-to-tightly coupled **PD**: Loosely coupled

Table A.9: Selected mission characteristics continued.

Characteristics	*Description*	Differences
UAS Cooperation	PD requires no explicit cooperation between the UASs. Most autonomous behaviors (e.g., DAA) employed by the PD UASs are reactive, not cooperative. LS UASs engage in a range of cooperative behaviors. An example is the UAS battery swap, where the persistent coverage task requires UASs that are low on battery to wait on task for a UAS with a fresh battery [32]. The on task UAS requests a replacement in sufficient time to allow the replacement to arrive at the on task UAS's location, and for the on task UAS to return safely to the landing area.	**LS**: Moderate **PD**: None
Deployment Duration	PD missions will require between 5 and 20 minutes to complete [5]. A PD mission consists of a single UAS delivering a single package, but a single UAS can sequentially execute multiple missions. LS missions require persistent monitoring during the mission. UASs will swap out during the mission, but the mission itself lasts the entire 10 hours.	**LS**: 10 hours. **PD**: 5-20 minutes
Flight Complexity	Nominal PD flights primarily require point-to-point navigation paths verified by the UTM a priori; thus, conflicts between UASs will be minimal. Simple DAA actions will constitute the most complex portion of a nominal flight, as after avoiding an obstacle a UAS must return to its original path. Nominal LS flights will be complex. All UASs must engage in topography following [28], adding computation and power consumption. UASs may need to coordinate their flight paths and communicate with one another (see Figure A.7) that will require dynamic battery management and speed control.	**LS**: Complex **PD**: Simple

Table A.9: Selected mission characteristics continued.

Characteristics	***Description***	**Differences**
Environmental Complexity	Environmental complexity represents the differences in the deployment environments, where PD occurs in Urban/Rural areas and LS occurs in Forest/Mountainous/Urban-interface terrain [28]. PD may have navigational complexity with buildings, and need to accommodate the urban environment when delivering a package via a drop mechanism, even though PD can occur in rural or suburban areas with fewer buildings. PD must lower the package into the built environment, even if the UAS is flying above that environment. The UAS is likely to fly closer to the built environment in urban areas. LS UAS will fly above most obstacles, but will encounter variable high altitude specific weather conditions and do terrain following. Terrain in these environments can vary significantly, as they are characterized by large elevation changes (e.g., cliffs), variable forest density (i.e., forested valleys vs. a mountain top tree line), and forest composition (i.e., tree species). These factors impact how high above the ground UASs must fly and how often large elevation changes are necessary for terrain following. Both scenarios have similar overall complexity values, but the factors influencing the complexities differ.	**LS**: 50 **PD**: 50
Autonomy Tasking Level	Both PD and LS represent a high-degree of UAS autonomy (i.e., minimal human intervention). The presented values are based on Sheridan's levels of autonomy [34], where 0 is full human control, and 100 is fully autonomous vehicle (i.e., no human inputs). The LS use case consists of almost all high-level UAS tasks and mission plans, but may include some mid-level tasking like selecting plays (e.g., coverage path) that require some elements to be specified. The PD Supervisor does not do tasking. Any unexpected event requiring a human response can be sent to the Unexpected Event Supervisor.	**LS**: 90 **PD**: 100

Table A.9: Selected mission characteristics continued.

Characteristics	***Description***	**Differences**
Handling of Unexpected Events	The PD Supervisor does not take any action in response to unexpected events, because the UAS's autonomy manages the vast majority of these events. Any unexpected event that requires human response is sent to the Unexpected Event Supervisor. The LS unexpected events are handled either by the UAS's autonomy or the Supervisor. Some unexpected events can only be addressed by the Supervisor (e.g., C2 station failure). Other unexpected events can be detected by the UASs autonomy, but may require the Supervisor to identify the best response (e.g., UAS flyaway, emergency in the airspace, software or hardware malfunctions). These cases typically require the Supervisor to choose between: landing the UAS in place, returning the UAS to launch site, or allowing the UAS to continue the mission. There are LS unexpected events that do not require any Supervisor intervention, including an "Unexpected Battery Depletion" where the UAS's autonomy informs the Supervisor of the event and automatically returns to the launch site.	**LS**: Very few - UAS must autonomously handle the majority. **PD**: None - Supervisor handles none, fully autonomous handling

Table A.9: Selected mission characteristics continued.

Characteristics	***Description***	**Differences**
Environmental Dynamics	PD UASs will operate in dynamic environments. Physical environmental changes due to construction can occur frequently. An increased number of UASs in the airspace may result in congestion. Further, UASs in the airspace may be non-PD UASs or PD UASs from other companies, so DAA capabilities become more critical. The overall likelihood of obstacle avoidance is higher for PD and may incur a higher cost than in the LS use case. PD delivery will conduct operations in a broader range of weather conditions. For example, PD UASs may deliver packages on rainy days. The LS UASs will operate in generally static environments. Natural environments do not change rapidly outside of weather events, so the environment will be relatively static. However, fires and storms may drastically and rapidly change the environment. LS UASs will also operate in remote locations where other aircraft are less likely to be operating.	**LS**: Mostly Static **PD**: Somewhat Dynamic
Mission Certainty	PD environments are somewhat dynamic, but also very certain. Buildings do not move and construction is typically a slow process. The vast majority of changes within a PD environment will be known with a reasonable lead time (e.g., construction, UAS route congestion, weather). LS environments are even less dynamic, but more uncertain. Each sector is characterized by different terrain, topology, and likelihood of encountering a fire. Further, its difficult to definitively know when and where lightning strikes may occur. All of which makes for uncertain and variable conditions.	**LS**: Semi-Certain **PD**: Certain

Table A.9: Selected mission characteristics continued.

Characteristics	***Description***	**Differences**
Mission Dynamics	Mission Dynamism can be decomposed into mission goal dynamism and mission plan dynamics. Both PD mission goal and mission plan dynamics are static. The PD mission goal is to ensure that the package is safely delivered to its location in a timely manner and the UAS returns to a landing area or continues to the next delivery mission assignment. The LS mission goal is static, but the mission plan is partially dynamic. The LS mission goal is to monitor for signs of a fire, but how this goal is achieved varies. UASs deployed in a large coverage area will have different mission plans compared to those deployed to cover many smaller independent locations. Additionally, the mission plan will change if signs of a fire are detected. The UASs will transition from monitoring their sector into monitoring a specific location and reporting the necessary information.	**LS**: **Mission goal**: Static **Mission plan**: Partially Dynamic **PD**: **Mission goal**: Static **Mission plan**: Static
Mission Goal Achievement Certainty	The PD mission goal is certain: was the package successfully delivered, attempted, or failed? The LS mission scans for signs of a fire based upon the location of historical and current lightning strikes. Multiple UASs surveil a sector and report overlapping information. This redundancy is intentional to ensure multiple sources corroborate the gathered data and increase the confidence of the team's conclusions. However, confidence may never reach 100%, as it is always possible some information was missed.	**LS**: Partially Uncertain **PD**: Fully certain

Table A.9: Selected mission characteristics continued.

Characteristics	***Description***	**Differences**
Mission Plan Complexity	The PD mission plan has low complexity, consisting of a single UAS picking up a package from a third party vendor or a base of operation, and delivering the package to a specified location. Each UAS executes their mission independently without collaborating with other UAS. The only interaction may occur when autonomous and reactive DAA maneuvers are executed. Further, most missions will be complete within 20 minutes. The LS mission plan has moderate to high complexity, but varies based upon the mission's characteristics. Each LS mission consists of a multiple UASs collectively monitoring a deployment sector. A single large coverage area within a deployment sector often requires explicitly coordinated flight paths to effectively monitor the area (see Figure A.7). A deployment sector can also consist of a collection of independently located points, requiring each UAS to monitor each point independently. LS UASs may also collect different types of data or be assigned to different task types. For example, one UAS may be necessary to establish reliable communications between the Supervisor and the UAS team. This singular UAS can act as a network node to facilitate UAS-Supervisor communication, as well as UAS-UAS communication when necessary. Multiple LS UASs can collaboratively and continuously monitor a sector over a 10 hour period. The UASs collectively monitor an area and gather potential signs of a fire from varying viewpoints. Supervisors may analyze the provided information to determine whether it is note-worthy. These interactions are more complicated than required for PD.	**LS**: Moderate-to-High complexity **PD**: Low complexity

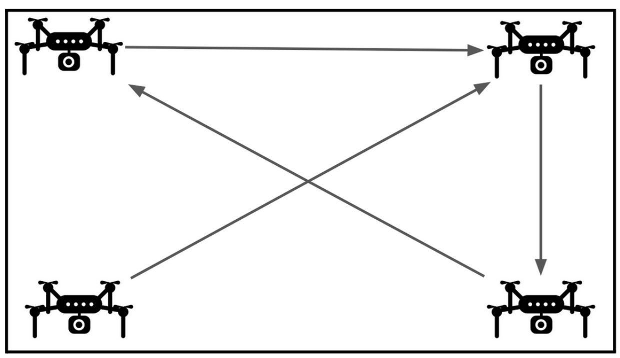


Figure A.7: Mission coupling area coverage example with four UASs.

B Small Delivery Drone: Baseline Human-in-the-Loop Evaluation

Please find the complete report on arXiv: OSU-Wing PIC Phase I Evaluation: Baseline Workload and Situation Awareness Results.

C Large UAS Wildland Fire Response

The large UAS wildland fire response evaluation leveraged an existing OrSU simulation system for large UAS. The original simulation supported investigating one remote pilot supervising up to seven large (i.e., Cesena) aircraft performing delivery operations between hub and spoke airports. An overview of the revised use case for this HITL is provided in Section 2.2. This appendix provides additional details regarding the remote pilot interface, the use case, scenario modeling, experimental design,and the results.

C.1 Use Case

The large UAS wildland fire response use case deploys four UAS on two flight routes from an untowered airport to drop water or fire retardant on an active wildland fire. A temporary flight restriction exists for the wildland fire operational area. This use case was developed based on prior wildland fire response knowledge and the large UAS delivery scenario [19]. The use case assumptions are provided in Table C.1

Table C.1: The large UAS wildland fire response use case assumptions.

General Assumptions
Operations occur using VFR.
Operations occur during daylight hours.
Operations do not occur during heavy weather (i.e., rain)
The UASs are located at an untowered airport.
UAS operations will usually be conducted over areas that are not densely populated, predominantly in rural or remote areas. However, it is possible that operations can occur at the rural/urban interface.
UASs will not be operated close to airports or heliports. 'Close' is initially defined as within 3 miles of an airport, unless permission is granted from air traffic control or the airport authority. A distance of greater than 5 miles will be examined if needed to support an appropriate level of safety.
An Air Boss instructs the remote pilot when to have UAS takeoff.
The UAS is a large vehicle that requires a runway and can carry water or fire retardant and can drop the load over the fire.
Multiple deployment teams may share an airport, but will have different flight paths.
The airspace in which the UAS operate is closed to commercial and private air traffic. Such air traffic must be above 3500 feet.
A remote pilot is responsible for operating the aircraft as well as monitoring for and responding to intruder aircraft.
Mission Assumptions
There are two flight paths, with designated waypoints.
Only the teams deploying large UAS for wildland fire response are the active aircraft at the airport.

Table C.1: Use case assumptions continued.

Each deployment team is assigned specific flight paths along which they are to conduct their operations.
UAS Specific Assumptions
Multiple UASs (i.e., 4) are required to complete these missions.
The UAS do not support digital communications, communications must be to the remote supervisor.
All communications are standard push-to-talk.
The UAS do not have autonomous DAA capabilities, the remote pilot is responsible for managing deconflictions.
The three air traffic concentric rings surrounding a specific UAS represent proximity zones for nearby aircraft: the blue ring indicates a distant aircraft zone (i.e., horizontal distance of 10 nautical miles and vertical separation of 1000 feet or more), the yellow ring denotes a caution zone (i.e., within 5 nautical miles horizontally and between 600–1000 ft vertically), and the red ring represents the incursion zone (i.e., less than 2 nautical miles horizontally or less than 600 feet vertically).
All UASs fly at least 1000 feet above ground.
All UASs operate up to 100 kilometers or 54 nautical miles from the airport.
All UASs have a typical flight speed of 140 knots (1̃60 miles per hour), with a maximum speed of 170 knots (2̃00 miles per hour).
All UAS land autonomously.
Remote Pilot Specific Assumptions
A remote pilot acts as a Supervisor.
The remote pilot uses a user interface that permits monitoring and modifying UAS operations as needed.
The remote pilot has a pilot certification.
The remote pilot is responsible for arming and executing takeoff, path waypoint changes, altitude, heading and altimeter commends.
The remote pilot is responsible for monitoring ADS-B traffic for intruder aircraft.
The remote pilot is responsible for taking any necessary interactions when an intruder aircraft impacts any of the pilot's UAS (i.e., DAA).
The remote pilot is responsible for communicating to air boss about actions taken in response to an intruder aircraft.
The remote pilot is responsible for monitoring the communications channels and responding to communications from air boss.
The remote pilot's user interface supports all monitoring and interaction actions necessary to manage four UAS.
The user interface displays a map-centric interface with UAS paths and ADS-B data.
The remote pilot's user interface supports communications via the interface or hardware radio.
The remote pilot's user interface provides a timeline for each UAS.
Unexpected Event Assumptions
The remote pilot is responsible for handling all DAA UEs.

C.1.1 Nominal Use Case

An overview of the nominal large UAS wildland fire response flight scenario is provided. The use case is presented by flight phase along with the actions the remote pilot can take with the user interface.

Launch, Ascent to Altitude

1. The remote pilot receives communications from the Air Boss to launch a UAS.
2. The remote pilot acknowledges the takeoff communication.
3. The remote pilot, via the user interface selects the specific UAS, arms the takeoff and executes it.
4. The UAS's path appears on the user interface along with the air traffic rings.
5. The UAS's timeline updates with the new route indicating the waypoints and the relative scheduled time.
6. The remote pilot communicates that the UAS is in the air or has taken off.

Enroute

7. The UAS(s) autonomously navigate to the route's waypoints.
8. The remote pilot monitors the flight of all their enroute UAS(s).
   (a) The remote pilot selects another of their UAS to display the selected UAS's route and air traffic range rings.
9. The remote pilot monitors all ADS-B traffic.

Return, Descent from Cruising Altitude, Landing

10. As a UAS completes its flight route
    (a) The UAS flies to the final waypoint.
    (b) The UAS autonomous lands and taxis off the runway.
11. Once all UASs have landed the mission is complete.

C.1.2 Unexpected Event

The only Unexpected Event developed and validated was the intruder aircraft (i.e., DAA) event. All relevant assumptions are provided in Table C.1. The UE was analyzed within the taxonomy and was described using the same format as was used for the Wildland Lightning Strike Monitoring UEs, see Section A.1.3.

Intruder Aircraft (DAA) - Distant Air Traffic Zone

Description: An intruder aircraft is detected within a UAS's distant air traffic zone (i.e., blue ring) indicating that the intruder aircraft is at least 10 nautical miles horizontally or 1000 feet vertically distant.

The remote pilot

1. Continues to monitor the intruder aircraft's route to determine the likelihood of an incursion and need to take evasive actions.
2. Continues to monitor all other enroute UAS.
3. No specific action is necessary at this time.

Intruder Aircraft (DAA) - Caution Air Traffic Zone

Description: An intruder aircraft is within a UAS's caution air traffic zone (i.e., yellow ring), which means the intruder is within 5 nautical miles horizontally and 600–1000 feet vertically of the Supervisor's UAS.

The remote pilot

1. Continues to monitor all other enroute UAS.
2. Continues to monitor the intruder aircraft's route to determine the likelihood of an incursion and need to take evasive actions.
   (a) If the intruder is the higher aircraft, then the remote pilot must take the appropriate action to avoid the intruder aircraft.
      i. The remote pilot modifies the UAS's path by
         - Arming and executing a change to the UAS's heading or altitude.
         - Selecting a future waypoint along the UAS's path that is then armed and executed.
      ii. The remote pilot communicates the evasive action to the Air Boss.
   (b) If the intruder is the lower aircraft
      i. The remote pilot takes no action per standard VFR deconfliction rules.

Intruder Aircraft (DAA) - Incursion Air Traffic Zone

Description: An intruder aircraft is within a UAS's incursion air traffic zone (i.e., red ring), which means the intruder aircraft is less than 2 nautical miles horizontally or less than 600 feet vertically from the Supervisor's UAS. Note that this situation is to be avoided.

The remote pilot

1. The remote pilot immediately assesses the intruder aircraft's proximity and trajectory.
2. The remote pilot attempts last-minute evasive action, if a safe maneuver is still feasible.
3. If the remote pilot has no evasive action to take, the remote pilot communicates such to the Air Boss.
4. The remote pilot continues to monitor all other enroute UAS.

C.2 Remote Pilot User Interface

The previously developed custom *m:N* simulation and control interface was designed to enable additional flexibility and granular control over the user interface components [19] and was adapted for the wildland fire large UAS HITL. The remote pilot interface simulates concurrent control of four UASs, each with configurable simulation parameters (e.g., aircraft type and control dynamics). The interface enables participants, serving as the remote pilot in command of multiple UAS, and to monitor, command, and control each simulated UAS, while giving experimenters a real-time overview of the simulated system state and remote pilot actions. The original remote pilot user interface requirements included:

1. Commands issued from the user interface shall follow an *arm/execute*[1] pattern.
2. The remote pilot shall be able to command UAS heading, airspeed, altitude, and altimeter setting.
3. The remote pilot shall be able to command a takeoff and modify UAS flight plans.
4. The remote pilot shall be able to use the user interface to communicate with or air traffic control through a radio assigned to each UAS. Each radio shall have a configurable frequency.
5. The remote pilot shall be able to visualize their UAS on a map and a timeline of upcoming events for each aircraft.
6. Licensed crewed aircraft pilots shall be able to effectively use the interface after a brief training session.

The primary difference for the wildland fire HITL was that the remote pilot also shall be able to use the user interface to communicate with other crewed and uncrewed aircraft pilots.

The original remote pilot user interface prototype details, and their development, are available in Dassonville's thesis [19]. The remote pilot uses a graphical user interface (see Figure C.1) and a physical radio interface (see Figure C.2). The remote pilot interface is composed of five areas: UAS list and selected UAS route, command, radio, map, and timeline.

The **command panel** facilitates interactions with a particular UAS. A UAS's available commands are state-dependent (e.g., a UAS cannot be commanded to takeoff when it is already flying). The remote pilot can change a UAS's flight route via the flight plan at the top of the command panel. Heading, altitude, airspeed, and altimeter commands are presented below the flight plan, and can be directly and independently controlled. The bottom of the command panel provides the *currently-armed* command, along with the execute and disarm commands. A new command cannot be armed until the currently-armed command is executed or disarmed. The **UAS List** provides each UAS's radio information, along with the current frequency, the facility name, the monitoring/transmitting state, and whether the radio is receiving a transmission. The selected UAS' flight path is displayed below the UAS list, it's flight path and associated air traffic rings are displayed on the map panel. Each radio's frequency can be modified through the user interface or via the physical radio interface. All communications are push-to-talk, just like in actual crewed aircraft, which requires pressing and holding the push-to-talk button to transmit communications. All incoming transmissions were audible through the headset speaker. The mute functionality was provided as needed. The **map panel** displays each UAS's location, altitude, airspeed, planned flight route, ADS-B information for other aircraft in the area, and weather information. The **timeline panel** presents the flight path and corresponding waypoints for each UAS as a linear representation.

The simulation backend incorporates a modified implementation of the open source AirTrafficSim [36] to model UAS's responses to commands. The AirTrafficSim modifications

[1]The *arm/execute* pattern is common in aerospace systems [35]. The remote pilot must first "arm" a command, and then "execute" that armed command, reducing the likelihood of unintentional commanding.

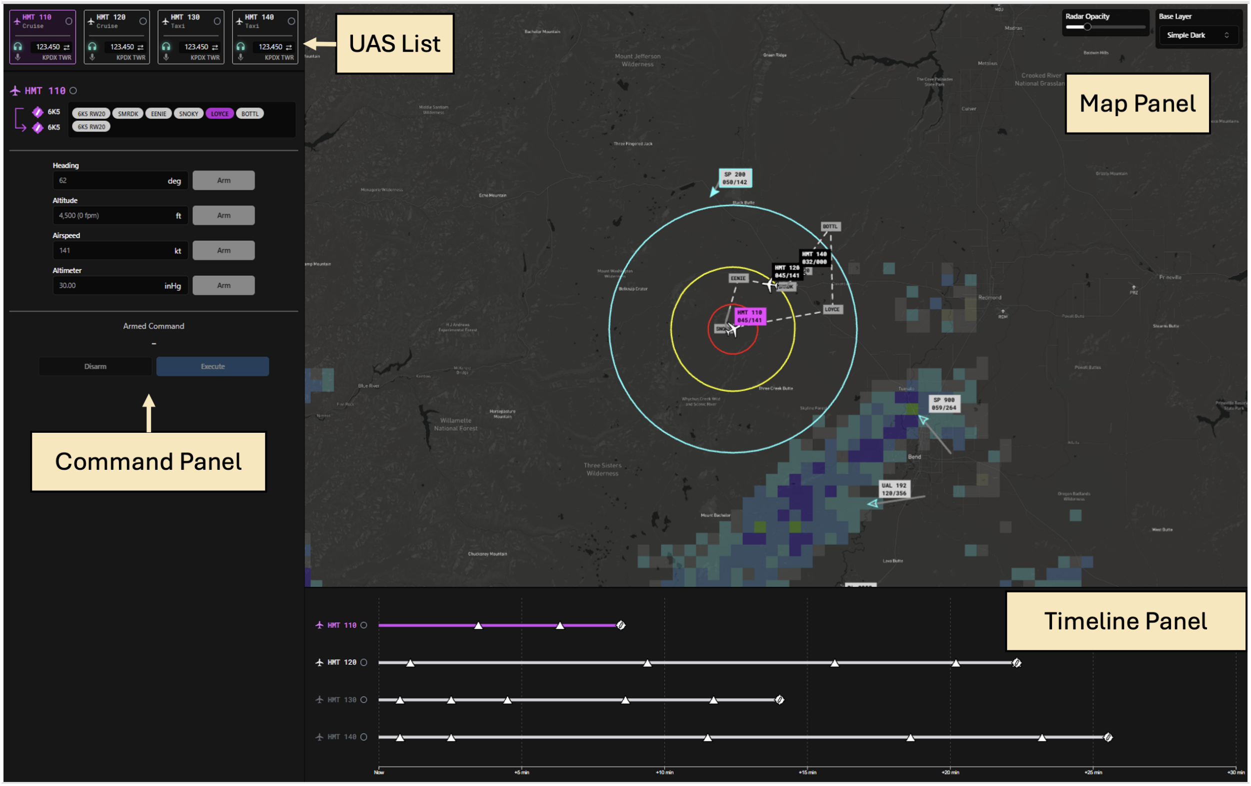


Figure C.1: The remote pilot interface with two UAS deployed.

Figure C.2: The physical radio interface.

enable real-time UAS commanding, additional telemetry for the remote pilot user interface map display, and the ability to dynamically create and remove aircraft.

The remote pilot's in flight UASs appear as white aircraft, and other ADS-B traffic based aircraft (appear as) cyan chevrons, as shown in Figure C.1. When the remote pilot selects a UAS from the UAS list, the timeline, or directly on the map, the UAS's flight path and waypoints are displayed along with three air traffic zone rings around the UAS. Selecting a different UAS hides the previous UAS's information and displays the same information for the newly selected UAS. The three air traffic zone rings are to assist the remote pilot with tracking other aircraft in the vicinity, and to determine when evasive actions are required to avoid an intruder aircraft (see the respective UE Use Cases in Section C.1.2). The cyan ring represents the distant air traffic zone, the inner yellow ring represents the caution air traffic zone, and the inner most red ring represents the incursion air traffic zone.

Voice communication is a core component of the remote pilot user interface. A custom built WebRTC-based voice communication capability provides end-to-end voice data control, and enables intentional distortion of simulated air traffic control broadcasts to ensure they closely resemble real radio-broadcast communications. Pre-recorded voice communications are played for background aircraft not controlled by the remote pilot, simulating multiple concurrent users. The physical radio panel incorporates one Elgato Stream Deck Plus device, shown in C.2, to mimic the user interface's push-to-talk radio capabilities. The hardware interface supports mute, push-to-talk, or changing each channel's frequency. Each UAS's aircraft identifier and monitored frequency for each channel are displayed. Transmit, mute, and receive states are mirrored between the user interface and the physical radio panel.

The entire experimental system automatically recorded variables throughout each trial. Information about each aircraft (e.g., location, heading, altitude, and speed) was recorded every simulation time-step. Transmission information (e.g., time, duration, and aircraft identifier) was logged for each communication broadcast. Logs were also recorded when a command was armed or executed and a new aircraft was selected.

C.3 IMPRINT Pro Modeling

IMPRINT Pro was used to model the large wildland Fire UAS response scenario. An r value of 0.5 was used in the logarithmic model (see Section A.2 for model details). Two models were developed, each incorporating four active UASs. Both models incorporated four nominal periods and three DAA periods, with three in situ workload probes occurring during each task period. The modeled scenarios closely mirrored the HITL evaluation's timeline. Section C.4's Figure C.5 provides a direct visual reference for the modeled scenario structure.

A total of 10 trials were completed per model, with each trial simulating multiple UAS assignments, including four instances of all four UAS being deployed, throughout a 30-minute mission window. Each UAS experienced all flight phases, including departures, active mission tasks, and returns. Intruder events were timed to occur during different flight stages.

C.3.1 Modeling Results

The IMPRINT Pro model provided estimates of overall operator workload throughout a 30-minute mission window for both low and high workload conditions. The continuous workload sampling at one-second intervals supports fine-grained analysis of workload in response to changing mission phases and intrusion (DAA) events. Figures C.3 and C.4 provide the average overall workload predictions for each condition, with overlays indicating DAA periods (purple or pink), nominal workload (NL; blue), and in situ workload probe segments (WL; orange).

The high workload trial had a slightly higher mean predicted overall workload ($M(SD) = 47.88(10.11)$) compared to the low workload trial ($M(SD) = 46.21(10.95)$). The high workload condition's maximum predicted workload was also higher (i.e., $M(SD) = 79.18(0.58)$) than the low workload trial (i.e., $M(SD) = 74.68(0.64)$). Both trials shared the same minimum value of 0, corresponding to idle phases during each trial's ramp-down period.

Although the mean difference appears modest, the high workload trial featured more frequent and sustained excursions near or above the overload threshold of 60, especially during DAA periods. These elevated segments contributed to a higher density of cognitive demand and interaction pressure across the trial. Component-level differences also reflected this trend, with the high workload trial showing increased speech and auditory workload values (consistent with a heavier communication burden and reduced spacing between tasks).

C.3.1.1 Low Workload Trial

The low workload trial modeled a nominal mission with evenly distributed aircraft activity, low event density, and minimal task overlap. The IMPRINT Pro mean predicted overall workload across all events for the 30-minute trial shows that all nominal workload periods (NL) and the in situ workload probe periods (WL) in Figure C.3 remained within the normal workload range. There is a clear ramp-up period and a ramp-down period, as seen for the 0-300 and 1320-1800 seconds time periods, respectively. There are clear overload periods predicted for all DAA events, with more prolonged overload periods for the first DAA single event (300-420 seconds) and the double DAA event (1020-1260 seconds).

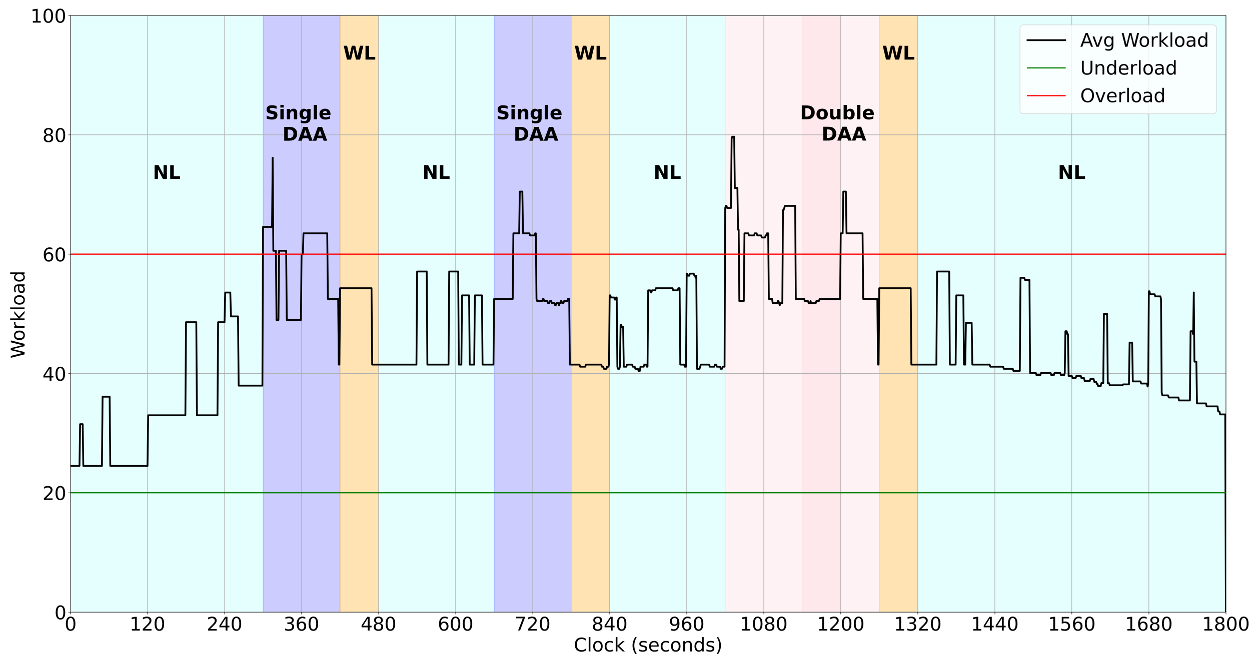


Figure C.3: The low workload trial IMPRINT model showing different trial phases, where NL = nominal load and WL = in situ workload probes.

The mean overall workload by task shows that on average the nominal tasks had substantially lower overall workload than the DAA events, as shown in Table C.2a. The double

Table C.2: The overall IMPRINT Pro workload prediction descriptive statistics - mean (SD) - by trial and task.

(a) Low workload trial.

Nominal #1	DAA: Single #1	Nominal #2	DAA: Single #2	Nominal #3	DAA: Double	Nominal #4
33.51 (8.64)	58.03 (6.78)	45.72 (6.48)	55.66 (6.08)	47.10 (6.60)	58.71 (7.51)	41.67 (6.56)

(b) High workload trial.

Nominal #1	DAA: Double #1	Nominal #2	DAA: Double #2	Nominal #3	DAA: Single	Nominal #4
39.88 (9.66)	54.58 (9.01)	45.78 (7.55)	58.04 (7.10)	45.43 (7.24)	55.55 (9.83)	40.76 (5.53)

DAA event had a mean indistinguishable from the first single DAA event, both of which were slightly higher on average ($< 5\%$) than the second single DAA event.

The IMPRINT Pro predicted cognitive and visual workload components, shown in Table Table C.3, were the highest (i.e., > 18). This outcome was expected, as the tasks have high cognitive and visual demands relative to the other workload components. The remote piloting task also involves interactions with the user interface and communicating with the Air Boss, both of which require fine motor movements, which was predicted to be the third highest contributor to overall workload. The IMPRINT Pro model incorporated the auditory and verbal interactions with the Air Boss and responses to the evaluation's in situ workload probes, which were the primary drivers of the predicted auditory and speech workloads. Since the remote pilots are generally expected to be sitting or standing at a workstation during the trials, the IMPRINT Pro model predicted gross motor workload to be zero. The tactile workload predictions resulted from pressing mouse or keyboard buttons, or similar actions on the physical push-to-talk hardware. These activities were modeled to occur more frequently during the unexpected DAA events, when the remote pilot may take actions to evade an intruder aircraft, as necessary.

Table C.3: The descriptive statistics for each components' IMPRINT Pro predicted workload by trial. The Gross Motor workload values were zero for all trials.

Workload Trial	Cognitive	Visual	Speech	Auditory	Fine Motor	Tactile
Low	18.25 (3.55)	20.25 (3.06)	1.76 (2.51)	1.15 (2.07)	4.13 (1.16)	0.67 (0.86)
High	18.56 (3.00)	20.51 (2.60)	2.26 (2.57)	1.38 (2.42)	4.32 (1.15)	0.84 (0.96)

C.3.1.2 High Workload Trial

The high workload trial was similarly modeled, but to now include two double DAA events followed by a single DAA event. Again, there is a ramp-up and ramp-down period for the first and last nominal load conditions, as seen in Figure C.4. Similar to the low workload trial, all nominal load and in situ workload probe periods remained within the normal load range, with slightly higher workload predicted for the first nominal load period. As expected, the DAA events demonstrated similar predicted overloaded workload patterns consistent with the low workload trial's single and double DAA events.

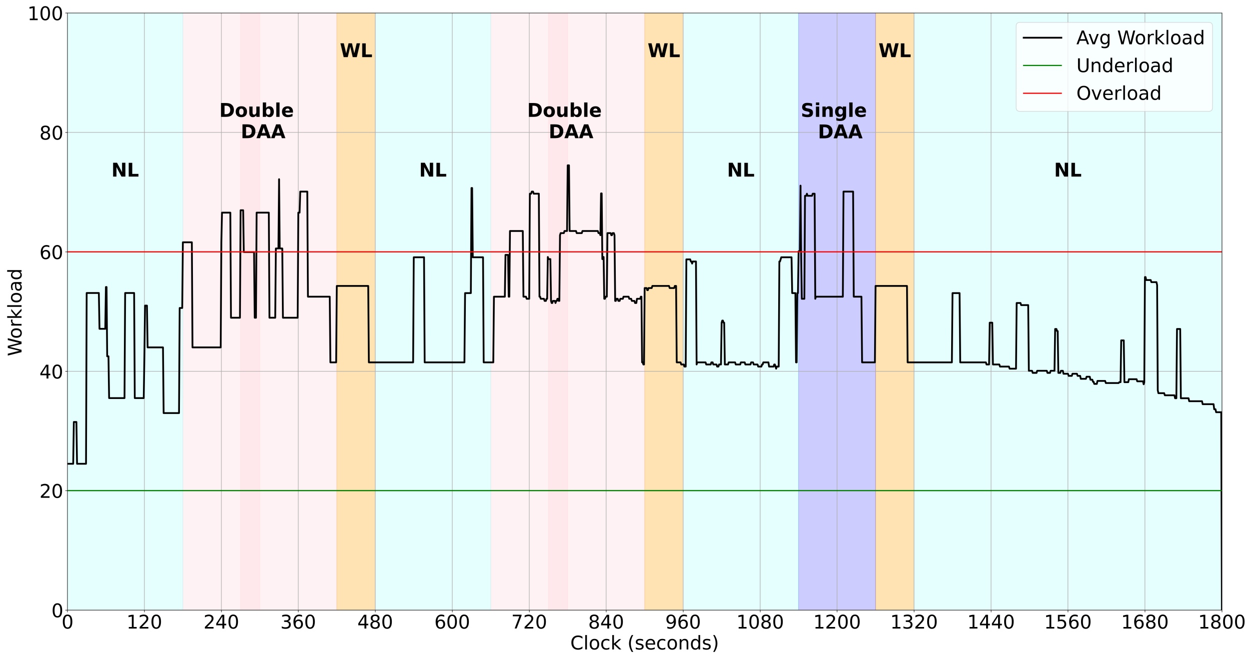


Figure C.4: The high workload trial IMPRINT model showing different trial phases, where Nl = nominal load and WL = in situ workload probes.

The mean predicted task workload was slightly lower for the second through third nominal workload periods, as shown in Table C.2b. The first Double DAA event had a slightly lower mean predicted workload than the later single DAA event; however, predicted workload for both of these events was lower than the second Double DAA event. It is noted, however, that this second Double DAA event during the high workload trial had effectively the same predicted workload as the low workload trial's double DAA event, so it does not appear inconsistent with task demands.

The increased activity in the high workload trials led to higher predicted workload component values, as shown in Table C.3. The more demanding and increased DAA event activity resulted in slightly higher workload estimates across each component, with the largest increase in the speech workload component.

C.4 Experimental Design

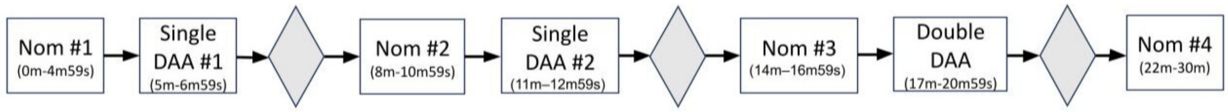
The large UAS wildland fire response evaluation assessed pilot workload under varying levels of operational complexity. The simulated wildfire response operations at an untowered airport required participants to supervise four UAS, while responding to scripted non-cooperative intrusion aircraft and managing associated communications. The number and composition of non-cooperative intruder aircraft was manipulated. The *general research question* was whether the remote pilot's workload and task performance were impacted by the operational complexity of airspace incursions when supervising a constant fleet of UAS under standardized environmental and communication conditions.

C.4.1 Independent Variables

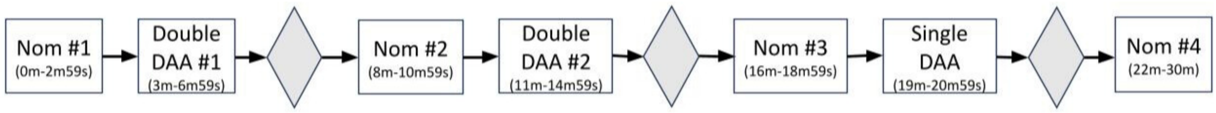
This within-subjects evaluation manipulated workload as a result of airspace incursion(s). The primary independent variables focused on airspace incursion configuration, which was operationalized as the number, type (i.e., crewed or uncrewed), and timing of non-cooperative intruder aircraft. Each participant supervised four UAS operating in the temporary flight restricted wildfire response airspace under VFR. All other scenario parameters (e.g., weather and aircraft control authority) were held constant across conditions. The scripted non-cooperative intruder aircraft were designed to vary the remote pilot's workload through the frequency and simultaneous nature of the airspace deconfliction demands. Intruder aircraft were classified as crewed or uncrewed. Crewed aircraft communicated over their own channels, typically with ATC at the Seattle Center, and the participants overheard these transmissions when the crewed aircraft were within reception range. Other UAS communicated with the Air Boss, who relayed any resulting flight path changes to the participants via a radio communication. Participants were responsible for any deconfliction decision-making, and relayed any actions taken to the Air Boss via the radio communications.

Each participant's aircraft flew on one of two flight paths. When selected, each UAS displayed air traffic zone rings (see Figure C.1). The non-cooperative intruder aircraft were embedded via pre-scripted tracks that appeared as ADS-B traffic. Pre-recorded communications permitted radio communication between the intruder aircraft and the Air Boss. The non-cooperative aircraft behavior during a DAA event was structured to impose different levels of cognitive and decision-making burden. The low workload condition incorporated two single DAA events and one double DAA event (see Figure C.5a), while the high workload trial incorporated two double DAA incursions and one single DAA event (see Figure C.5b).

All non-cooperative aircraft telemetry was provided via the integrated ADS-B source displayed on the user interface map. Participants monitored the ADS-B traffic to identify any non-cooperative intruder aircraft. The nominal condition had no intruders. A single incursion (i.e., Single DAA) condition involved one non-cooperative aircraft, and the dual incursion (i.e., Double DAA) condition involved two aircraft impacting at least two of the participant's UASs. The intruder aircraft(s) for each respective DAA event are shown as the purple circled aircraft in Figure C.6, where all images were captured at the time the intruder aircraft entered the caution air traffic zone (*Note:* For the double DAA figures, in addition to the first intruder aircraft, the track and impacted UAS's air traffic rings for the second DAA event are displayed in a lighter tone to demonstrate the comprehensive situation).



(a) The low workload condition.



(b) The high workload condition.

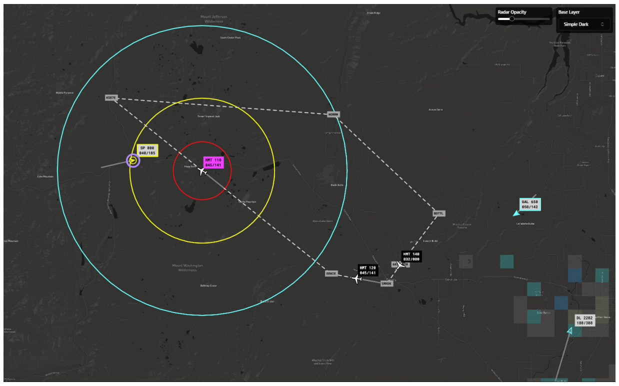
Figure C.5: The two workload condition trial thirty-minute timelines. Each trial has four nominal use case portions (Nom) and three in situ workload probes (diamonds). The low workload condition had two single DAA events and one double DAA, while the high workload condition began with two double DAA events and a single DAA event.

C.4.2 Dependent Variables

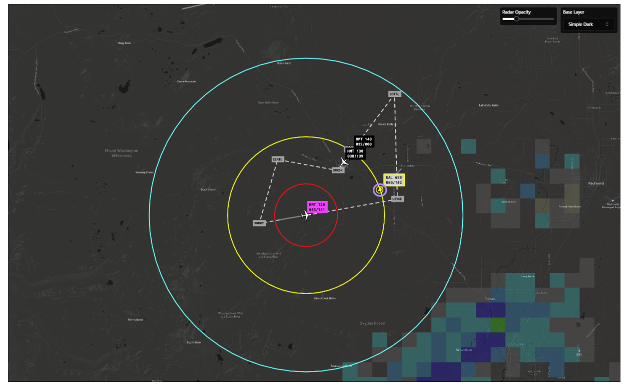
The primary dependent variables were the physiological data collected via wearable sensors, and the subjective in situ workload probes administered throughout each trial. The multi-dimensional workload algorithm [37] used the continuous physiological data to estimate overall workload based on each of the seven workload components: cognitive, visual, speech, auditory, gross motor, fine motor, and tactile. These estimates were generated on a continuous 0–100 scale. Overall workload estimates between 20 and 59 were classified as normal workload, values ≥ 60 represented overload, and values < 20 indicated underload.

Sensors provided the raw data corresponding to each workload component. The sensor suite included the Zephyr BioHarness, the Pupil Labs Neon eye tracker, two Myo armbands, a Shure microphone, a Reed decibel meter, and a headset-mounted microphone. The BioHarness recorded heart rate, heart rate variability, respiration rate, and postural magnitude. Heart rate variability was used to estimate cognitive workload, and respiration rate and postural magnitude contributed to gross motor workload. The eye tracker captured ocular metrics (i.e., pupil diameter, blink rate, blink latency, fixations, and saccades) to inform both cognitive and visual workload. The gaze concentration and fixation count were used to estimate visual attention and engagement. The Myo armbands recorded surface electromyography (sEMG) and inertial data (e.g., acceleration and angular velocity) that were used to estimate the fine motor and tactile workload components. A headset-mounted microphone and Shure wireless microphone captured voice intensity, pitch, speech rate, and other vocal features, which were used to estimate speech and cognitive workload. The decibel meter recorded ambient environmental noise levels to estimate auditory and cognitive workload.

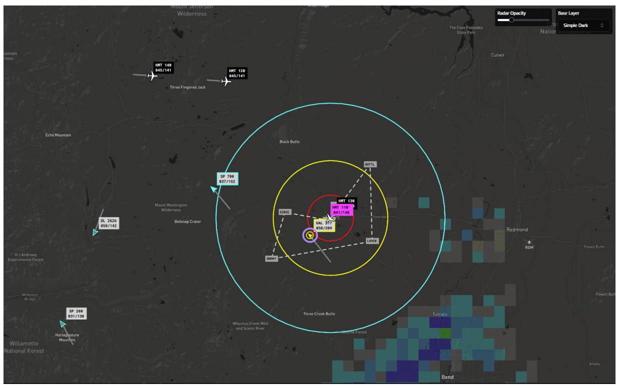
Eye tracking metrics can be used to interpret the human's focus of attention on the user interface workstation, but doing so requires defining areas of interest (AOI). The user interface's four key panels: the Command panel, Radio panel, Map panel, and Timeline panel (explained in detail in Section C.2) were defined as relevant AOIs. Fixation counts and durations were analyzed based on these AOIs to evaluate operator attention and scanning behavior. The UAS List AOI incorporated both the list of the UAS and the selected UAS flight path information, shown in Figure C.1. The remote pilots were permitted to zoom and pan the Map panel as desired, which occurred frequently; thus, it was not feasible to analyze



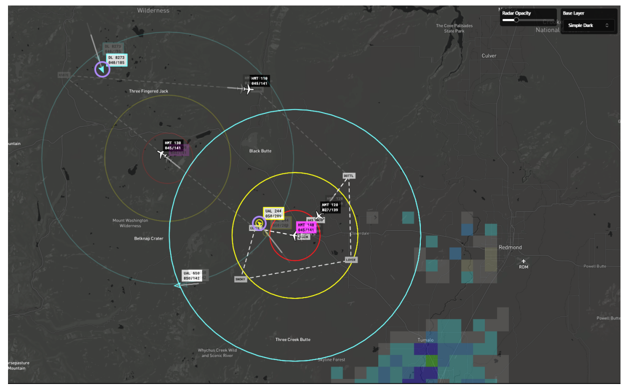
(a) Low Workload, DAA:Single #1.



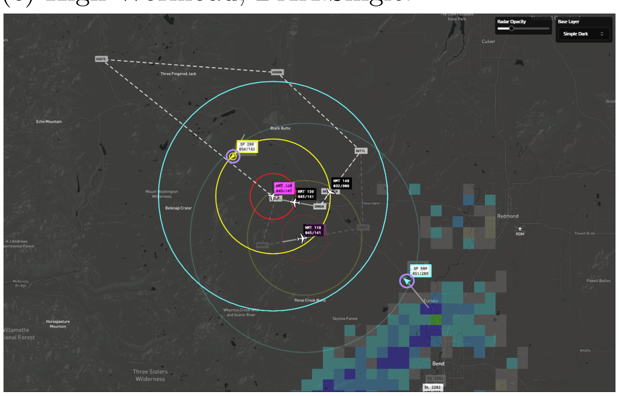
(b) Low Workload, DAA:Single #2.



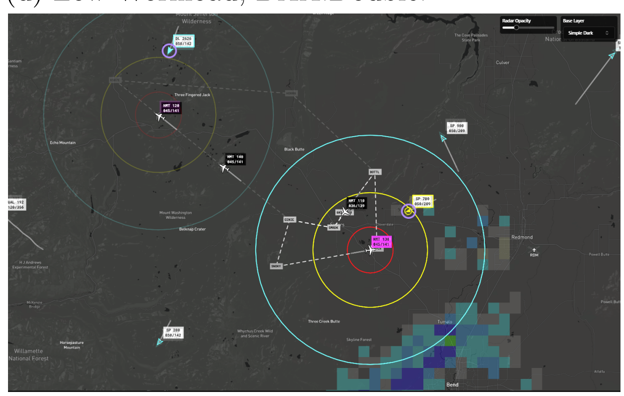
(c) High Workload, DAA:Single.



(d) Low Workload, DAA:Double.



(e) High Workload, DAA:Double #1.



(f) High Workload, DAA:Double #2.

Figure C.6: Depictions of each DAA event with the impacted UAS and the intruder aircraft (highlighted as the purple circle around a chevron). The double DAA events show all aircraft at the time of the first intruder entering the caution zone.

these results with a finer grained AOI matrix.

The subjective in situ workload probes were administered after the DAA events during both trials, as shown in Figure C.5. This workload probe timing was chosen to avoid interference with airspace incursion events, and responding to these seven probes (i.e., one for each component) required approximately one minute. Participants rated their perceived workload for each workload component on a 7-point scale (i.e., 1 (exceptionally low) to 7 (exceptionally high) demand). Subjective workload responses were recorded via an online data collection platform (e.g., Qualtrics).

The user interface recorded discrete operator interactions, including aircraft selection, command arming and execution, map layer toggles, and radio transmission button presses. Each user interaction was time-stamped and associated with relevant identifiers (e.g., selected aircraft and command type). Voice communication transmissions were recorded and later categorized by type (e.g., read backs, status reports, responses to queries, and other utterances). A complete list of the logged variables is provided in Table C.4.

Table C.4: Data logged from the simulation and user interfaces.

Event	Recorded Variables
Simulation and Communication Actions	
Simulation time-step	Aircraft locations, headings, altitudes, speeds, and altimeter settings
Communication Transmission	Time, Duration, Script Identifier, Frequency Identifier, and Aircraft Identifier
Remote Pilot Actions	
Aircraft Selection	Time and Aircraft Identifier
Command Arm	Aircraft Identifier, Time, Command, and Value
Command Execution	Aircraft Identifier, Time, Command, and Value
Map layer selection	Time and Map Layer Identifier
Radio Transmission Button Press	Time, Duration, and Frequency Identifier

Some *task performance* metrics were experimenter collected to identify whether an intruder aircraft entered the incursion air traffic zone (i.e., the red circle on the interface, see Figure C.1), and if the remote pilot correctly reported the number of waypoints accurately to the Air Boss (i.e., an experimenter). These metrics served as objective indicators of situational awareness and overall mission execution effectiveness. A post-trial voice transmission analysis (*Note:* not available for final grant report) will summarize speech task performance. Five utterances will be coded: (1) departure/takeoff, (2) waypoint location reports, (3) altitude change instructions, (4) general remote pilot commands, and (5) status reports. The Air Boss, in the low workload trial, issued three take-off requests, two general remote pilot commands, and four altitude changes. The Air Boss also requested four waypoint, and two status reports, during the low workload trial. During the high workload trial, the Air Boss issued four departure calls, two general remote pilot commands, and two altitude changes, along with requesting five waypoint, and two status, reports.

The *execution latency* is the time between the end of the initial Air Boss transmission and the execution of the relevant command. The *readback latency* is the time between the end of the initial Air Boss transmission and the beginning of the final remote pilot transmission within a particular transaction. Prior work determined that a five second or less readback latency is preferred for crewed aircraft pilot readback to ATC [23]. The remote pilot communicates to the Air Boss, and to our knowledge, no similar threshold metric exists, but such communications need to be completed as quickly as possible [38].

The task durations across the low and high workload trials varied slightly in length, as shown in Figure C.5. These different task durations were compensated for by calculating the mean rate of the specific performance metrics per minute to facilitate direct comparison across tasks. Thus, the mean and standard deviation for the communication rate (transmissions per minute), fixation rate (fixations per minute), selection rate (selections per minute), and interaction rate (interactions per minute) for each task and workload condition were calculated. The mean and standard deviation for each metric were calculated per participant, followed by the overall mean and standard deviation across all participants.

A post-trial questionnaire collected participant self-ratings of overall workload, perceived effectiveness, and communication clarity. After completing both trials, the post-experimental questionnaire collected additional subjective results (e.g., overall impressions).

C.4.3 Procedure

The evaluation lasted approximately two hours. Upon arrival, participants reviewed and signed an informed consent form and completed a brief demographic questionnaire. Participants were fitted with physiological sensors, including a BioHarness chest strap, two Myo armband devices (one on each forearm), a Pupil Labs Neon eye tracker, a Shure lapel microphone, and an over-the-ear headset. Any sensor calibration activities were completed after donning the sensors.

Before starting the trials, each participant received a briefing regarding the nature of the evaluation but received no specific details about the non-cooperative intruder aircraft events. Participants were instructed that their role was akin to a "remote pilot-in-command" in which they were supervising multiple UAS in a wildfire mission, and that while the simulation involved no real flight risk, they were to act as if the safety of real aircraft was at stake.

An experimenter provided a ten minute structured orientation for a nominal VFR scenario using the simulator and user interface to familiarize participants with the interface. Participants were introduced to the custom supervisory interface, including the interface's map with ADS-B traffic, and flight route overlays, timeline panel, UAS command panel, and UAS panel. The experimenter demonstrated all relevant actions (e.g., takeoff, heading, and altitude arm and execute), and participants practiced each command at least once. The participants were also provided instructions related to the in situ subjective workload probes, including definitions of the seven workload dimensions (i.e., cognitive, speech, auditory, visual, gross motor, fine motor, and tactile) and the scale values. Participants practiced push-to-talk radio communications via the user interface and the physical radio stack (see Section C.2 for details). Importantly, participants were exposed to a distinct set of aircraft tracks, waypoints, and communication activities during training that did not appear in the actual trial scenarios.

Each participant completed two 30-minute trials, one under each workload condition, as shown in Figure C.5. Trial order was counterbalanced to mitigate learning effects. Participants were seated at a workstation and communicated with the Air Boss through a simulated radio. Two experimenters facilitated each session: one served as the simulated Air Boss and handled all scripted communications with non-cooperative intruder aircraft, while the other remained in the simulation room. During each trial, the participant managed four UAS while responding to routine mission tasks, unexpected non-cooperative intruder aircraft (i.e., DAA events), monitored communication traffic, and communicated when required. Participants were also instructed to provide position reports when their UAS crossed specific waypoints, as part of the scenario's communication requirements. The in situ subjective workload ratings were verbally administered at three fixed time points by the experimenter located in the evaluation space, who recorded all subjective workload responses in real-time.

Upon completing the first trial, the participants completed a post-trial survey that assessed perceived workload, task performance, and interface usability. A five-minute break followed, during which the system was reinitialized for the second trial, after which the post-trial survey was repeated. Upon completing both trials, participants filled out a final post-evaluation questionnaire capturing overall impressions and interface feedback. Participants were then debriefed and compensated with a $75 Amazon gift card.

C.4.4 Participants

A power analysis was conducted using G*Power 3.1 for a one-tailed paired-samples t-test. Assuming a medium effect size ($d_z = 0.60$), $\alpha = .05$, and desired power ($1-\beta = .80$), this analysis indicated that a minimum of 19 participants were required. The planned total number of participants was 20, but this target sample size was not fully reached as data collection was halted at 18 participants due to scheduling constraints associated with an unexpected updated project termination date from the research sponsor.

Eighteen pilots ($N = 18$) completed the evaluation. All participants held valid pilot certifications, with a median of 100–250 logged flight hours, which ensured a baseline of aviation knowledge and radio communication proficiency. Participants were screened for any medical limitations that may interfere with the physiological sensors. Participants represented a diverse age range of adults (median age = 25–34 years; 15 male, 3 female), with multiple participants in the 50+ age range. Seven participants hold a college degree, four with a graduate degree, and seven had some college or technical training. The median computer usage among participants was 20–40 hours per week, while the median gaming or simulator usage was < 1 hour per week. Two participants were also UAS pilots.

Eight participants completed the experiment at the headquarters of our industry partner. Two other locations were used at OrSU, with seven evaluations conducted in one location, and three in the other. All participants completed the entire experiment and received a $75 Amazon gift card, as approved by the OrSU Institutional Review Board.

C.5 Results

The results are organized based on the research question of whether the remote pilots' performance was impacted by the operational complexity of airspace incursions when supervising a constant fleet of UAS using VFR in the temporary flight restriction operational area with standardized environmental and communication conditions. Analyses was conducted for the nominal and DAA UEs.

C.5.1 Locus of Attention

The overall user interface incorporated five areas, which represented the AOIs (see Figure C.1). The fifth primary user interface (UI) area was the empty area below the Command panel, termed *UI Other*. Participants may also look off the screen, which is captured in the

Off Screen metrics. The remote pilots were to take specific actions depending on which air traffic zone was affected by the intruder aircraft, per the UE Use Cases provided in Section C.1.2. Participants were free to zoom and pan the map displays as preferred, which they did frequently. Given the large amount of zoom actions, an overall analysis of the map panel divided by AOIs was not feasible.

The reported fixation durations are shorter than the full 30 minute trials. Generally, the Pupil Labs Neon eye tracker's limitations include the loss of fixation data during rapid head movements (e.g., shaking or turning) and any physical eye tracker adjustments by the participant that may partially cover the camera momentarily. The Pupil Core software is sensitive to lighting changes, and the different evaluation locations had differing lighting. Two locations had similar lighting and little impact on the eye tracking results, but lighting did impact the eye tracking results for seven participants.

The low workload condition had 10.66% fewer fixations than the high workload trial. Overall, 88.39% of the remote pilots' total fixations were on the four primary user interface areas (i.e., UAS list, Command Panel, Map and Timeline) for 88.5% of the fixation duration across both trials. The remainder of the time, remote pilots were looking Off screen, or at the UI Other region. The fixation counts and durations, presented in Tables C.5 and C.6, respectively, on the four primary user interface areas were both higher during the high workload condition. The results for the UI Other area and the Off screen were effectively the same across the two workload conditions. Overall, these results demonstrate that the remote pilots were generally engaged in the trials and focused on relevant areas of the user interface.

Table C.5: The total fixation counts and percentages by trial and user interface section.

Workload Trial	**UAS List**		**Command Panel**		**Map Panel**		**Timeline Panel**		**UI Other**		**Off Screen**		**Total**
Low	2044	6%	2204	6%	26681	75%	412	1%	1487	4%	2963	8%	35791
High	3133	8%	2917	7%	29124	73%	536	1%	1459	4%	2895	7%	40064
Total	5177	7%	5121	7%	55805	73.5%	948	1%	2946	4%	5858	8%	75855

Considering the results based on the four primary user interface areas, the map had 73.5% of all fixations for 73.57% of the total fixation duration. The UAS list and the Command panel were effectively the same, with 7% and 8% of the fixations for 7% and 6.8% of the fixation duration respectively. The Timeline was focused on the least across both trials. These results were also similar within each workload level. These overall results align with the experimenter's observations, that the remote pilots primarily focused on the map panel. Overall, these results demonstrate that the remote pilots were engaged in the tasks throughout each trial, and focused their visual attention consistent with successful completion of their assigned flight duties. Plotting the fixations by workload condition on the user interface clearly shows the saturation of fixations on the map, as shown in Figure C.7, more importantly, it also shows that the remote pilots attended to all areas of the display.

The by task user interface fixation patterns matched the overall condition results, with the majority of fixations occurring on the map, followed closely by the UAS list and the command panel. Fixations analyzed by task are provided in Table C.7 and C.8, but note that not all tasks had the same duration, thus a direct comparison of the raw fixation counts across tasks is not appropriate. Thus, mean fixations per minute (Fix/Min) is included to

Table C.6: The total fixation durations (hh:mm:ss) by trial and area.

Workload Trial	UAS List	Command Panel	Map Panel	Timeline Panel	UI Other	Off Screen	Total
Low	0:21:34	0:21:15	4:03:50	0:03:43	0:13:26	0:25:05	5:28:41
High	0:25:45	0:24:35	4:10:35	0:04:25	0:13:19	0:25:21	5:43:19
Total	0:47:19	0:45:50	8:14:26	0:08:08	0:26:46	0:50:27	11:12:01

provide a more accurate comparison across tasks.

The low workload Nominal #2 and #3 tasks as well as the high workload Nominal #4 task each followed a single DAA event, while the low workload Nominal #4 task and high workload Nominal #2 and #3 tasks all followed a DAA:Double event. The Nominal tasks that followed the DAA:Single events all had lower mean Fix/Min than those that followed a double DAA task. There was effectively no difference in the Fix/Min between the single DAA events and the Nominal task that followed (e.g., DAA:Single 1 - Nominal #2), which were almost the same as the low workload Nominal #1 Fix/Min. The high workload Nominal #1 had the lowest mean Fix/Min, but the DAA:Single that followed it had the highest mean Fix/Min of the Single DAA events. Further, the high workload condition Nominal #3 that followed the single DAA had the largest drop in mean Fix/Min. Similarly, there was very little difference in the average Fix/Min between the Nominal events on either side of the DAA:Double event, Nominal #3 - 69.8, DAA:Double - 68.4, and Nominal #4 - 66.1 (all with similar SDs). However, the high workload Nominal trials that followed a Double DAA event had substantially higher mean Fix/Min than the actual DAA events, DAA:Double 1 - 74.9, Nominal #2 - 103.6, DAA:Double 2 - 92.0, and Nominal #3 101.3. Further, the Nominal tasks that follow the high workload double DAA events had the largest standard deviations.

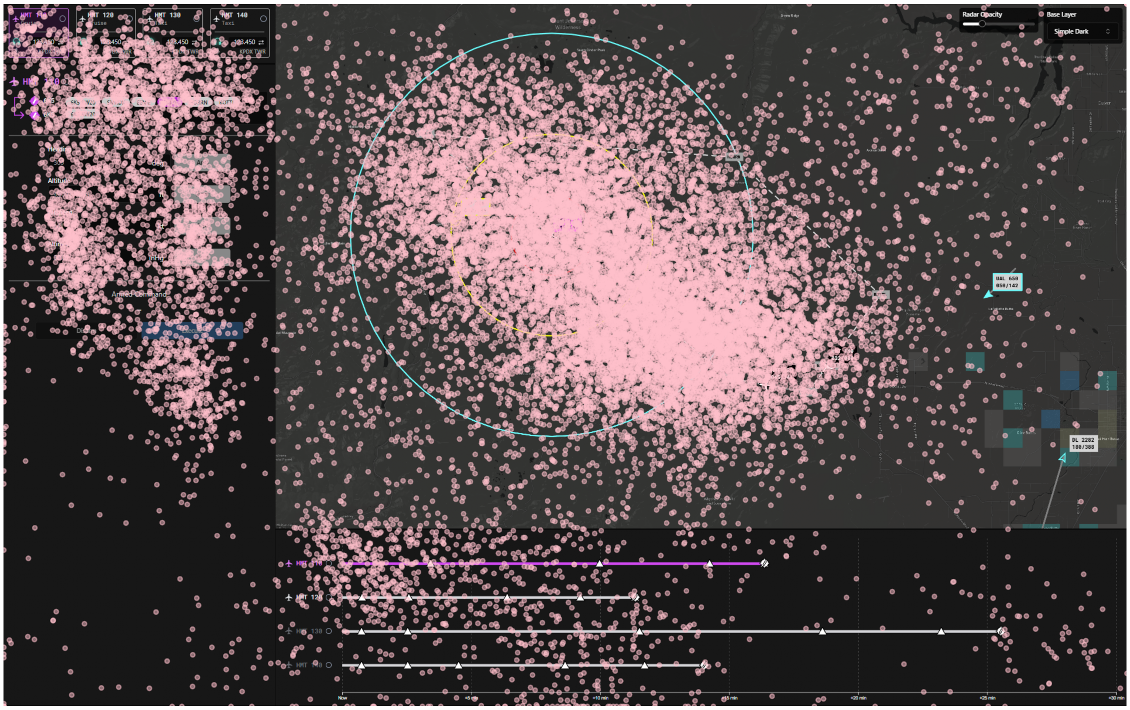
C.5.1.1 Unexpected Events

Each DAA intruder aircraft encounter appeared on the map. These encounters were required the remote pilots' attention and depending on the intruder aircraft's actions, the remote pilot was to take appropriate actions per the UE use cases in Section C.1.2.

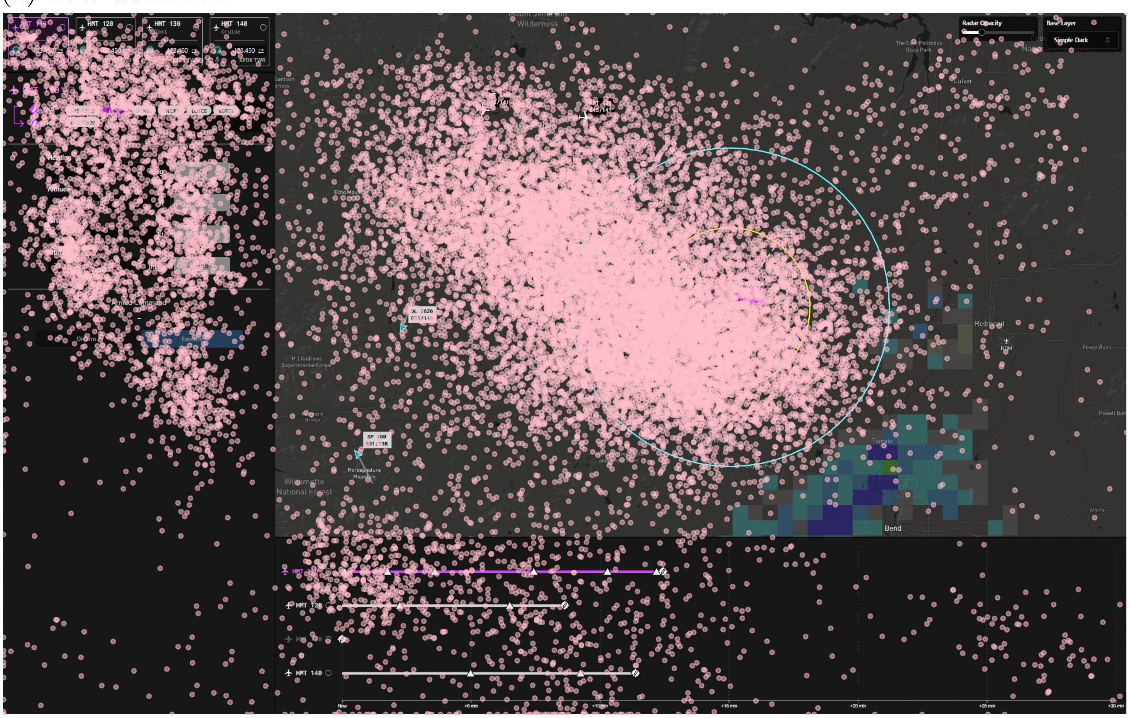
Detect and Avoid: Single Aircraft

The first locations of the DAA:Single intruder aircraft inside the caution air traffic zone for both trials are shown in Figures C.6a, C.6b and C.6c. The fixations during the single DAA events were overlaid onto the same images, and provided in Figures C.8a, C.8b and C.8c. All figures show the intruder aircraft, highlighted using an added colored circle, and the images were captured as the intruder aircraft entered the air traffic caution ring.

The first low workload DAA:Single task had the fewest total fixations (2365), which was slightly lower than the second low workload single DAA event, as shown in Tables C.7. The high workload trial, in which the single DAA event occurred after the two DAA:Double events had the highest total fixation count (2789). The mean Fix/Min results reflect this overall pattern. The total fixation durations across the three single DAA events were effectively equivalent, as shown in Table C.8.



(a) Low workload.



(b) High workload.

Figure C.7: The eye fixations (pink circles) mapped to the user interface areas by condition.

Fixation patterns on the user interface during this event match the above overall patterns, with the map being the most fixated upon, followed by the UAS list and command panel.

Table C.7: The total fixation counts by trial, area, and task. The Fix/Min descriptive statistics provide a fair comparison across the tasks.

Workload Trial	UAS List	Command Panel	Map Panel	Timeline Panel	UI Other	Off Screen	Total	Fix/ Min
Nominal #1 (Low: 5 minutes, High: 3 minutes)								
Low	71	357	5520	21	92	4	6065	67.4 (18.5)
High	26	132	2041	8	35	1	2243	41.5 (12.5)
Nominal #2 (3 minutes)								
Low	292	286	2747	63	120	132	3640	65.2 (22.1)
High	449	440	4223	97	185	202	5596	103.6 (31.1)
Nominal #3 (3 minutes)								
Low	281	193	2914	6	105	140	3639	69.8 (19.8)
High	422	290	4381	9	158	211	5471	101.3 (30.4)
Nominal #4 (8 minutes)								
Low	691	620	6649	70	667	1007	9704	66.1 (21.6)
High	519	466	4997	53	501	757	7293	50.6 (15.2)
DAA: Single (2 minutes)								
Low: 1	201	112	1723	16	149	164	2365	65.7 (19.7)
Low: 2	211	117	1801	29	156	172	2486	69.1 (20.7)
High	238	132	2037	19	169	194	2789	77.5 (23.2)
DAA: Double (4 minutes)								
Low	148	380	2926	164	126	1108	4852	68.4 (20.2)
High: 1	554	611	3029	183	139	875	5391	74.9 (22.5)
High: 2	643	713	4624	123	153	368	6624	92.0 (27.6)
Workload Probes (1 minute)								
Low: 1	30	105	1162	30	20	144	1491	82.8 (24.8)
Low: 2	72	8	786	0	26	23	915	50.8 (15.2)
Low: 3	47	26	453	13	26	69	634	35.2 (10.6)
High: 1	18	62	1038	18	4	93	1233	68.5 (20.6)
High: 2	167	18	1830	0	62	53	2130	118.3 (35.5)
High: 3	97	53	924	26	53	141	1294	71.9 (21.6)

The total number of map panel fixations during the High trial was > 11% more than the low trial single DAA totals, while the fixation durations varied by only one second.

The map panel fixations highlight the remote pilots' behavior during the DAA:Single events. The three single DAAs had similar fixation distributions, as shown in Figures C.8a, C.8b and C.8c. Note that the orange circles have been added to the images to highlight the intruder aircraft locations. Generally, the remote pilots maintained attention across the entire operational area in the map during the single DAA events.

C.5.1.2 Detect And Avoid: Double Crewed Aircraft

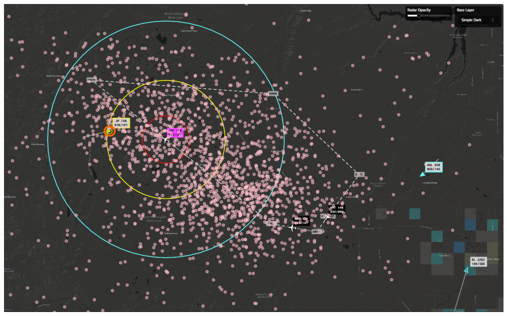
The locations of both DAA:Double intruder aircraft, captured at the time the first intruder entered the caution air traffic zone ring, for both trials are provided in Figures C.6d, C.6e and C.6f. The fixations during the single DAA events were overlaid onto those images, as provided in Figures C.8d, C.8e and C.8f.

Table C.8: The total fixation duration (hh:mm:ss) by trial, area, and task.

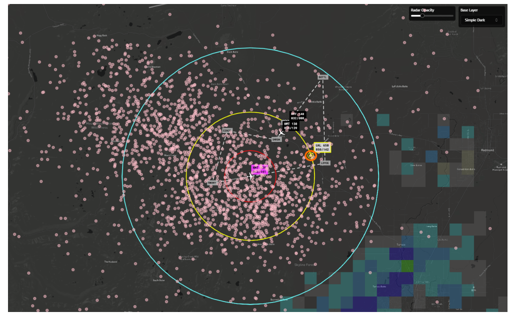
Workload Trial	UAS List	Command Panel	Map Panel Panel	Timeline Panel	UI Other	Off Screen	Total
Nominal #1 (Low: 5 minutes, High: 3 minutes)							
Low	0:00:37	0:03:10	0:49:08	0:00:11	0:00:49	0:00:02	0:54:00
High	0:00:22	0:01:54	0:29:28	0:00:06	0:00:30	0:00:00	0:32:24
Nominal #2 (3 minutes)							
Low	0:02:35	0:02:32	0:24:27	0:00:33	0:01:04	0:01:10	0:32:24
High	0:03:07	0:03:03	0:29:25	0:00:40	0:01:17	0:01:24	0:38:59
Nominal #3 (3 minutes)							
Low	0:02:30	0:01:43	0:25:56	0:00:03	0:00:56	0:01:14	0:32:24
High	0:02:56	0:02:01	0:30:31	0:00:03	0:01:06	0:01:28	0:38:07
Nominal #4 (8 minutes)							
Low	0:06:09	0:05:31	0:59:11	0:00:37	0:05:56	0:08:57	1:26:24
High	0:06:08	0:05:31	0:59:11	0:00:37	0:05:56	0:08:58	1:26:24
DAA: Single (2 minutes)							
Low: 1	0:01:50	0:01:01	0:15:53	0:00:13	0:01:21	0:01:29	0:21:36
Low: 2	0:01:49	0:01:00	0:15:54	0:00:16	0:01:21	0:01:29	0:21:52
High	0:02:06	0:01:05	0:15:54	0:00:14	0:01:24	0:01:33	0:21:36
DAA: Double (4 minutes)							
Low	0:04:08	0:04:53	0:22:38	0:01:19	0:01:03	0:08:07	0:42:10
High: 1	0:04:26	0:04:53	0:24:16	0:01:27	0:01:06	0:07:00	0:43:12
High: 2	0:04:28	0:04:58	0:32:13	0:00:51	0:01:03	0:02:33	0:46:09
Workload Probes (1 minute)							
Low: 1	0:00:13	0:00:48	0:13:40	0:00:13	0:00:09	0:01:07	0:16:13
Low: 2	0:00:50	0:00:05	0:09:16	0:00:00	0:00:18	0:00:16	0:10:48
Low: 3	0:00:48	0:00:26	0:07:43	0:00:13	0:00:26	0:01:10	0:10:47
High: 1	0:00:09	0:00:32	0:09:05	0:00:09	0:00:02	0:00:48	0:10:48
High: 2	0:01:09	0:00:07	0:12:45	0:00:00	0:00:25	0:00:22	0:14:50
High: 3	0:00:48	0:00:26	0:07:42	0:00:13	0:00:26	0:01:10	0:10:48

The low workload DAA:Double task had the fewest total fixations (4852) of all such events, as shown in Tables C.7. The second high workload double DAA event was designed to be the most challenging. The event positioned the two intruder aircraft at the opposite sides of the remote pilot's operational area (as shown in Figure C.6f), which increases visual workload. This DAA:Double event resulted in the highest total fixation count, which was 36.5% higher than the low and 8% higher than the second high workload double DAA event. The mean Fix/Min relationships between the events were similar to those of the total fixations. The total fixation duration for the second high workload double DAA was only 9.4% higher than the equivalent low workload event, and 7.6% higher than the first high workload event, as shown in Table C.8. The first high workload double DAA event had 11% more fixations than the low workload's equivalent event, with only a 2.5% longer fixation duration.

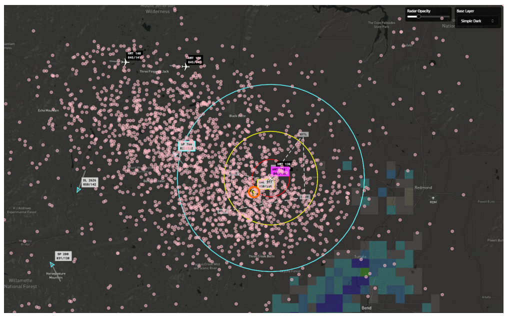
The fixation patterns during this event on the user interface match the overall fixation patterns, with the map being the most dominant, followed by the UAS list and the Command



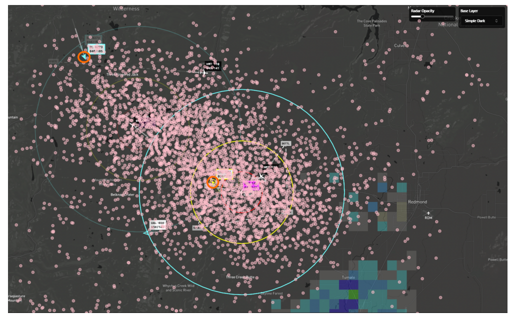
(a) Low Workload, DAA:Single #1.



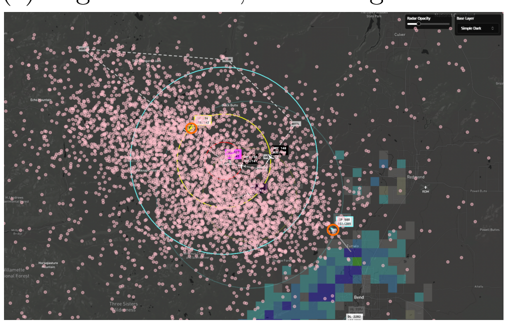
(b) Low Workload, DAA:Single #2.



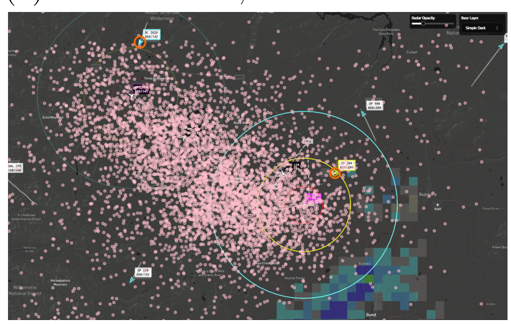
(c) High Workload, DAA:Single.



(d) Low Workload, DAA:Double.



(e) High Workload, DAA:Double #1.



(f) High Workload, DAA:Double #2.

Figure C.8: The DAA:X tasks fixations overlaid onto each task by trial, where the single DAA events lasted 2 minutes and the double DAA events 4 minutes. The orange circles have been added the images to indicate the locations of the intruder aircraft.

panel. The total number of Map panel fixations during the first high trial double DAA event was 3.5% higher than the low trial double DAA total, while the second high workload event had 58% more fixations than the low trial event, and 53% more fixations than the first high workload double DAA event. The number of UAS list fixations during the low workload event were significantly lower than either of the high events (DAA:Double 1: 73%, DAA:Double 2: 77%). The first high workload event had a fixation duration on the Map Panel that was less than 2 minutes longer than the low workload double DAA event, but the second high workload event was almost 10 minutes longer than the low workload event. Similarly, the low workload double DAA event's Command panel fixations were substantially lower than the high workload's events (DAA:Double 1: 37%, DAA:Double 2: 47%). Even though the total number of fixations on the UAS list and Command panel differed substantially, there was at most a 20 second difference in the respective durations.

The DAA:Double events were two minutes longer than the DAA:Single events, thus, it is unsurprising that the total fixation counts and durations are significantly larger and longer, respectively. Similar to the DAA:Single events, the remote pilots during the double DAA events maintained attention on a broad area. However, it is known that the remote pilots frequently zoomed the map in and out, which means the actual area each remote pilot focused on likely differed. One remote pilot specifically mentioned that when the map was zoomed in, an intruder aircraft was missed. This participant suggested adding a warning notification to alert the remote pilot that there is, in this case, another potential incursion.

C.5.2 Workload

The subjective workload results are reported. The objective workload results that report continuous estimated overall workload based on the physiological sensors and the noise meter were not available due to the shortened performance period.

C.5.2.1 Subjective In Situ Workload

The remote pilots provided ratings for each workload component. While there are well documented limitations of subjective responses, the in situ workload probes provide insights into the remote pilots' perceived workload immediately after handling a DAA event. The presented results are normalized (i.e., overall workload raw value/[49 = 7 point Likert scale x 7 workload components], and component workload raw value/7 point Likert scale). There are a total of 108 in situ workload responses (i.e., 3 prompts after each DAA event x 2 trials x 18 remote pilots).

The in situ overall workload results by trial were in the normal workload range for both trials. The low workload trial's mean subjective workload was 27.0 (SD = 14.7), with the High workload trial's having a higher mean of 31.2 (SD = 17.8). The post DAA events reported mean in situ overall workload was highest after the double DAA events during both trials, as shown in Table C.9.

Table C.9: The normalized in situ overall workload descriptive statistics by trial.

Workload Trial	**Workload Estimate**
DAA: Single	
Low 1	22.8 (13.1)
Low 2	27.6 (15.0)
High	29.5 (14.5)
DAA: Double	
Low	30.6 (15.0)
High 1	34.5 (20.9)
High 2	29.6 (16.8)

The Low workload trial showed a clearly increasing in situ overall workload rating trend with each successive DAA task (i.e., DAA: Single 1 - DAA: Single 2 - DAA: Double), with the largest increase occurring between the first and second single DAA events. The high workload trial resulted in the highest reported workload for the first double DAA event, with a decrement for the remaining DAA events. There was virtually no difference between the second double DAA event and the final single DAA event in the high workload condition.

The subjective workload responses generally support expectations that the visual and cognitive workload components were loaded the most for the remote pilots. The speech, auditory, fine motor and tactile components were rated approximately the same, as shown in Table C.10. The high workload trial resulted in self-reported workload levels that were higher for all workload components as compared to the low workload trial.

Table C.10: The normalized in situ workload descriptive statistics by workload component.

Trial	**Cognitive**	**Visual**	**Speech**	**Auditory**	**Gross Motor**	**Fine Motor**	**Tactile**
Low	48.5 (21.6)	41.7 (22.2)	26.9 (20.1)	25.3 (16.9)	10.2 (14.1)	20.7 (22.0)	15.7 (18.5)
High	51.2 (22.2)	46.0 (22.2)	29.0 (19.8)	27.2 (21.6)	14.2 (20.6)	28.7 (26.9)	22.2 (23.4)

C.5.3 User Interactions with Displays/Materials

A comprehensive review of remote pilot performance requires understanding their interactions with the user interface, which was automatically recorded here. The overall number of interactions per trial was roughly 9.8% higher for the high workload condition, with all interaction types being higher than the low workload trial, as shown in Table C.11. The *Other* Commands represent placing the cursor in a command panel text field, or either selecting disarm, or a waypoint to arm. Notably, the remote pilots armed more commands than were executed during both trials, but the percentage of unexecuted, but armed, commands was similar across workload trials ($\leq 6\%$).

Table C.11: The total interaction counts by trial and workload condition.

Workload Trial	**Selections**	**Commands**			**Transmissions**	**Total**
		Arm	**Execute**	**Other**		
Low	1948	384	362	314	1432	4440
High	2317	433	410	347	1369	4876

The median total interactions per participant was 253 during the low workload condition and 259 for high workload, with a similar minimum to maximum range (low: minimum = 109, maximum = 339; high: minimum = 178, maximum = 370). The low workload trial had a smaller mean number of total interactions per participant, 246.7 (SD 42.7), while the high workload condition demonstrated more variance (mean = 272, SD = 56.1) across participants.

Independent of workload condition, the remote pilots most frequently selected aircraft, which was closely followed by transmitting communications. These actions correspond to multiple user interface areas. The aircraft can be selected directly on the Map, from the UAS list, or from the Timeline. Based on observations by the experimenters, aircraft were predominately selected via the Map. Most aircraft command related actions occurred in the Command panel, but the waypoint commands included in the Other command category did also occur on the Map. Based on experimenter observations, all communications were transmitted by the remote pilots using the physical communications hardware.

The total number of interactions varied by task (shown in Table C.12), but given the differing task times, the metric is reported as mean interactions per minute (Inter/Min). The high workload condition had higher Inter/Min for the Nominal #1 tasks, as well as for the DAA:Single Events and the first DAA:Double events. Inter/Min during the Nominal #3 task was similar across trials. The low workload condition had higher Inter/Min due to the addition of two Air Boss initiated altitude changes intended to maintain remote pilot vigilance during this task. Inter/Min during the in situ workload probe periods, provided in the Table for completeness, generally had lower Inter/Min.

Table C.12: The overall user interface interactions by trial and task. The Interactions/Minute (Inter/Min) descriptive statistics facilitate comparisons across tasks.

Workload Trial	Selections	Commands			Transmissions	Total	Inter/ Min
		Arm	Execute	Other			
Nominal #1 (Low: 5 minutes, High: 3 minutes)							
Low	170	50	45	74	240	579	6.4 (2.0)
High	237	46	43	75	207	608	11.3 (2.4)
Nominal #2 (3 minutes)							
Low	173	63	61	48	247	592	11.0 (2.0)
High	272	15	14	43	194	538	10.0 (2.6)
Nominal #3 (3 minutes)							
Low	228	10	10	34	174	456	8.4 (2.8)
High	204	36	35	27	128	430	8.0 (2.7)
Nominal #4 (8 minutes)							
Low	575	56	50	64	304	1049	7.3 (2.7)
High	531	32	29	23	205	820	5.7 (2.8)
DAA: Single (2 minutes)							
Low: 1	106	26	25	38	149	344	9.6 (1.7)
Low: 2	160	24	22	4	34	244	6.8 (2.4)
High	176	68	64	39	121	468	13.0 (2.2)
DAA: Double (4 minutes)							
Low	367	129	125	44	237	902	12.5 (3.7)
High: 1	342	111	106	104	344	1007	14.0 (2.6)
High: 2	311	90	86	27	124	638	8.9 (2.9)
Workload Probes (1 minute)							
Low: 1	42	13	11	3	18	87	4.8 (2.3)
Low: 2	63	7	7	0	20	97	5.4 (3.1)
Low: 3	64	6	6	5	9	90	5.0 (3.5)
High: 1	115	23	20	6	30	194	10.8 (5.4)
High: 2	65	9	10	0	11	95	5.3 (3.6)
High: 3	64	3	3	3	5	78	4.3 (3.3)

The low workload Nominal #1 task's mean Inter/Min was the lowest of all this condition's

Nominal tasks. This condition's Nominal #2 and #3 tasks occurred after the two single DAA events (i.e., Low: 1 and Low: 2 in Table C.12). Nominal #2 had the highest Inter/Min of all Nominal tasks, and was substantially higher than Nominal #1 and #4. Nominal #3 also had a higher mean Inter/Min, but was lower than Nominal #2. Notably, the mean Inter/Min for these tasks were higher than the mean Inter/Min than the single DAA events they followed. Nominal #4's Inter/Min dropped from the DAA:Double events 12.5 Inter/Min.

The high workload condition's Nominal task #1 had the highest mean Inter/Min, which is directly related to taking off aircraft at the start of the trial. Generally, the Inter/Min decreased from Nominal #1 to Nominal #4. The high workload DAA:Double events preceded Nominal tasks #2 and #3. These Nominal tasks had lower mean Inter/Min. The drop in Inter/Min from the DAA:High 2 to Nominal #3 was the smallest of all DAA to Nominal task transitions, while the transition from the high workload's DAA:Single to the Nominal #4 task had the largest drop (7.3 Inter/Min).

Investigating the types of interactions, the total aircraft selections were substantially higher than the second most frequent interaction type, communication transmissions, for the Nominal #2-#4 tasks during both workload conditions. The exception was for the low workload Nominal#2 task, where transmissions were higher much higher than selections. During the Nominal #1 task, the number of communication transmissions exceeded the number of aircraft selections for the low workload condition, but this pattern was reversed for the high workload condition.

The majority of all arm and execute command interactions, Low: 46.4% and High 39.6%, were due to Altitude changes, which was followed by Altimeter changes (Low: 16.4%, High: 17.8%), per Table C.13. There were more takeoff actions during the high workload condition, which represented 17.2% of all such commands. Selecting a different waypoint had the fewest arm and executes (Low: 9.0%, High: 10.9%). During the high workload condition, only the Altitude interactions were lower than the corresponding low workload results.

Table C.13: The total number of commands armed and executed (Exec) by trial.

Workload Trial	Takeoff		Waypoint		Altitude		Heading		Altimeter	
	Arm	**Exec**	**Arm**	**Exec**	**Arm**	**Exec**	**Arm**	**Exec**	**Arm**	**Exec**
Low	54	53	34	33	178	168	50	48	62	60
High	74	71	48	44	170	164	60	59	78	72

C.5.3.1 Unexpected Events

The UEs were expected to change the remote pilots interactions with the interface. Specifically, these interactions were expected to reflect more information gathering activities as remote pilots made decisions regarding how best to handle each UE.

Detect and Avoid: Single Aircraft

The single DAA events mean Inter/Min increased substantially from the low to high workload conditions. There was a slight decrease between the two low workload events, as shown in Table C.12.

The total number of aircraft Selections during both condition's DAA:Single events was lower than Selections for all corresponding Nominal tasks, and the total number of Transmissions was lower for all DAA:Single events for each condition when compared to the respective Nominal tasks. Both the second low workload single DAA event (i.e., Low: 2) and the high workload DAA:Single event had substantially more aircraft Selections than Transmissions. This pattern was reversed for the first low workload event, which had substantially more Transmissions. The second low workload DAA event had far fewer total Other interactions with the Command panel than the other DAA:Single events.

The most common command armed and executed during the single DAA events was an Altitude change. The second low workload event (Low: 2) had ten Heading arm and execute commands, more than twice the number for the other two single DAA events. The number of Takeoff arm and execute commands was effectively equivalent across all three single DAA events, and no altimeter commands were armed or executed for any of these events.

Detect and Avoid: Double Crewed Aircraft

The first high workload DAA:Double event resulted in higher mean Inter/Min than all DAA:Single events, and the low workload event and High: 1 had higher Inter/Min than all Nominal tasks. The high workload's first DAA:Double event had the highest Inter/Min, while the same trial's second DAA:Double event had the lowest. This result is likely due to the double DAA event's intruder aircraft being the most spatially separated, which required the remote pilots to do more spatially distributed visual observation and cognitive reasoning, rather than user interface interactions.

Aircraft Selections interactions dominated the low workload and second high double DAA tasks, as shown in Table C.12, followed by communication Transmissions. The number of aircraft Selections and Communication transmissions differed by two during the first DAA:Double task in the high workload condition. The number of Arm and Execute commands was the highest (254) during the low workload's double DAA event, while both high workload events had fewer, with the High: 2 having only 176. The first high workload DAA:Double event contained a very high amount of the Other command panel interactions, which was a substantially smaller number for the other two such events.

The double DAA event results differed from the single DAA events with regard to the Command arm and execute distributions. The low workload double DAA event had a very large total (43 total each) of Altimeter changes, followed by 22 arm and execute Altitude changes. Ignoring Takeoff commands, the two high workload double DAA events both had the most arm and executes for Altitude, followed by Heading changes.

C.5.4 Task Performance

Task performance was measured as the number of times potential intruder aircraft did NOT enter a remote pilot's incursion air traffic zone (i.e., red ring in Figure C.1). The low workload trial contained a total of 72 potential intruder aircraft instances across the two DAA:Single and the DAA:Double events (i.e., 4 intruder aircraft/trial * 18 remote pilots), while the high workload trial had a total of 90 intruder aircraft incidents across the DAA:Single and the two DAA:Double events.

The remote pilots generally had a high degree of task performance. The remote pilots handled 93% of the low workload intruder aircraft before they reached the incursion air traffic zone. During the high workload trial, the remote pilots responded to 86.7% of all intruder aircraft before they reached the incursion air traffic zone for any UAS.

C.5.4.1 Unexpected Events

Detect and Avoid: Single Aircraft

The remote pilots had an overall 96.3% success rate when handling the 54 total DAA:Single events. The low workload condition's first DAA:Single event was the only instance during which two remote pilots had intruder aircraft enter a UAS's incursion air traffic zone.

Detect and Avoid: Double Crewed Aircraft

The remote pilots responded appropriately to 86% of the 108 total intruder aircraft when considering all double DAA events. The low workload double DAA event resulted in three intruder aircraft entering a UAS's incursion air traffic zone; a 91.6% success rate. Two thirds of the incursion zone breaches occurred with the first intruder aircraft.

While the remote pilots had a 100% success rate during the high workload's first double DAA instance, the second instance resulted in only a 67% success rate. A total of twelve intruder aircraft entered the incursion zone during the second DAA:Double instance. Seven of the intruder aircraft to enter the incursion zone (39%) were the first instance, while 28% of the second intruder aircraft entered the incursion zone. This particular event was designed to separate the intruders by the largest spatial distance, producing the highest level of workload on the remote pilots. This distance clearly impacted the outcome, particularly if a remote pilot had zoomed the map display in and was thus unable to maintain awareness of the overall operational area.

C.5.5 Communications

The evaluation had three types of communication, those initiated by either the Air Boss or the remote pilot, and communications between crewed aircraft and ATC. The crewed aircraft and ATC communications were intended to serve as background communications for the remote pilots to monitor. There were over 1,000 communications during each 30-minute trial, as shown in Table C.14. The distribution of the communications by trial are provided graphically by workload condition and task in Figure C.9. The low workload condition had 4.6% more communications than the high workload condition, which was due to adding two Air Boss initiated requests during the fourth Nominal task as a means to maintain remote pilot engagement. No Air Boss initiated communications had to be repeated during any trials. Across the two trials, the remote pilot initiated communications were substantially more than the other two types, and the high workload condition had 67 more remote pilot imitated communications than occurred during the low workload condition. Overall, this evaluation was not designed to require a heavy amount of communications. The 756 (i.e., 7 probes x 18 participants x 3/trial x 2 trials) workload probes asked by the experimenter were not included in the communication results. However, there were 93 communications initiated during the workload probe periods, where 91 of these were the Air Boss requesting the report pilot reporting when over a waypoint.

Table C.14: Total communications by workload condition and communication source.

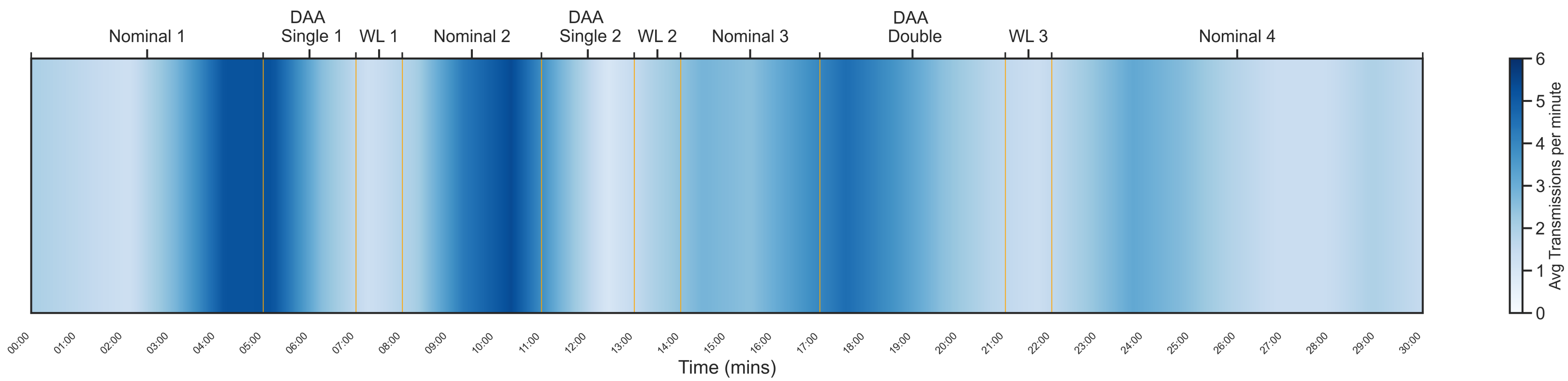
Workload	Air Boss Initiated	Remote Pilot Initiated	Crewed & ATC	Total
Low	402	714	316	1432
High	397	781	191	1369
Total	799	1495	507	2801

The overall mean Comms/Min results, provided in Table C.15, demonstrate that the communications were generally low. The low workload trial varied by at most 2.5 Comms/Min across the Nominal tasks, which was slightly higher than the high workload condition. Even though the fourth low workload Nominal task added two additional communication events, it had the second lowest Nominal task mean Comms/Min. The carry over from the DAA events to the Nominal events on the mean Comms/Min varied. The low workload Nominal #2 and #3 Comms/Min increased after their respective DAA:Single events, while the same metric fell for Nominal #4 after the DAA:Double event. During the high workload condition, the Comms/Min fell for Nominal #2 and #4 after their respective DAA Events, but increased during Nominal #3 after the very low Comms/Min for the second DAA:Double event.

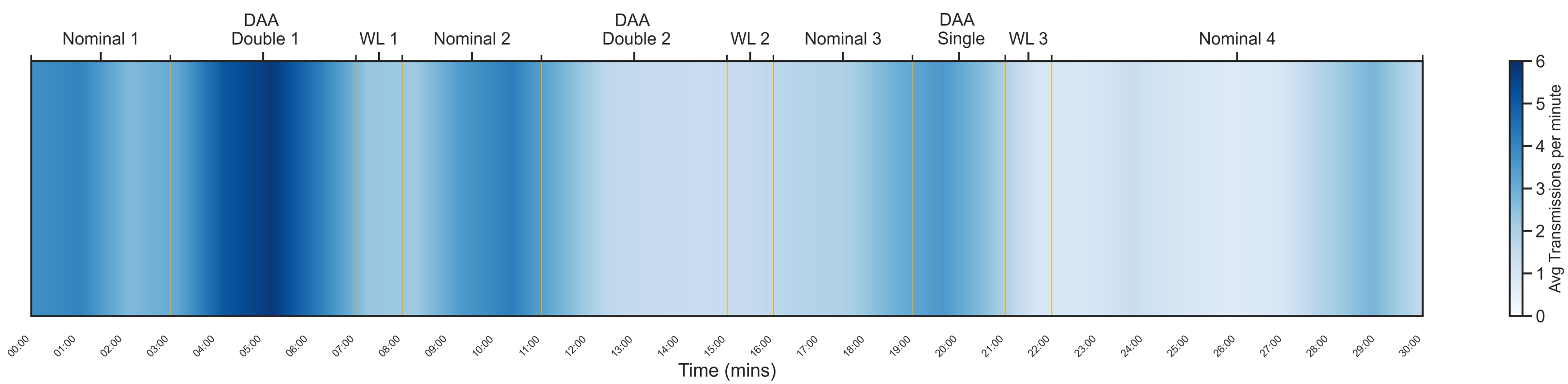
The communications analysis related to execution and readback latency included commands to change an aspect of a UAS's flight (i.e., increase altitude) from the Air Boss with information requests (e.g., report HMT-110's altitude). These communications need to be analyzed by type, which was infeasible given the accelerated project end date. The remote pilot behavior relative to acknowledging the Air Boss initiated communications needs to be analyzed, as it is known that the qualitative differences in how the remote pilots responded to these prompts did impact the latencies, in many instances making them appear longer than they may actually be. As such, many of the readback latency's exceed the five second deemed acceptable by air traffic controllers when interacting with crewed aircraft [23].

The execution latency (Execute in Table C.16) during the low workload Nominal tasks was generally longer, with little variability. Nominal #3's execution latency in the low workload condition was the shortest within these tasks. The low workload's double DAA task had a longer mean execution latency, but this latency was lower than Nominal tasks #1, #2 and #4. The Nominal tasks that were preceded by a DAA event all had an execution latency that was longer than the respective DAA events. There was more variance in the the high workload's Nominal tasks' execution latency that ranged from a mean of 10.28 to 16.44 seconds. After the DAA:Double events, the execution latency for Nominal #2 and #3 increased over the respective DAA's latency. After the high workload's single DAA event, the execution latency during Nominal #4 dropped slightly.

The low workload's Nominal task's mean readback latencies varied from 5.53 to 8.78 seconds, as shown in Table C.16. No clear pattern existed in relation to the readback latency for the Nominal tasks that followed a DAA event. The low workload's Nominal #2's latency increased, while Nominal #3's and #4's decreased, although the drop was marginal for Nominal #3 (0.1 second). The mean readback latency during the high workload condition



(a) Low Workload.



(b) High Workload.

Figure C.9: A heatmap of the average communications per minute by each workload condition with the task periods highlighted.

Table C.15: Communication patterns by task and workload trial. The Comms/Min descriptive statistics support cross task comparisons.

Workload	Air Boss Initiated	Remote Pilot Imitated	Crewed & ATC	Total	Comms/ Min
Nominal #1 (Low: 5 minutes, High: 3 minutes)					
Low	71	97	72	240	2.67 (0.66)
High	66	105	36	207	3.83 (0.42)
Nominal #2 (3 minutes)					
Low	73	102	72	247	4.57 (1.11)
High	60	100	34	194	3.59 (1.16)
Nominal #3 (3 minutes)					
Low	47	93	34	174	3.22 (1.73)
High	41	68	19	128	2.37 (0.88)
Nominal #4 (8 minutes)					
Low	80	156	68	304	2.11 (0.60)
High	42	112	51	205	1.42 (0.38)
DAA: Single (2 minutes)					
Low: 1	49	64	36	149	4.14 (1.12)
Low: 2	3	31	0	34	0.94 (1.04)
High	41	65	15	121	3.36 (1.01)
DAA: Double (4 minutes)					
Low	59	144	34	237	3.29 (1.31)
High: 1	123	185	36	344	4.78 (1.26)
High: 2	16	108	0	124	1.72 (1.09)
Workload Probes (1 minute)					
Low: 1	9	9	0	18	1.00 (1.28)
Low: 2	7	13	0	20	1.11 (1.41)
Low: 3	4	5	0	9	0.50 (1.04)
High: 1	7	23	0	30	1.67 (1.41)
High: 2	1	10	0	11	0.61 (0.78)
High: 3	0	5	0	5	0.28 (0.57)

Nominal tasks demonstrated a larger range (minimum: 4.12, maximum: 9.42 seconds) than the low workload instances. The high workload trial's readback latency for Nominal #3 was the lowest across all tasks. Similar to the low workload trial, the read back latency for Nominal tasks that followed a DAA event were mixed. The Nominal #2 and #4 tasks' mean readback latency increased, while the Nominal #3 task's latency fell sharply.

The communication type impacted the mean readback latencies, as shown in Table C.17. The low workload condition resulted in longer mean readback latency for most communication types in comparison to the high workload instance. None of the low workload's readback latencies were below the five second threshold deemed acceptable to ATC controllers [23], but three were < 6 seconds. The remote pilots had the slowest readback latency during the low workload trial in response to Air Boss updates related to other wildland fire UAS in the

Table C.16: The communication execution and readback latency descriptive statistics (seconds).

Workload Trial	Execute	Readback
Nominal #1		
Low	15.74 (12.37)	5.53 (5.26)
High	10.28 (8.97)	5.52 (8.67)
Nominal #2		
Low	15.02 (14.87)	8.29 (10.06)
High	13.58 (11.43)	8.54 (10.87)
Nominal #3		
Low	11.85 (11.32)	8.78 (8.07)
High	16.44 (14.93)	4.12 (3.90)
Nominal #4		
Low	15.45 (13.81)	6.17 (6.50)
High	11.94 (14.38)	9.42 (13.03)
DAA: Single		
Low: 1	10.59 (12.68)	7.61 (8.49)
Low: 2	7.81 (5.68)	8.88 (12.21)
High	12.87 (11.49)	6.03 (8.75)
DAA: Double		
Low	12.52 (10.50)	8.29 (9.07)
High: 1	11.59 (10.70)	6.47 (7.05)
High: 2	10.19 (3.02)	12.25 (8.53)

operational area. The high workload condition's readback latencies were mostly lower than the low workload condition, with three communication types having a latency of less than five seconds. All high workload readback latencies were less than seven seconds.

Table C.17: The readback latency descriptive statistics (seconds) for each instruction by workload condition.

Communication Type	Low		High	
	Count	Latency	Count	Latency
Takeoff	54	7.03 (7.59)	72	4.53 (4.71)
Change Altitude	72	5.19 (4.37)	36	4.64 (4.13)
Change Altimeter	18	9.90 (8.31)	18	6.12 (7.20)
Report Heading	18	6.17 (7.44)	18	4.73 (4.29)
Report Over Waypoints	72	5.65 (5.12)	72	5.80 (6.37)
Other UAS Status	18	10.41 (11.32)	54	6.55 (8.27)
Verification Request	18	5.29 (6.17)	18	6.89 (9.56)

The most consistent readback latency across the workload conditions, which was close to the ATC five second threshold, occurred for the reports when over waypoints. The Air

Boss requested ten such updates during the low workload condition, with the remote pilots responded to 87.8% of them. The median number of waypoint report responses was nine, as one remote pilot responded to only three requests and eight participants responded to all requests. The high workload's overall waypoint report response rate percentage was slightly lower (83.8%) for the twelve reports. The median response rate was ten, with a minimum of seven responses by one remote pilot, while only four remote pilots responded to all requests.

C.5.5.1 Unexpected Events

Detect and Avoid: Single Intruder Aircraft

The low workload condition's first DAA:Single event had the highest mean Comms/Min, while the second low workload single DAA event had the lowest Comms/Min of any task across both workload conditions. The total number of remote pilot initiated communications varied across the DAA:Single events, where Low:1 and High were similar representing 43% - 53% of the total communications, respectively. However, the Low: 2 remote pilot initiated communications represented 91% of the total. The Air Boss initiated communications were also effectively the same for the Low: 1 and the High DAA:Single events, but were higher than the crewed and ATC communications across all three single DAA events.

Similarly, the Low: 1 and High single DAA events' readback latencies were lower than for the second low workload instance. Overall, the execution latencies during the single DAA events varied by approximately 5 seconds. There was much less difference in the DAA:Single mean readback latencies, just under three seconds. The high workload single DAA event had the highest execution latency, but the lowest readback latency.

Detect and Avoid: Double Intruder Aircraft

The high workload condition's double DAA event had a slightly narrower range of mean Comms/Min across these events as compared to the single DAA events. The High:1 event had the highest mean Comms/Min of all tasks across both workload conditions. The remote pilot initiated communications dominated across all three double DAA events, ranging from the High: 1's 53.7% to the High: 2's 87%. representing more than 50% of the total communications. The Air Boss initiated communications were higher than the crewed to ATC communications across all three double DAA events.

The low workload DAA:Double execution latency was the longest, while the High: 2 event, designed to be the hardest DAA event, had the lowest execution latency. All three events' execution latency was within the range of the overall latencies across the tasks. The DAA:Double readback latencies across workload conditions and instances had an almost six second difference. The fastest mean readback latency occurred for the first high workload event, and the longest occurred for that trial's second DAA:Double event.

C.6 Discussion

The remote pilot participants were generally successful in handling all Nominal tasks, as well as the single and double DAA events across both workload conditions. The remote pilots maintained their engagement with the tasks during both trials, with higher fixations during the high workload condition DAA events. The high workload's DAA:Double events resulted in the highest fixations during Nominal events. The remote pilots focused primarily on the map display, on which the UAS that they were responsible for, as well as all other air traffic were presented. The visual fixations were distributed across the operational area, with slight differences based on the specific DAA events' intruder aircraft's behavior and remote pilot responsive actions. Most remote pilot interactions also occurred on the user interface's map via aircraft selections, and the amount of these interactions did also fluctuate as a result of task demands; when remote pilots were under high visual and cognitive workload (e.g., high workload DAA: Double 2), selections and communications were reduced.

The remote pilots were responsible for responding to Air Boss communications, which made their interactions with the push-to-talk communication system the second most dominant interaction. All participants used the hardware communication system over the graphical user interface. The remote pilots initiated nearly twice as many communications with the Air Boss than the Air Boss initiated with them. Importantly, the Air Boss did not have to repeat any communications to the remote pilots. The remote pilot readback latency was generally longer than the crewed aircraft pilot to ATC controller advised five second latency [23], but there is no established corresponding latency for wildland fire remote pilot responses to the Air Boss. It was found that the high workload condition led to faster readbacks for the single and easier double DAA events, as well as aircraft related commands over requests for information. In especially demanding situations, such as with the second double DAA in the high workload condition, readback latency was slowest. Given these results and the demands placed on remote pilots in a wildland fire responder situation, it is important that a similar readback latency threshold be established.

The remote pilot's subjective in situ workload ratings related to the DAA events found both workload conditions did not overly tax workload, but that the Double DAA events had slightly higher workload than DAA:Single. Consistent with expectations, cognitive and visual workload were rated the highest for remote pilots, independent of workload condition. Combined with the performance results, the DAA: Double events did reduce the remote pilot's overall performance in relation to multiple metrics, and especially so in the second DAA:Double in the high workload condition which was designed to be most taxing on the remote pilots. This particular event had two intruder aircraft that were spatially at opposite sides of the remote pilot's operational area. The remote pilots demonstrated increased visual and cognitive workload in relation to this event, and had the lowest success rate in successfully mitigating the intruder situations.