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New Jersey 08405

Evaluation of Unmanned Aircraft Systems for Live Monitoring to Enhance Situational Awareness During an Aircraft Rescue and Firefighting Response

March 2024

Final Report

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16. Abstract

The Federal Aviation Administration (FAA) Airport Technology Research and Development Branch conducted a research effort to explore the use of small unmanned aircraft systems (UASs) to improve the situational awareness and effectiveness of aircraft rescue and firefighting (ARFF) personnel when monitoring the response to an ongoing ARFF accident/incident. The purpose of this effort was to develop minimum recommended performance specifications and technical/operational considerations for the use of UAS to aid ARFF response.

This research effort was conducted in three phases. The first two phases consisted of testing of various UASs and sensor payloads at Atlantic City International Airport to develop preliminary minimum performance specifications and best practices for how to use UASs during an ARFF response. Phase 1 consisted of daylight testing, while Phase 2 consisted of daylight, twilight, and nighttime testing. The third phase was conducted at Dallas/Fort Worth International Airport's Fire Training Research Center in conjunction with two of their Advanced Strategies and Tactics for Aviation Incidents classes. During Phase 3, UASs were flown during live-fire training exercises while providing responders with the live payload feed to evaluate the benefits and limitations of UASs and validate the recommended performance specifications and technical/operational considerations for how to use UASs during an ARFF response.

This report provides a comprehensive summary of the testing conducted and recommended UAS platform and payload specifications. Based on analysis of footage and feedback collected during testing, UASs equipped with thermal and visual cameras were found to provide a significant situational awareness benefit to incident commanders in a variety of ARFF response scenarios. FAA researchers set minimum performance specifications, including minimum live-streamed video resolutions of 1280 horizontal pixels x 720 vertical pixels (720p) for visual cameras and 640 horizontal pixels x 512 vertical pixels for thermal cameras.

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1	Replaced Operating Temperature Range for Parrot Anafi USA from -32 °F –110 °F to -32 °F– 122 °F	Page 10, Table 1, third column	03/14/24
2	Replaced temperature data from -4 °F to 14 °F.	Section 6.3.6 Environment Tolerances, Page 71, first paragraph	03/14/24
3	Replaced Operating Temperature Range for Mavic 2 Enterprise Dual from -50 °F to 14 °F	Appendix A, Page A-2, Table A-2	03/14/24
4	Replaced Operating Temperature Range for Parrot Anafi USA from -32 °F –110 °F to -32 °F– 122 °F	Appendix A, Page A-2, Table A-3	03/14/24

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- Atlantic City International Airport
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TABLE OF CONTENTS

APPENDICES

LIST OF FIGURES

LIST OF TABLES

LIST OF ACRONYMS

3D	Three-dimensional
AAIS	Air Accident Investigation Sector of the United Arab Emirates
AC	Advisory Circular
ACY	Atlantic City International Airport
AGL	Above ground level
AOA	Air operations area
ARFF	Aircraft rescue & firefighting
ATC	Air traffic control
C.F.R.	Code of Federal Regulations
COA	Certificate of waiver or authorization
CONOPS	Concept of operations
DFW	Dallas/Fort Worth International Airport
DJI	Da-Jiang Innovations
EO	Electro-optical
EOC	Emergency Operations Center
FAA	Federal Aviation Administration
FLIR	Forward-looking infrared
FOV	Field of view
fps	Frames per second
FTRC	Fire Training Research Center
GCCA	General Civil Aviation Authority of the United Arab Emirates
GCS	Ground control station
GPS	Global positioning system
HRET	High-reach extendable turret
IC	Incident commander
IEC	International Electrotechnical Commission
IP	Ingress protection
IR	Infrared
LWIR	Long-wave infrared
M210	DJI Matrice 210 RTK v2
M2ED	DJI Mavic 2 Enterprise Dual
mK	Millikelvin
MP	Megapixel
NTSB	National Transportation Safety Board
RF	Radio frequency
RPIC	Remote pilot-in-command
SAFT	Specialized Aircraft Fire Trainer
SM	Statute mile
TFR	Temporary flight restriction
UA	Unmanned aircraft
UAS	Unmanned aircraft system
UAE	United Arab Emirates
WJHTC	William J. Hughes Technical Center

EXECUTIVE SUMMARY

Aircraft rescue and firefighting (ARFF) personnel and incident commanders (ICs) currently have limited visibility and situational awareness when viewing an incident/accident scene. It is often impossible for responding ARFF personnel and the IC to view an entire incident/accident scene from the cab of a rescue vehicle or standing at ground level. Fire, smoke, water spray, and foam can further restrict the visibility of onsite personnel. These limitations can critically impair an IC or individual ARFF vehicle operator's ability to coordinate the incident/accident response.

To address these limitations, the Federal Aviation Administration's (FAA) Airport Research and Development Branch conducted a research effort to explore the use of small unmanned aircraft systems (UASs) to improve situational awareness, visibility, and effectiveness of ARFF personnel when responding to an incident or accident. The purpose of this effort was to develop minimum recommended performance specifications and technical/operational considerations for the use of UASs to aid ARFF response.

This research effort was conducted in three phases. The first two phases consisted of testing of various UASs and payloads at the FAA's William J. Hughes Technical Center (WJHTC), which is collocated with the Atlantic City International Airport (ACY), to develop preliminary performance specifications and best practices on how to use UASs during an ARFF response. Phase 1 consisted of daylight testing, while Phase 2 consisted of daylight, twilight, and night testing. A total of 34 UAS test flights were conducted by contracted personnel at WJHTC/ACY during phases 1 and 2 over simulated aircraft accident scenes to evaluate the capabilities of various UAS platforms and sensor payloads to enhance the ARFF response. The findings and lessons learned from this testing were used to develop preliminary UAS platform and payload performance specifications and best practices.

Phase 3 testing was conducted at the Dallas/Fort Worth International Airport (DFW) Fire Training Research Center (FTRC) in conjunction with the facility's Advanced Strategies and Tactics for Aviation Incidents classes to evaluate the benefits and limitations and validate the recommended performance specifications and technical/operational considerations of using UASs for ARFF response. For this testing, UASs were flown by contracted personnel during 17 live-fire training scenarios. FAA researchers observed the ARFF response while providing the IC with a tablet displaying the UAS payload video feed. The payload video collected during each exercise was analyzed alongside feedback from each IC to develop the benefits and limitations of utilizing UASs, as well as additional operational and technical considerations regarding using UASs to support an ARFF response.

Based on analysis of footage and feedback collected during testing, FAA researchers found that, when equipped with thermal and visual cameras, UASs provided a significant situational awareness benefit to ICs in a variety of ARFF response scenarios. UASs provided the most benefit for complex scenarios requiring a larger area to be monitored. The primary benefits UASs provided in these scenarios included providing enhanced initial 360° assessments, detecting heat signatures/hot spots, searching for victims, and monitoring areas outside the view of the IC for situational awareness purposes. These benefits were limited, however, by the availability of staffing required to operate the UAS, inclement weather conditions, and current federal restrictions on UAS operations in controlled airspace.

Minimum performance specifications were also identified to ensure adequate clarity of the live payload video, including minimum video resolutions of 720p (1280 horizontal pixels x 720 vertical pixels) for visual cameras and 640 horizontal pixels x 512 vertical pixels for thermal camera payloads. FAA researchers also developed technical and operational considerations to maximize the benefits of UASs for ARFF live monitoring. These considerations address technical aspects such as the UAS platform, ground control stations (GCSs), payloads, and the wireless video transmission. In addition, this guidance addresses operational considerations regarding using an UAS to monitor an ARFF incident.

This report provides a summary of testing conducted at ACY and DFW, and provides benefits and limitations, recommended performance specifications, and technical and operational considerations for using UASs to enhance situational awareness during an ARFF response.

1. INTRODUCTION

Aircraft rescue and firefighting (ARFF) personnel and incident commanders (ICs) currently have limited visibility and situational awareness when viewing an incident/accident scene. It is often impossible for responding ARFF personnel and the IC to view an entire incident/accident scene from the cab of a rescue vehicle or standing at ground level. Fire, smoke, water spray, and foam can further restrict the visibility of onsite personnel. These limitations can critically impair an IC or individual ARFF vehicle operator's ability to coordinate the incident/accident response.

To address these limitations, the Federal Aviation Administration's (FAA) Airport Research and Development Branch conducted a research effort to explore the use of unmanned aircraft systems (UASs) to improve situational awareness and visibility of ARFF personnel when responding to an incident or accident. This research focused solely on small UAS, which are defined in 14 C.F.R. 107.3 as an unmanned aircraft weighing less than 55 pounds on takeoff, including everything that is on board or otherwise attached to the aircraft. (Definitions, 2016). This report provides a summary of research conducted and provides recommended minimum performance specifications and technical/operational considerations for the use of UASs for ARFF live monitoring.

1.1 BACKGROUND

Two major aircraft accident responses have emphasized the need for increased visibility and situational awareness for ARFF personnel. The first accident involved Asiana Flight 214, a Boeing 777, which struck the seawall at the approach of Runway 29 at San Francisco International Airport (SFO) on July 16, 2013. During the response, the situational awareness of ARFF personnel on the ground was significantly hindered by smoke, foam, and the collapsed gear with the fuselage on the ground that restricted visibility. Figure 1 shows a screenshot taken from helmet camera footage recorded during the response.

Figure 1. Screenshot Taken from Helmet Camera Footage During Asiana 214 Response (Real World Police, 2020)

In the Aircraft Accident Report, NTSB/AAR-14/01: *Descent Below Visual Glidepath and Impact With Seawall, Asiana Airlines Flight 214, Boeing 777-200ER, HL7742 San Francisco, California, July 6, 2013*, published by the National Transportation Safety Board (NTSB), investigators stated that,

> Neither high reach extendable turret (HRET)-equipped vehicle was used to the best of its capabilities in the initial fire attack. This was initially due to improper decision-making and vehicle positioning on the part of the ARFF crewmembers. Once the vehicles were out of position, command personnel failed to properly reposition them such that they could be most effectively used. (NTSB, 2014)

The NTSB report went on to state that the positioning of these ARFF vehicles, "rendered them incapable of direct fire attack" (NTSB, 2014).

The other notable accident occurred on August 3, 2016, involving Emirates Flight 521, a Boeing 777-31H carrying 282 passengers and 18 crew. Emirates Flight 521 impacted Runway 12L during an attempted go-around at Dubai International Airport, United Arab Emirates (UAE). Approximately 9 minutes and 40 seconds after the aircraft came to rest, the center fuel tank in the right wing exploded and fatally injured a firefighter. The aircraft was eventually destroyed due to the subsequent fire (General Civil Aviation Authority, 2020).

The Accident Final Report, AIFN/0008/2016: *Runway Impact during Attempted Go-Around*, published by the UAE's General Civil Aviation Authority (GCCA) Air Accident Investigation Sector (AAIS) identified the need for an improved assessment of the accident site prior to asset positioning, stating that,

> The positioning of the fire commanders' vehicle inside the incident area did not allow him proper surveillance capability of the accident site…No fire vehicle or firefighters were appropriately positioned…and no detailed assessment of this area was conducted by the crew managers. (GCAA, 2020)

UASs equipped with thermal and visual camera payloads have the potential to provide many benefits for an ARFF response. The *birds-eye* aerial view provided by a UAS may help improve real-time decision-making by ICs and ARFF personnel by providing increased visibility and situational awareness of the scene. The UAS could enhance initial assessments by the IC upon arriving on the scene and influence tactical decisions and strategy as the situation evolves. For example, during the response, the UAS live video feed could allow the IC to monitor and report progress, such as:

- Are agent streams hitting the target?
- Are people in harm's way?
- Is an interior fire attack underway?
- Has the exterior fire extended to interior?
- How effective are firefighting efforts?
- Has there been a change in fire dynamics?

This information has the potential to improve real-time decision-making, enhance ARFF effectiveness, and ultimately save lives.

1.2 PURPOSE

The purpose of this research effort was to evaluate the capability of UASs to improve situational awareness of ICs and ARFF personnel when responding to an aircraft incident or accident and to develop minimum performance specifications and technical/operational considerations for the use of UASs for ARFF live monitoring.

1.3 OBJECTIVES

The objectives of this research effort consisted of the following:

1. Evaluate the benefits and limitations of utilizing UASs in ARFF applications.
2. Develop and validate recommendations for UAS platform and payload minimum performance specifications.
3. Provide technical and operational considerations for the use of UASs for ARFF live monitoring via testing and stakeholder feedback.

1.4 RELATED DOCUMENTS

1. FAA Advisory Circular (AC) 150/5200-31C, Airport Emergency Plan
2. FAA AC 150/5200-12C, First Responders' Responsibility for Protecting Evidence at the Scene of an Aircraft Accident/Incident
3. FAA AC 150/5210-13C, Airport Water Rescue Plans and Equipment
4. Title 14 Code of Federal Regulations (C.F.R.) Part 139, Certification of Airports
5. National Fire Protection Association 2400 Standard for Small Unmanned Aircraft Systems (UASs) Used for Public Safety Operations
6. FAA AC 107-2A, Small Unmanned Aircraft System (Small UAS)

1.5 RESEARCH APPROACH

This research effort was conducted in three phases. The first and second phases consisted of testing of various UAS platforms and payloads at the FAA William J. Hughes Technical Center (WHJTC), which is collocated with the Atlantic City International Airport (ACY), NJ, to develop preliminary performance specifications and guidance. Phase 1 consisted of daylight testing, while Phase 2 consisted of daylight, twilight, and night testing. Phase 3 consisted of additional testing during various live fire-training exercises at the Dallas/Fort Worth International Airport (DFW) Fire Training Research Center (FTRC) to further evaluate the benefits and limitations of UASs and validate the recommended performance specifications and technical/operational considerations of using UASs for ARFF response.

2. UAS ARFF LIVE-MONITORING CONCEPT OF OPERATIONS

In the initial stage of this research effort, FAA researchers developed an overall concept of operations (CONOPS) for the ARFF live-monitoring use case. Sections 2.1–2.3 provide details regarding the CONOPS.

2.1 CORE REQUIREMENTS

First, FAA researchers developed a set of basic requirements for UASs used for live monitoring, which consisted of the following:

- Provide live visual and thermal video camera feeds of the incident/accident scene;
- Transmit or stream these live video feeds from the UAS to multiple locations, such as the incident command post, emergency operations center (EOC), and off-site stakeholders; and
- Record the video footage for later review/investigative purposes.

The purpose of the visual camera is to provide general situational awareness, including locating personnel and vehicles, determining the effectiveness of ARFF agent dispersal, and viewing other scene details. The purpose of the thermal camera is to provide situational awareness in low-light or low-visibility conditions, including environments with smoke and dust. Past FAA research has shown that thermal imaging cameras are also an effective tool for identifying and monitoring hotspots on aircraft fuselages (Short, Torres, & Kreckie, 2017).

The purpose of the video transmission/streaming functionality is to ensure that video feeds captured by the UAS are accessible to the IC and other personnel who might not be collocated with the UAS remote pilot-in-command (RPIC). This function also allows video feeds from multiple UASs to be displayed at one location, such as the EOC, further enhancing situational awareness by allowing multiple angles to be viewed simultaneously.

The purpose of the video recording functionality is to preserve the video evidence of the incident/accident response, in accordance with FAA Advisory Circular (AC) 150/5200-12C, *First Responders' Responsibility for Protecting Evidence at the Scene of an Aircraft/Incident* (FAA, 2009). These video recordings can be used by accident investigators to document the sequence of events during the response and show the original locations of objects or victims that were required to be moved in the interest of preserving life. The videos can also be used for training purposes to help ARFF departments learn from the emergency event and improve future ARFF responses.

2.2 SYSTEM OVERVIEW

The live-monitoring concept includes two primary systems: the UAS and the video streaming system. The purpose of the UAS is to fly above the scene and capture real-time and recorded video using its onboard sensors. The purpose of the video streaming system is to transmit the real-time video feeds from the RPIC's location to the IC, EOC, and other stakeholders. Figure 2 shows an overview of each of these systems. The specific devices shown in Figure 2 are for illustrative purposes and not intended as endorsements of specific products.

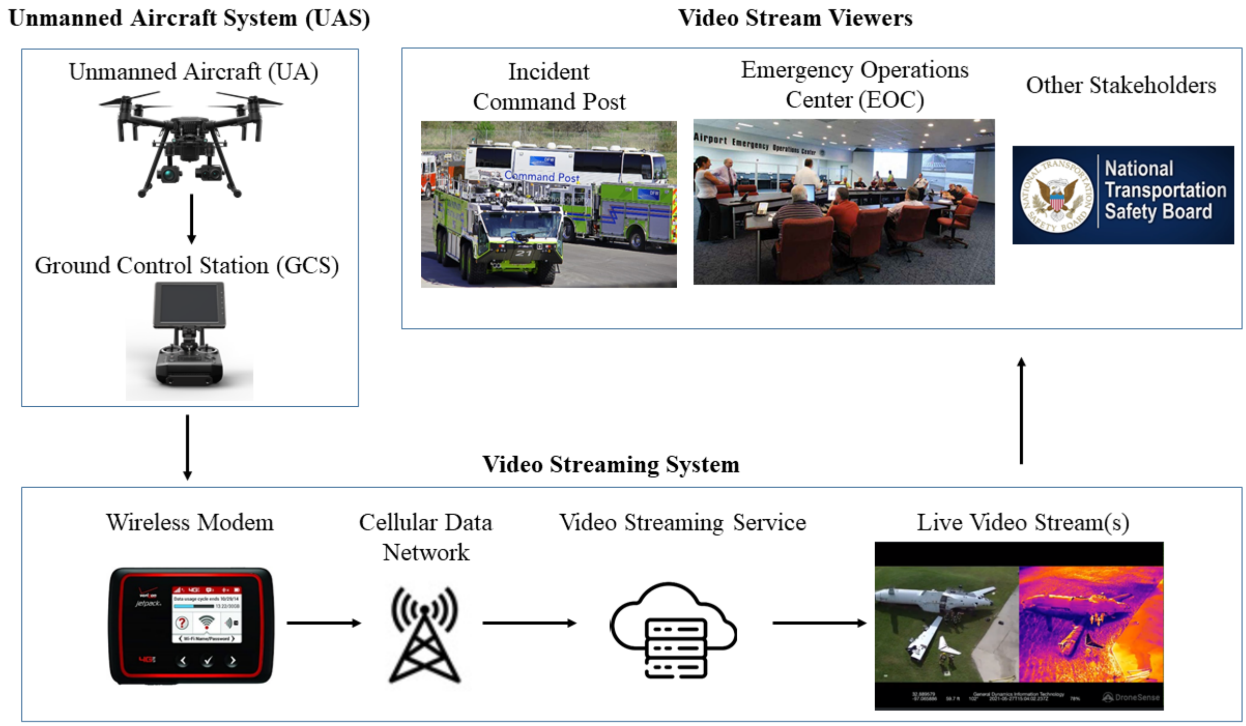

Figure 2. UAS ARFF Live-Monitoring CONOPS Diagram

As defined in 14 C.F.R. 107.3, the UAS includes the "the unmanned aircraft (UA) and its associated elements (including communication links and the components that control the small unmanned aircraft) that are required for the safe and efficient operation of the small unmanned aircraft in the national airspace system" (Definitions, 2016). For ARFF live monitoring, the UA would be equipped with both visual and thermal camera sensors. Depending on the UAS model, these camera sensors may be permanently integrated with the UA or mounted as external payloads. The ground control station (GCS) is used by the RPIC to control the UA. The GCS will often include a mounting bracket for a touch screen smartphone or tablet. These devices are used for displaying the live video feeds; viewing battery status; adjusting settings; and displaying flight telemetry data, such as altitude, speed, and location. In many cases, the GCS contains external ports for connecting an additional monitor to display the video feed for individuals collocated with the RPIC. For maximum resolution, video would be recorded on a physical memory card onboard the UA. However, if this is not possible, a screen recording can be made directly on the GCS tablet.

The video streaming system consists of a wireless internet connection and a video streaming service. The internet connection is typically provided via a wireless Wi-Fi hotspot with cellular data service. The video streaming service is a service that allows the viewing of the real-time video feeds from the UAS on any internet-connected device, including computer monitors, tablets, or smartphones. The video streaming services are typically cloud-based and require a monthly subscription. Several video streaming services exist, some of which are designed for specific UAS models. Depending on the company, the video streaming service consists of an application designed to run on the GCS tablet or may be a separate unit that connects to the GCS via a video cable. These services may offer additional features, such as tracking the location of the UA and UAS fleet management and logging pilot flight time.

2.3 OPERATIONAL DESCRIPTION

Depending on the airport's organizational structure, the personnel deploying the UAS may be part of the ARFF department, airport operations department, or another department or entity. It is expected that each airport will develop and adopt standard operating procedures for UAS operations. In addition, all UAS operations in controlled airspace must be conducted with air traffic control (ATC) approval, which is typically obtained through an airspace authorization received in advance of the operation.

The UAS must be operated in compliance with all applicable FAA regulations by a trained and certified RPIC. The UAS should be operated within visual line of sight of RPIC and any visual observers. The RPIC operates in accordance with all provisions of the airspace authorization, such as contacting the ATC facility prior to conducting UAS operations, monitoring the local ATC frequency during the operation, and ensuring the UAS remains within the approved airspace volume. In most cases, the UAS would be operated from a closed runway or taxiway. However, the RPIC is still responsible for giving way to manned aircraft that might be present.

Due to the time-sensitive nature of ARFF response, the UAS should be deployed as soon as practical upon initial response to the incident/accident site. Before launching the UA, the RPIC performs a brief preflight checklist and verifies that there are no aircraft or obstructions above, or in the immediate vicinity, of their location. In most cases, the UAS would be stored in a case that would be removed from a vehicle and require some amount of assembly prior to flight. However, certain UASs could be deployed automatically from vehicle-mounted base stations. Once the UAS is launched, personnel within the incident command structure can log in to the video streaming service using a prearranged website link and login password to view the live video feeds.

Throughout the operation, the RPIC maintains two-way communications with the IC or a designated representative. This occurs either through face-to-face conversation (if pilot is collocated with the incident command post) or using a portable radio. This communication allows the RPIC to receive commands based on what view is needed by the IC (e.g., where to maneuver the UA, where to aim the camera, zoom in or out.). The RPIC can also use this communications channel to report what they are seeing in the video feed, report battery status, and other information. Once the mission is completed, the RPIC lands the UA and transfers and copies the video footage from the physical memory card for archival purposes and provides a copy to accident investigators, as requested.

3. PHASE 1 TESTING: WJHTC/ACY

Phase 1 testing took place at the FAA's WJHTC, collocated with ACY. ACY is a towered airport certificated under Title 14 C.F.R. Part 139 and located in Class C airspace. In this phase, flights were conducted at various altitudes with multiple UAS platforms over a simulated accident scene while collecting video with visual and thermal camera payloads. Each piece of video footage was reviewed and evaluated regarding their respective quality and usefulness for enhancing the situational awareness of ARFF responders. This analysis was used to identify initial findings regarding minimum technology performance specifications and operational recommendations for UAS platforms, payloads, and GCS when assisting an ARFF response.

Testing at ACY was performed inside a designated operations area to the northeast of the airfield's movement areas, as illustrated in Figure 3. This area includes the ARFF test area and the Fire Test Facility, and contains three retired aircraft, a Boeing 747, Boeing 737, and a Lockheed L-1011, that serve as test articles for FAA research purposes. The ARFF test area is pictured in Figure 4.

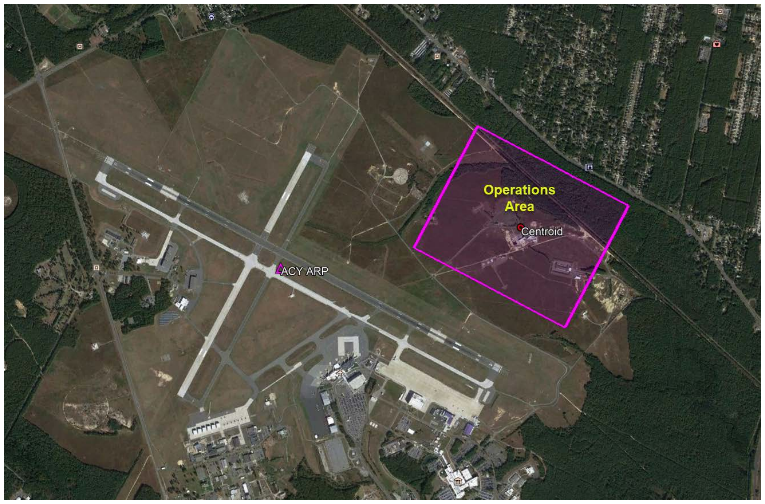

Figure 3. The ACY ARFF UAS Operations Area

Figure 4. The ARFF Test Area at ACY

3.1 UAS AND PAYLOADS

Sections 3.1.1–3.1.3 describe the UAS platforms and payloads used to conduct Phase 1 testing.

3.1.1 UAS Selection Criteria

Prior to testing, researchers developed basic UAS selection criteria to meet to adequately perform ARFF live monitoring in an airport environment, including safety, cybersecurity, deployment time, ease-of-use, environmental tolerance, and cost effectiveness. These criteria were used to select UASs and payloads included in this testing effort.

3.1.1.1 Safety

Safety is the top priority for all activity in the airport environment. Therefore, the UAS selected for this research effort included safety features such as a lost link return-to-home failsafe mode and geofencing capability (software restricting the ability of the UAS to leave its designated airspace limits) to minimize hazards with aircraft, people, and property. Other safety features included an anti-collision beacon for safely conducting twilight and night operations.

3.1.1.2 Cybersecurity

Cybersecurity measures must prevent outside persons from knowingly or unknowingly accessing or interrupting data communications. This includes data used for command and control of the aircraft as well as payload footage. The UAS selected for this research program featured secure, encrypted connections between the aircraft, GCS, and any other devices that receive data.

3.1.1.3 Deployment Speed

For maximum usefulness and value to ARFF responders and ICs, the UAS must be launched and begin recording and transmitting data as soon as possible after arriving on scene. Because the speed and efficiency of response has a dramatic effect on survivability, researchers tested systems that were capable of rapid deployment.

3.1.1.4 Ease-of-Use

An ARFF responder or IC could be multitasking and perhaps overwhelmed by the incident/accident while experiencing sensory overload in the cab of the ARFF vehicle. UASs were selected that would be as simple as possible to operate, minimizing potential delays in launching the aircraft and reducing the chance of user error.

3.1.1.5 Environmental Tolerance

The UAS should have the ability to operate in inclement weather and other environmental conditions that might exist during an incident/accident. This includes excessive cold/heat, wind, precipitation, dust, and smoke. UASs were selected with various levels of ingress protection (IP) against water and particulates, and features such as self-heating batteries for operations in cold conditions.

3.1.1.6 Cost

Airports vary significantly in the resources that can be utilized to purchase ARFF equipment. Therefore, UAS platforms ranging in price from $3,850 to $28,000 were included in testing to find solutions that could be effective for different organizational budgets.

3.1.2 UAS Platforms

FAA researchers selected the following three commercial-off-the-shelf, multi-rotor UAS platforms that met the selection criteria in Section 3.1.1. The selected UAS platforms represent a variety of sizes, payload capabilities, and price points:

- Da-Jiang Innovations (DJI) Matrice 210 RTK v2 (M210)
- DJI Mavic 2 Enterprise Dual (M2ED)
- Parrot Anafi USA.

These UASs are pictured in Figure 5. Table 1 provides an overview comparison of key specifications for each UAS. Additional specifications for each platform are presented in Appendix A.

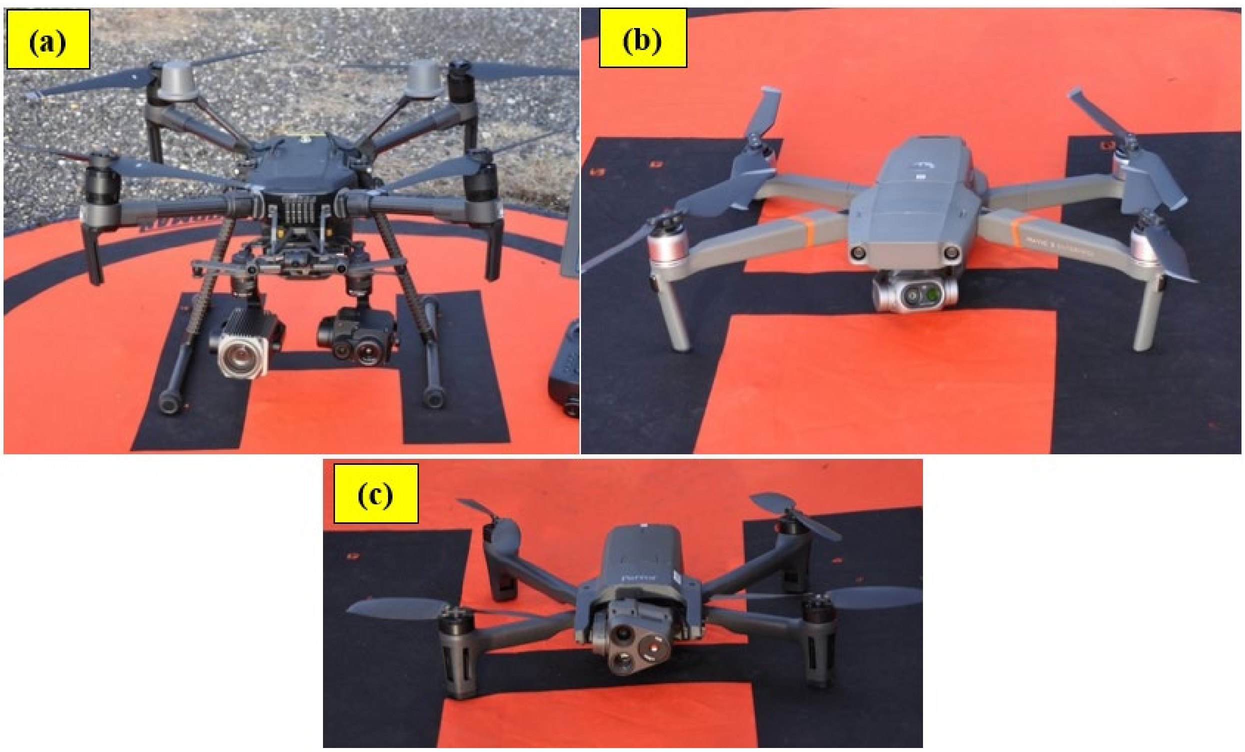

Figure 5. UAS Platforms: (a) DJI M210, (b) DJI M2ED, and (c) Parrot Anafi USA

Table 1. Comparison of UAS Specifications (DJI, 2020; DJI, 2021a; Parrot, 2020)

	DJI M210	DJI M2ED	Parrot Anafi USA
Maximum takeoff weight (lb)	13.5	2.4	1
Airframe dimensions	34.8″ x 34.9″ x 16.8″	12.7″ x 9.5″ x 3.3″	11.1″ x 14.7″ x 3.3″
Endurance	24 min	31 min	32 min
RF Range	5 miles	5 miles	2.5 miles
Data Encryption	AES 256-bit encryption	AES 256-bit encryption	AES 128-bit encryption
3-axis Gimbal	Yes	Yes	Yes
IP rating	IP43	N/A	IP53
Operating temperature range	-4 °F to 122 °F	14 °F – 104 °F	-32 °F to 122 °F
Maximum wind resistance	26 mph	23 mph	32.88 mph
Interchangeable payloads	Yes	No	No
Estimated cost	UAS: $28,000 (with XT2 and Z30 payloads)	$3,850	$7,000

RF = Radio frequency

Each UAS platform used in this research effort utilized a different GCS to evaluate varying specifications with regard to form factor, screen size, and screen brightness. The GCSs used during Phase 1 testing included the DJI Cendence controller and CrystalSky Tablet, the DJI Smart Controller, and the Parrot Skycontroller 3. Screen brightness is traditionally measured in candelas per square meter, which is also known as *nits*. These GCSs are pictured in Figure 6. A comparison of key specifications for these GCSs are presented in in Table 2.

Figure 6. Ground Control Stations: (a) DJI Cendence Controller and CrystalSky Display, (b) Parrot Skycontroller 3 and iPad Mini®, and (c) DJI Smart Controller

Table 2. Ground Control Station Specifications (DJI, 2018a; DJI, 2021b; Apple, 2022)

UAS Platform	DJI M210	DJI M2ED	Parrot Anafi USA
GCS controller	DJI Cendence	DJI Smart Controller	Parrot Skycontroller 3
GCS screen	DJI CrystalSky Tablet		Apple iPad Mini® (5th generation)
Screen size	7.85″	5.5″	7.9″
Screen brightness	2,000 nits	1,000 nits	500 nits
Integrated screen & controller	No	Yes	No

3.1.3 Payloads

FAA researchers tested the following visual and thermal camera payloads to determine minimum performance requirements for ARFF live-monitoring implementation.

- DJI Zenmuse Z30 (visual camera with 30x optical zoom)
- DJI Zenmuse XT2 9mm (dual visual and thermal camera)

- DJI Zenmuse XT2 13mm (dual visual and thermal camera)
- DJI Zenmuse XT2 19mm (dual visual and thermal camera)
- DJI Zenmuse XT2 25mm (dual visual and thermal camera)
- DJI M2ED Integrated Camera (dual visual and thermal camera)
- Parrot Anafi Triple Integrated Camera (dual visual cameras and one thermal camera)

These payloads are pictured in Figure 7. Table 3 compares key specifications of each payload. Detailed specifications for each payload are presented in Appendix B.

Figure 7. UAS Camera Payloads: (a) DJI Zenmuse XT2, (b) DJI Zenmuse Z30, (c) Anafi USA Triple, and (d) M2ED Integrated Camera

Table 3. UAS Comparison of Camera Payload Specifications (DJI, 2018b; DJI, 2019; DJI, 2021a; Parrot, 2020)

	Zenmuse XT2	Zenmuse Z30	M2ED Integrated Camera	Anafi Triple
Compatible UAS platform	DJI M210		DJI M2ED	Parrot Anafi USA
Visual camera resolution recorded	3840 x 2160 (4K); 1920 x 1080 (1080p)	1080p	4K	4K
Visual camera resolution streamed	1080p	1080p	1080p	720p
Visual camera zoom	1x, 2x, 4x, 8x digital	30x optical continuous; 6x digital continuous	N/A	1x to 5x optical continuous; 5x to 32x digital continuous
Visual camera FOV	57.12°× 42.44°	63.7°(max) – 2.3°(min)	85°	Wide: 84° Zoom: up to 75.5°
Visual camera sensor size	1/1.7″, 12MP	1/2.8″, 2.13 MP	1/2.3″, 12 MP	Wide: 1/2.4″, 21MP Zoom: 1/2.4″, 16MP
Thermal camera resolution	9mm: 336 x 256 13mm: 640 x 512 19mm: 640 x 512 25mm: 640 x 512	N/A	160 x 120	320 x 256
Thermal camera FOV	9mm: 35° x 27° 13mm: 45° x 37° 19mm: 32° x 26° 25mm: 25° x 20°	N/A	57°	50° horizontal
Thermal camera zoom (digital)	336: 1x, 2x, 4x 640: 1x, 2x, 4x, 8x	N/A	N/A	N/A
Thermal camera sensitivity	< 50 mK	N/A	Not Specified	< 60 mK
Additional features	EO/IR Image Blending, Temperature measurement	N/A	EO/IR Image Blending	EO/IR Image Blending
Approximate cost	$6,000 (336 x 256) $10,000 (640 x 512) (Payload only)	$3,000 (Payload Only)	$3,850 (with UAS)	$7,000 (with UAS)

EO = Electro-optical
IR = Infrared
MP = megapixel
FOV = Field of view
mK = millikelvin

3.2 TEST METHODS AND PROCEDURES

Sections 3.2.1–3.2.5 describe the test setup and procedures employed during Phase 1 UAS testing at ACY.

3.2.1 Site Setup

During Phase 1 testing, FAA researchers created a simulated accident scene centered on the Lockheed L-1011 test article in the FAA's ARFF testing area. This simulated accident scene, shown in Figure 8, included live fire and smoke, personnel in varying levels of personnel protective equipment, and an ARFF vehicle staged near the aircraft.

Figure 8. Simulated ARFF Accident Scene During Phase 1 Testing

3.2.2 Test Procedures

Phase 1 UAS testing consisted of a total of nine flights, each with different UAS/payload combinations. All UAS flights were conducted by contracted personnel. To ensure consistency, these flights were conducted using preprogrammed waypoint flight plans. Each UAS was flown in a 300-foot radius orbit maneuver around the center of the simulated accident site (illustrated in Figure 9) to view the scene from all vantage points. This radius was selected based on a typical practice of designating a *hot zone* of 300 ft surrounding a large ARFF incident. This hot zone represents a clear area in which only ARFF and emergency response personnel are permitted during an ongoing incident. The UAS cameras were programmed to automatically remain focused on the center point of the orbit throughout the flight. All flights took place during sunny daylight conditions.

To test the effect of altitude on the quality and usefulness of footage, initial flights were conducted with a single UAS at altitudes ranging from 75 ft above ground level (AGL) to 125 ft AGL. The minimum altitude of 75 ft AGL was selected to ensure clearance from any obstacles, including the tail of the Boeing 747 airframe and the Fire Test Building. Based on these initial tests, it was determined that lower altitudes allow the UAS to capture footage with greater detail, and the remaining test flights were conducted at an altitude of 75 ft AGL. All flights were conducted within a 90-minute period in the afternoon to minimize the effect of sun angle changes and solar loading changes on the visual and thermal camera footage. This ensured an equal comparison of footage quality between payloads. A complete list of test flights and parameters completed during Phase 1 is presented in Appendix C.

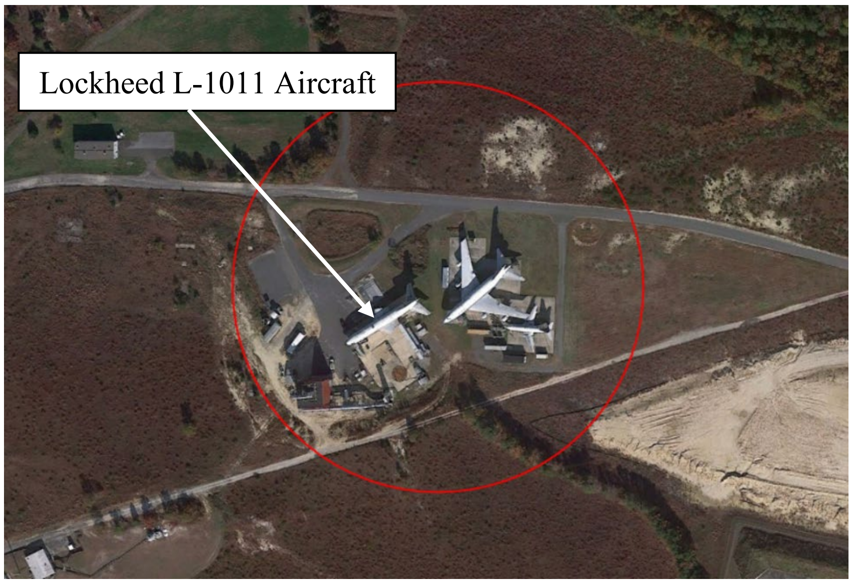

Figure 9. The ACY ARFF Test Area with UAS Orbit Flight Path (red circle)

3.2.3 Data Collection

Two types of data were recorded for subsequent analysis. These included the full-resolution payload video footage recorded directly onboard the UA to a secure digital memory card, as well as recordings of the live feed, as displayed on the GCS. Depending on the UAS platform in use, the live feed was recorded either by a screen recording program installed on the GCS display or by an external video recording device connected to the GCS. The external video recording device (shown in Figure 10) was used to record the live payload feed while using the M210 via a high-definition, multimedia-interface cable connection with the CrystalSky. This external recording device stored footage on a USB media drive at a resolution of 1080p. The live video feed was also displayed on an external monitor (shown in Figure 11), allowing for real-time verification of its capture and quality.

Figure 10. External Video Capture Device

Figure 11.External Monitor Displaying Live Video Feed

3.2.4 Data Analysis

When the test flights were complete, FAA researchers evaluated the recorded video footage and provided feedback regarding the quality of the video from each payload. Separate analyses were performed for the recordings of the live video feeds and the full-resolution visual camera footage recorded onboard the UA. These analyses were used to develop minimum performance specifications regarding video resolution and frame rate for each video type.

The distinction between the live video feeds and footage recorded onboard the UA was made for two reasons. First, both types of videos serve different purposes. The live-streamed video will be used during an ARFF response, while the recorded video will be used for post-accident/incident investigative purposes. Second, currently available UAS platforms are often unable to stream video at the full resolution of their visual camera payloads, particularly when the visual camera records video at a resolution of 4K. The visual camera payloads included in this testing recorded video at resolutions of 1080p and 4K but could only transmit live video at resolutions of 720p and 1080p.

The distinction between live-streamed and recorded footage made for visual camera footage was not made for thermal camera footage because of the lower resolutions captured by this type of camera payload. The lowest streaming resolution of any system included in this test effort (720p) was considerably greater than the highest resolution recorded thermal camera footage (640 x 512).

3.2.5 Safety and Coordination

All UAS operations were conducted in accordance with the regulations of Title 14 C.F.R. Part 107 and an FAA-approved Certificate of Waiver or Authorization (COA), which permitted the operation of UASs in the operating area at ACY, specified in Figure 3 in Section 3. This included radio communication between the RPIC and visual observers, and constant crew monitoring of the appropriate ATC frequencies. In addition, all members of the flight crew were FAA-certified RPICs experienced in the operation of UASs at airports.

In preparation for working at ACY, evaluations were completed to check for potential flight restrictions enforced by DJI. ACY is in a locked geo zone, and authorization is required to conduct operations. FAA researchers submitted credentials and unlocked the zone prior to commencing operations with the M210 and M2ED UASs.

Prior to UAS operations, the RPIC presented a safety briefing to all those present during testing, informing them of relevant federal regulations, internal safety protocols, and emergency procedures. During pre- and post-flight procedures crew members used established internal checklists to ensure safety and maintained a sterile cockpit while operating the UAS.

3.3 RESULTS AND DISCUSSION

Sections 3.3.1–3.3.2 summarize the results from Phase 1 UAS testing at ACY.

3.3.1 Visual Camera Analysis

Sections 3.3.1.1–3.3.1.2 summarize results for the live and recorded video footage, respectively.

3.3.1.1 Live Video Feeds

Figure 12 compares screenshots taken from live visual camera footage from each UAS included in Phase 1 testing. All footage was collected without zoom; therefore, any perceived difference in zoom level is a product of differences between each camera's lens and field of view (FOV).

All live visual camera feeds were found to be acceptable for ARFF live monitoring, including video transmitted at resolutions of 1080p and 720p. This was true for video that was downsized from a higher resolution, as in Figure 12(b–d), as well as video that was streamed at its native resolution, such as in Figure 12(a). Each video feed provided an adequate level of detail, allowing reviewers to locate and identify all key aspects of the scene, including the fire, aircraft, and ARFF personnel.

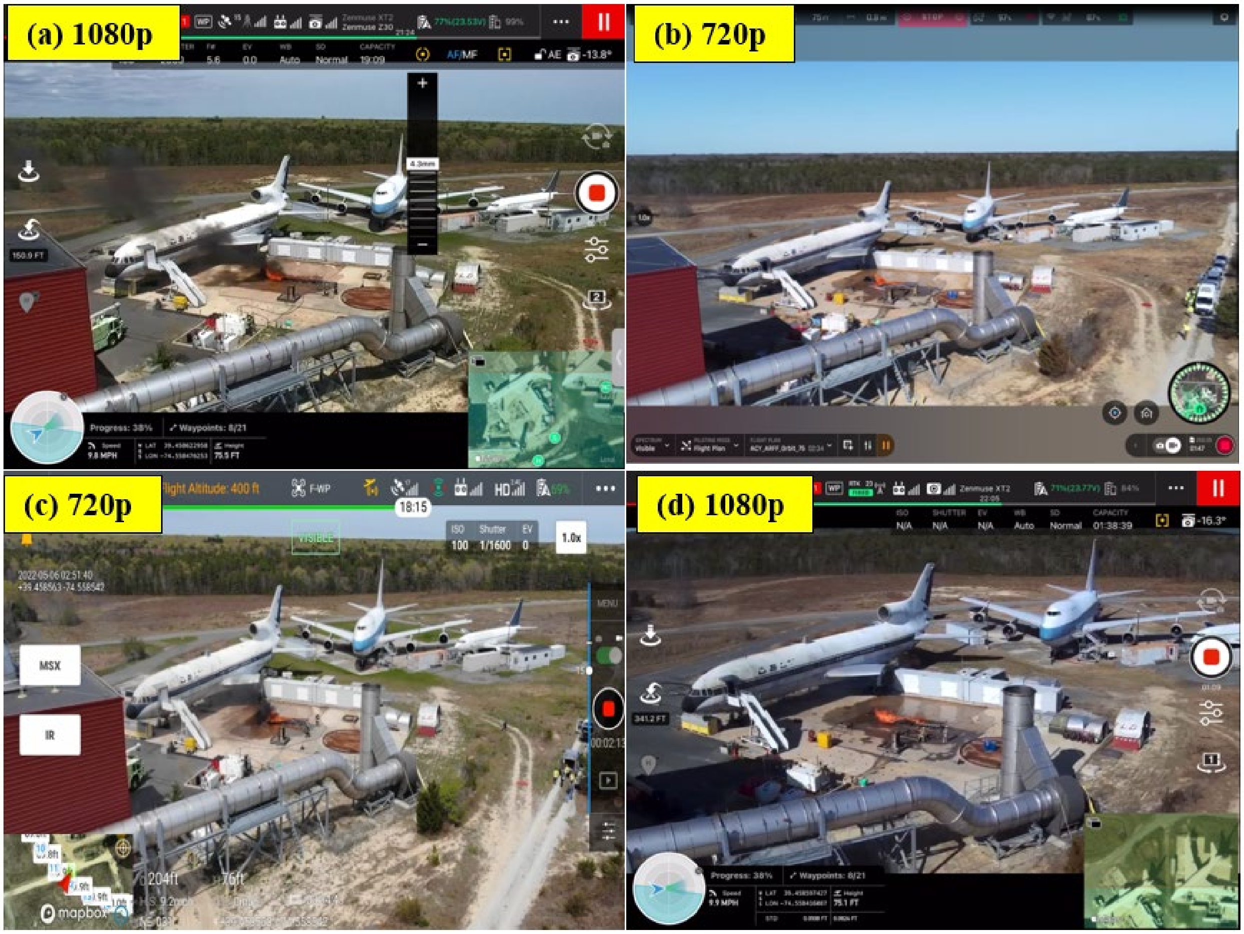

Figure 12. Comparison of Live-Streamed Visual Camera Footage: (a) M210 with Z30 Payload, (b) Parrot Anafi USA, (c) M210 with XT2 9-mm Payload, and (d) M2ED

<u>3.3.1.2 Onboard Video Recording Analysis</u>

Figure 13 compares screenshots taken from the full-resolution visual camera footage recorded onboard each UA during Phase 1 testing. All recorded visual camera payload videos, including those recorded at resolutions of 1080p and 4K, were found to be acceptable, providing a high level of detail of the scene and allowing personnel and vehicles to be easily identified. It should be noted that the XT2 19-mm and XT2 25-mm payloads were not included in the comparison because they have the same visual camera sensor as the XT2 9-mm and XT2 13-mm payloads.

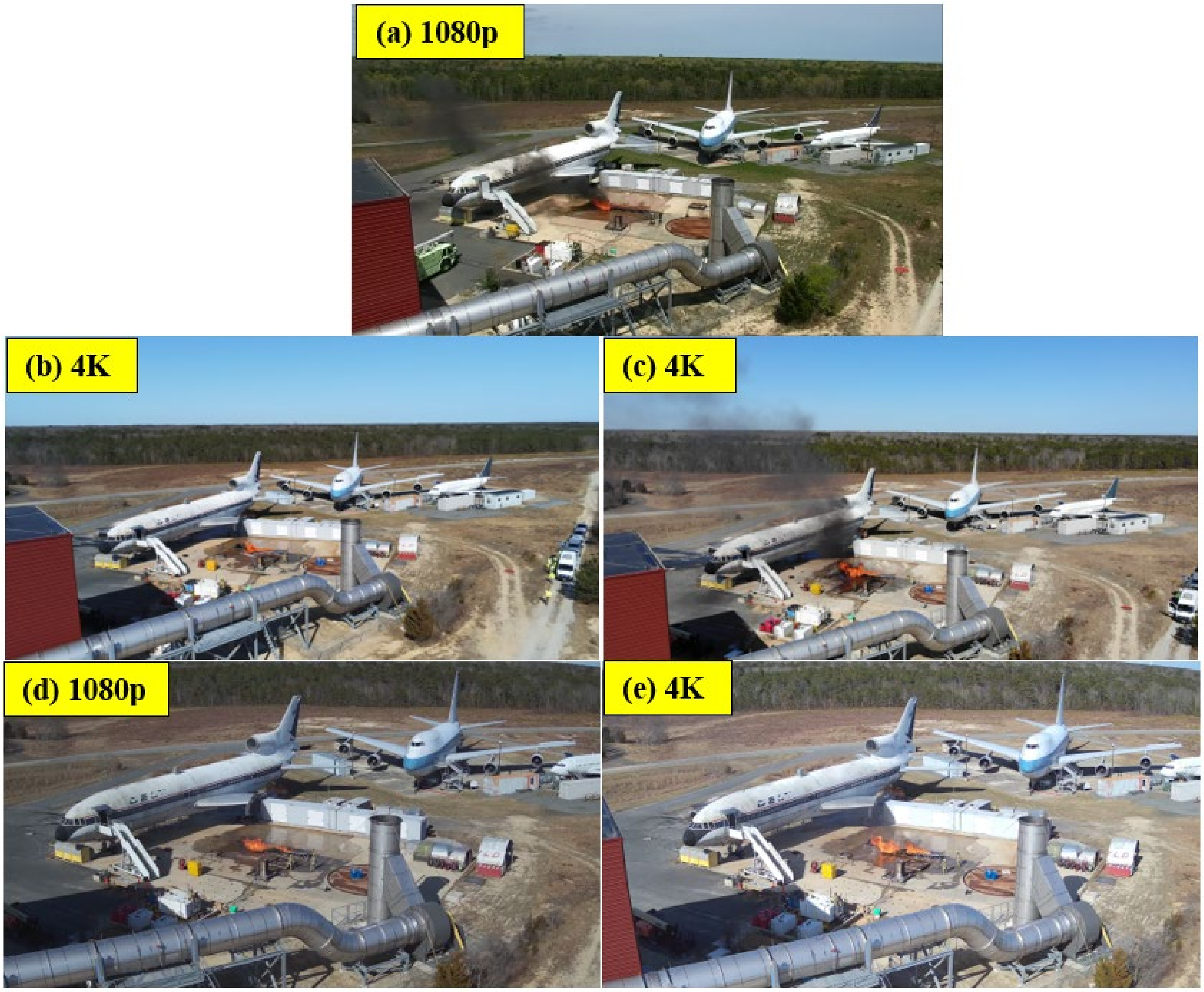

Figure 13. Comparison of Recorded Visual Camera Footage: (a) Z30, (b) Anafi Triple, (c) M2ED, (d) XT2 9mm, and (e) XT2 13mm

3.3.2 Thermal Camera Analysis

Figure 14 compares screenshots taken from recorded footage from each thermal camera payload included in Phase 1 testing. Each flight was conducted at an altitude of 75 ft AGL. No zoom was employed during these test flights, and any perceived difference in zoom between the images in Figure 12 is a product of differences between each camera's lens and FOV.

Evaluators overwhelmingly agreed that the footage from the 160 x 120 thermal camera on the M2ED, shown in Figure 14(b), was not suitable for ARFF applications. The heat signature from the fire is identifiable in footage from this thermal camera, but the ARFF responders, aircraft, and additional ground equipment could not be clearly seen.

The Parrot Anafi USA's 320 x 256 resolution thermal camera was not found to be adequate for ARFF response during Phase 1 testing; although the blended visual camera shows the location of the firefighters, the thermal camera did not produce clear thermal signatures for them. This suggests that the thermal camera cannot resolve smaller heat signatures next to a larger one, such as the fire, and that the firefighters would not be visible if the thermal image was not enhanced by the visual image.

The 640 x 512 resolution XT2 thermal cameras were able to clearly identify critical details in the scene, including distinguishing ARFF personnel close to the fire, as shown in Figure 14(d–f). The 336 x 256 resolution XT2, shown in Figure 14(c), was found to have significantly less clarity than the higher-resolution payloads, and was unable to identify the firefighters or additional details of the scene.

As shown in previous research documented in FAA Report DOT/FAA/TC-17/27, *Thermal Imaging for Aircraft Rescue and Fire Fighting Applications* (Short, Torres, & Kreckie, 2017), differences in camera filtering software can play a role in what is seen through a thermal camera. Therefore, some of the differences observed for each camera may have also been due to these filtering techniques.

Figure 14. Comparison of Recorded Thermal Camera Performance: (a) M2ED, (b) Anafi Triple, (c) XT2 9mm, (d) XT2 13mm, (e) XT2 19mm, and (f) XT2 25mm

3.4 PHASE 1 FINDINGS SUMMARY

Below are the primary findings from Phase 1 UAS testing at ACY:

1. A resolution of 720p (1280 x 720) was found to provide an acceptable level of detail for visual camera live video feeds.
2. A resolution 640 x 512 was found to be the minimum acceptable resolution for thermal cameras to outperform lower-resolution cameras and provide the clearest image. This allowed ARFF personnel to faster identify all elements of the scene including distinguishing ARFF personnel close to the fire.
3. A resolution of 1080p (1920 x 1080) was found to provide a suitable combination of image detail and file size for recorded visual camera payload videos.
4. Flying at a lower altitude (75 ft AGL) provided a greater level of detail compared to flying at a higher altitude (125 ft AGL); however, flying at the higher altitude provided a better view over the top of the aircraft.

4. PHASE 2 TESTING: WJHTC/ACY

Phase 2 of ARFF UAS testing followed a similar approach as Phase 1: collecting video utilizing various UAS platforms and camera payloads while observing a simulated accident scene at ACY. Phase 2 expanded upon the previous testing by including flights in a variety of lighting conditions, including during daylight, twilight, and night. The goal of this phase was to further develop and refine the minimum technology performance specifications and operational recommendations for UAS platforms, payloads, and GCS when assisting an ARFF response.

4.1 UAS AND PAYLOADS

Sections 4.1.1–4.1.3 describe the UAS platforms, payloads, GCSs, and additional equipment used to conduct Phase 2 testing.

4.1.1 UAS Platforms

Phase 2 UAS testing utilized the same UAS platforms that were used in Phase 1, which included the following:

- DJI M210
- DJI M2ED
- Parrot Anafi USA.

These UAS platforms are pictured in Figure 5 in Section 3.1.2. A comparison of key specifications for these UASs is presented in Table 1 in Section 3.1.2, and detailed specifications for each platform are presented in Appendix B.

Phase 2 UAS testing also used the same GCSs as Phase 1. These are the DJI Cendence controller and CrystalSky display, the DJI Smart Controller, and the Parrot Skycontroller 3 with iPad Mini display. Specifications for these GCSs are presented in Table 2 in Section 3.1.2. Photos of each GCS are presented in Figure 6 in Section 3.1.2.

4.1.2 Payloads

The following camera payloads were used to collect footage during Phase 2 UAS testing at ACY:

- DJI Zenmuse Z30 (visual camera)
- DJI Zenmuse XT2 9mm (visual and thermal camera)
- DJI Zenmuse XT2 13mm (visual and thermal camera)
- DJI M2ED Integrated Camera (visual and thermal camera)
- Parrot Anafi Triple Integrated Camera (dual visual cameras and one thermal camera)

The camera payloads included in this testing are pictured in Figure 7 in Section 3.1.3. Table 3 in Section 3.1.3 compares key specifications of each payload. Detailed specifications for each payload are presented in Appendix C.

Due to the inclusion of flights during daylight, twilight, and night, the number of potential test parameters during Phase 2 was considerably greater than in Phase 1. To increase efficiency and reduce redundancy, the XT2 19mm and XT2 25mm payloads were not included in testing because they collect thermal and visual footage with the same sensors and at the same resolutions as the XT2 13mm payload.

In addition to camera payloads, researchers also evaluated the effectiveness of two spotlight payloads when used in conjunction with camera payloads during test flights in low-light conditions. These spotlights included the Wingsland Z15 Gimbal Spotlight, compatible with the M210 UAS, and the Mavic 2 Enterprise Spotlight, compatible with the M2ED. The Wingsland spotlight has a brightness of 10,200 lumens, and the M2ED spotlight has a brightness of 2,400 lumens. These spotlight payloads are pictured below in Figure 15.

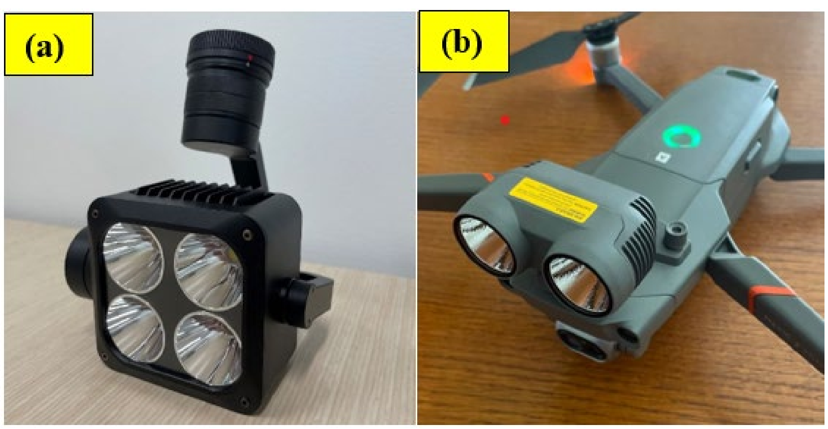

Figure 15. UAS Spotlight Payloads: (a) Wingsland Z15 and (b) DJI M2ED

4.1.3 Additional Equipment

During testing, the live streamed payload video was displayed on a 55-in. Skyvue high-brightness monitor located near the GCS. This monitor has a peak brightness of 1500 nits and was used by ACY ARFF responders to observe the footage and provide real-time feedback.

4.2 TEST METHODS AND PROCEDURES

Phase 2 testing took place at ACY at the same location as Phase 1. During Phase 2 testing, the UASs used visual and thermal camera payloads to collect video footage while observing a simulated accident scene using the L-1011 test article.

4.2.1 Site Setup

A simulated accident scene was set up similar to the one constructed during Phase 1. The scene in Phase 2 contained additional elements, including smaller fires contained in steel buckets, an additional human subject in the cockpit of the L-1011, manikins, and a heating element located near the forward landing gear. A photograph of Phase 2's simulated accident scene during twilight is shown in Figure 16. The additional bucket fires and a manikin are shown in Figure 17.

Figure 16. Phase 2 Simulated Accident Scene at Twilight

Figure 17. Manikin and Bucket Fires

4.2.2 Test Parameters

A total of 24 test flights were conducted by contracted personnel using 3 UAS platforms, 5 camera payloads, and 2 spotlight payloads during daylight (10 test flights), twilight (4 test flights), and night conditions (10 test flights). These varying lighting conditions allowed FAA researchers to conduct a more thorough test of each payload's capabilities and limitations when observing a scene in suboptimal lighting conditions. Appendix A contains a detailed list of test flights conducted during this test effort.

4.2.3 Test Procedure

UAS test flights were conducted using preprogrammed waypoint flight plans to ensure safety and consistency when evaluating the payloads. During Phase 2 testing, the aircraft stopped and hovered at two strategically selected waypoint locations on either side of the aircraft fuselage.

A Google Earth™ image depicting the hover waypoint locations is presented in Figure 18. During Phase 1, an orbit flight path was used to view the scene from all vantage points to develop operational recommendations regarding the best viewing positions and angles. Based on findings from Phase 1, it was determined that while an orbit may be of use to an IC upon arriving on scene, most likely a stationary hover at key locations would be used to increase safety and minimize the chance of flying over nonparticipants.

All daylight flights were conducted within a 90-minute period in the afternoon to minimize the effect of sun angle changes and solar loading changes on the visual and thermal camera footage. All twilight flights were conducted within a 45-minute period. This ensured an equal comparison of footage quality between payloads.

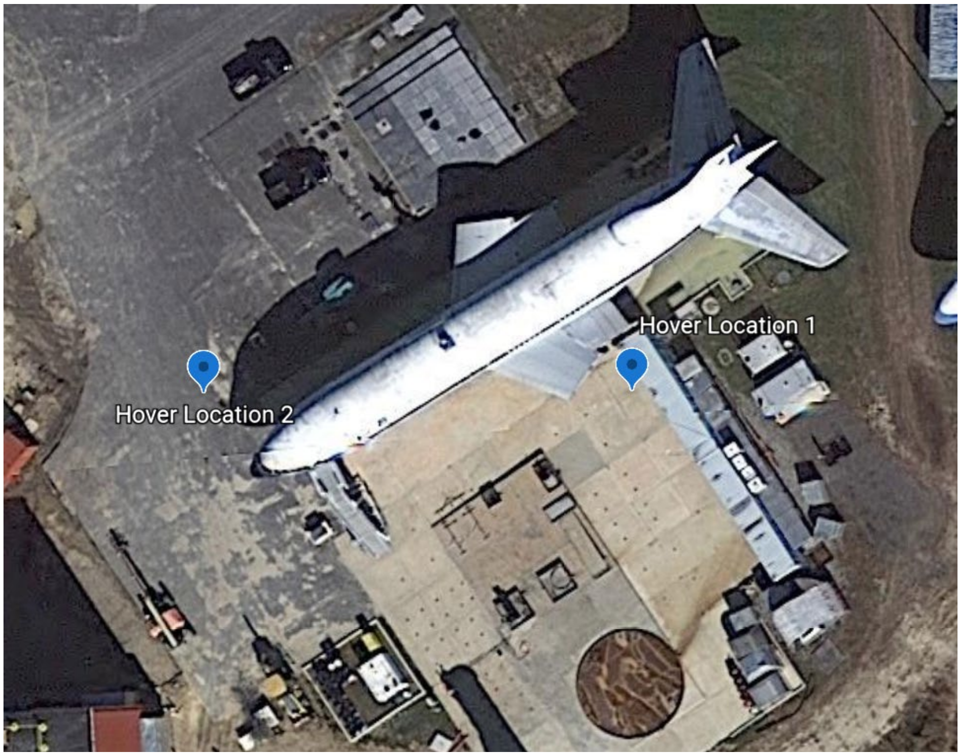

Figure 18. Phase 2 UAS Hover Locations

During testing, the UA hovered at each waypoint at an altitude of 100 ft AGL. used in Phase 1. During Phase 2 the UA was considerably closer to the aircraft and fire, so the altitude was increased from the 75-ft altitude utilized in Phase 1 due to the increased proximity to obstacles, fire, and the smoke plume. In addition to increasing safety by providing space from the aforementioned hazards, the increased altitude allowed the payload to provide a better view over the aircraft fuselage to the other side.

While hovering at each waypoint, the RPIC manipulated the payload to observe various elements of the scene, including the primary fire, smaller fires contained in steel buckets, smoke, the application of water used to combat the fire, ARFF responders, the additional human subject, manikins, and ARFF vehicles.

During testing, the live payload feed was displayed on a 55-in. Skyvue high-brightness, external monitor to allow for real-time evaluation of the footage. Throughout data collection, ACY ARFF personnel and ARFF subject matter experts viewed the live payload feed on the external monitor and provided feedback regarding the overall usefulness of UAS footage to provide enhanced situational awareness for ARFF responders. The external monitor displaying the live-streamed visual camera payload feed from the M2ED during testing is shown in Figure 19.

Figure 19. Live Payload Feed Displayed on External Monitor

4.2.4 Safety and Coordination

Phase 2 UAS testing followed all the safety and coordination procedures from Phase 1, described in Section 3.2.5; however, the addition of UAS testing in nighttime conditions required additional protocols. Title 14 C.F.R. Part 107 allows operation of UASs at night only if the RPIC received their initial certification or recurrent training after April 6, 2021. Since the RPICs during this test effort were certified prior to this date, all operations conducted more than 30 minutes after civil twilight were done so under the authorization of an FAA-approved daylight operation waiver. To comply with this waiver, all UASs operated at night were equipped with anti-collision lighting visible for greater than 3 statute miles (SMs), and all operators received specific night operations training. Prior to night operations, the RPIC gave an additional safety briefing informing all those present of the risks, safety protocols, and emergency procedures specific to night UAS operations (Small Unmanned Aircraft Systems, 2022).

4.3 RESULTS AND DISCUSSION

Sections 4.3.1–4.3.4 summarize the results from Phase 2 UAS testing at ACY.

4.3.1 Visual Camera Analysis

4.3.1.1 Live Video Feed

Following Phase 2 UAS testing, the live-streamed camera footage collected during daylight, twilight, and night was analyzed to develop minimum performance specifications regarding video resolution. It should be noted that the live-streamed video collected using the DJI M210 and XT2 13mm payload utilized a split-screen mode that simultaneously displayed both the visual and thermal camera feeds to test the usefulness of this feature and determine whether it had a negative effect on the ability to see details in either image.

Figure 20 compares screenshots taken from live-streamed footage captured during daylight testing from each UAS included in Phase 2 testing. Each screenshot was obtained from footage collected at an altitude of 100 ft AGL at hover location 2, identified in Figure 18 in Section 4.2.3.

Figure 20. Daylight Comparison of Live-Streaming Performance: (a) Parrot Anafi USA, (b) M2ED, (c) M210 with Z30 Payload, and (d) M210 with XT2 13mm Payload

Figure 21 compares screenshots taken from live-streamed footage captured during twilight from each UAS included in Phase 2 testing. Each screenshot was taken from footage collected at an altitude of 100 ft AGL at hover location 2, identified in Figure 18 in Section 4.2.3.

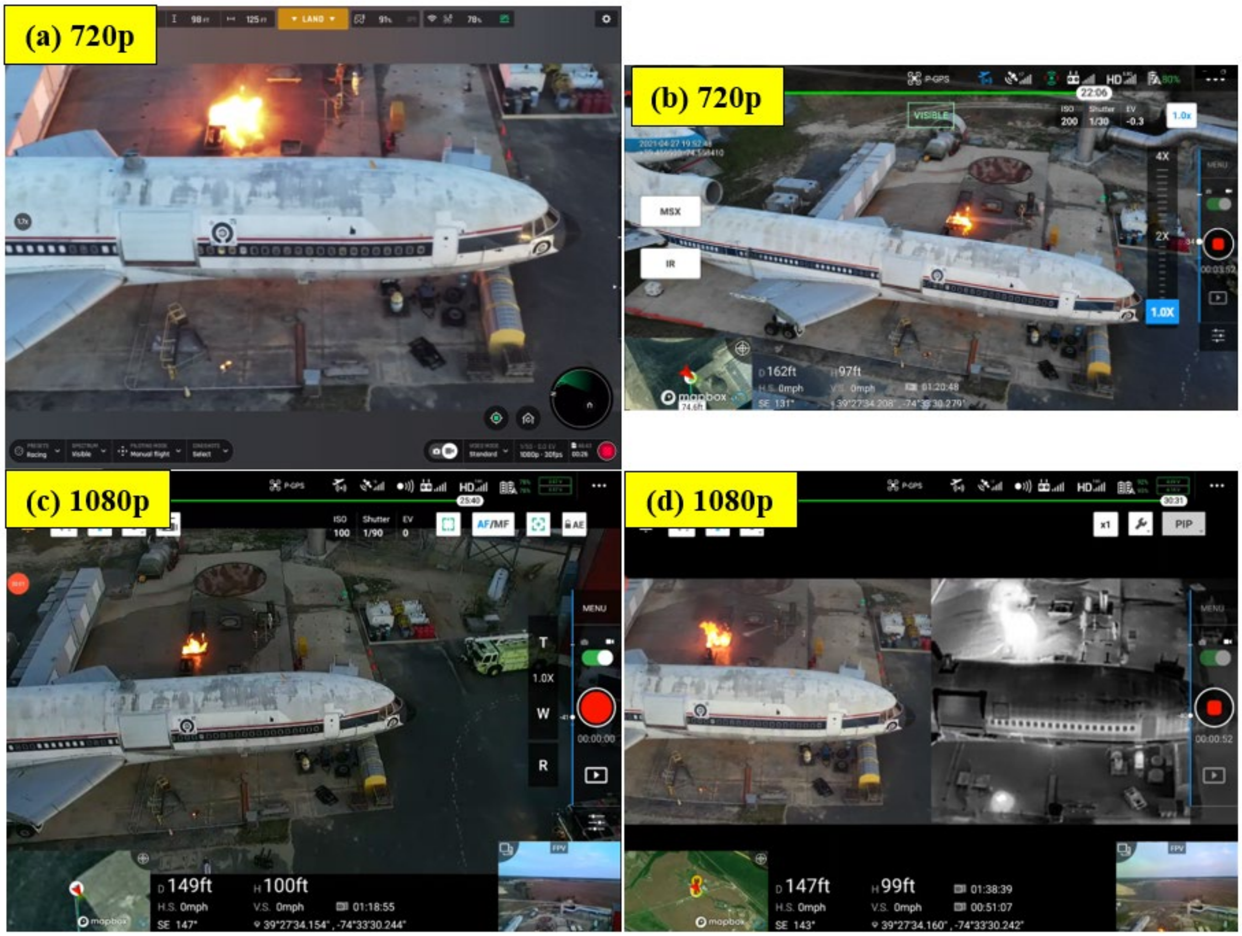

Figure 21. Twilight Comparison of Live-Streaming Performance: (a) Parrot Anafi USA, (b) DJI M2ED, (c) DJI M210 with Z30, and (d) DJI M210 with XT2 13mm

Figure 22 compares screenshots taken from live-streamed footage captured during the night from each UAS included in Phase 2 testing. Each screenshot was taken from footage collected at an altitude of 100 ft AGL at hover location 1, identified in Figure 18in Section 4.2.3.

Figure 22. Nighttime Comparison of Live-Streaming Performance: (a) Parrot Anafi USA, (b) DJI M2ED, (c) DJI M210 with Z30, and (d) DJI M210 with XT2 13mm

All live-streamed visual camera payload video in all lighting conditions was found to be acceptable for ARFF live monitoring, including video streamed at resolutions of 1080p and 720p. This confirmed findings from Phase 1 testing. Each video provided an adequate level of detail, allowing reviewers to locate and identify all key aspects of the scene, including the fire, aircraft, ARFF vehicles, and ARFF personnel.

Video captured by the DJI M210 and Z30 during daylight and twilight conditions, shown in Figures 20(c) and 21(c), appears darker than the video captured by other payloads during this testing. This is most likely because it has the smallest visual camera sensor of the payloads tested. Having a smaller sensor limits the camera’s ability to compensate for different lighting conditions. This did not have a significant effect on the usefulness of the footage for viewing the scene and identifying key aspects.

The split-screen mode utilized to display video collected using the DJI M210 and XT2 13mm did not negatively impact the footage quality of usefulness. During their assessments when viewing the live payload feeds on the external monitor, ACY ARFF personnel viewing the live video feed preferred viewing the footage in the split-screen mode, since it allowed for quick, at-a-glance viewing of both feeds without the need to switch back and forth.

4.3.1.2 Recorded Video

Figure 23 compares screenshots taken from recorded footage captured during daylight testing from each visual camera payload included in Phase 2 testing. Each screenshot was obtained from footage collected at an altitude of 100 ft AGL at hover location 2, identified in Figure 18 in Section 4.2.3.

Figure 23. Daylight Comparison of Recorded Visual Camera Footage: (a) Anafi Triple, (b) M2ED, (c) Z30, and (d) XT2 9mm

Figure 24 compares screenshots taken from recorded footage captured during twilight from each visual camera payload included in Phase 2 testing. Each screenshot was obtained from footage collected at an altitude of 100 ft AGL at hover location 2, identified in Figure 18.

Figure 24. Twilight Comparison of Recorded Visual Camera Footage: (a) Anafi Triple, (b) M2ED, (c) Z30, and (d) XT2 9mm

Figure 25 compares screenshots taken from recorded footage captured during the night from each visual camera payload included in Phase 2 testing. Each screenshot was obtained from footage collected at an altitude of 100 ft. AGL at hover location 2, identified in Figure 18.

Figure 25. Nighttime Comparison of Recorded Visual Camera Footage: (a) Anafi Triple, (b) M2ED, (c) Z30, and (d) XT2 9mm

During daylight, twilight, and nighttime conditions, all recorded visual camera footage was found to perform adequately, including video recorded at resolutions of 4K and 1080p. Each video provided an adequate level of detail, allowing reviewers to locate and identify all key aspects of the scene, including the fire, aircraft, ARFF vehicles, and ARFF personnel.

Video captured by the DJI M210 and Z30 during daylight and twilight, shown in Figures 23(c) and 24(c), appears darker than the video captured by other payloads during this testing. As mentioned in Section 4.3.1.1, this is most likely because it has the smallest visual camera sensor of the payloads tested. Having a smaller sensor limits the camera’s ability to compensate for different lighting conditions. This did not have a significant effect on the usefulness of the footage for viewing the scene and identifying key aspects.

As shown in Figure 26, the optical zoom capability of the Z30 provided a high level of detail, allowing the IC to see individuals inside the cockpit of the L-1011. ACY ARFF personnel viewing the live feed on the external monitor during testing found this feature particularly useful for enhancing the situational awareness benefits of UASs.

Figure 26. Z30 Optical Zoom Comparison: (a) 1x Zoom and (b) 30x Zoom

4.3.2 Thermal Camera Analysis

Figure 27 presents a comparison of screenshots taken from footage from each of the thermal camera payloads during night testing. The M2ED standalone thermal camera footage with a resolution of 160 x 120, shown in Figure 25(a), proved ineffective at distinguishing any thermal signatures besides the primary flame. This supported the analysis from Phase 1 that the M2ED 160 x 120 resolution thermal camera is not sufficient for use supporting ARFF live monitoring.

The Parrot Anafi USA's 320 x 256 resolution thermal camera footage is shown in Figure 25(b). This resolution was also found to be unacceptable for ARFF live monitoring. The thermal camera was able to detect heat signatures from the primary flame and bucket fires but could not clearly detect thermal signatures of the ARFF responders.

The XT2 9mm 336 x 256 resolution footage, shown in in Figure 27(c), also allowed for detection and identification of all elements of the scene, but with significantly more pixilation than the higher resolution XT2 13mm. This loss of clarity could cause a delay in the positive identification of scene elements or result in observers missing them altogether.

The XT2 13mm 640 x 512 resolution thermal camera, shown in Figure 27(d), provided significantly greater clarity that the other payloads tested, allowing for faster identification of all elements of the scene, including the primary flame, secondary bucket fire, heating element by the forward landing gear, ARFF responders, and airframe.

Figure 27. Nighttime Comparison of Recorded Thermal Camera Footage: (a) M2ED, (b) Anafi Triple, (c) XT2 9mm, and (d) XT2 13mm

4.3.3 Blended Thermal and Visual Camera Analysis

Figure 28 presents a comparison of screenshots taken from footage collected by the M2ED and Parrot Anafi USA during night testing. Both UASs have the capability of blending the thermal and visual camera feeds into a single video to improve the usefulness of the thermal camera footage. Evaluators found that the blending feature significantly increases the usefulness of the thermal camera footage but found that it does not provide an adequate substitute for a higher resolution thermal camera in low-light conditions.

Figure 28. Nighttime Comparison of Blended Footage with Thermal Camera Footage: (a) M2ED Blended, (b) Anafi Triple Blended, (c) M2ED Thermal, and (d) Anafi Triple Thermal

4.3.4 Spotlight Results

Figure 29 presents screenshots taken from recorded video from the M2ED and the XT2 13mm both with and without the aid of an additional spotlight payload. These screenshots have been cropped to focus on the area illuminated by the spotlight. The red box indicates the location of a manikin used to illustrate the spotlight's capability to assist with detecting subjects at night. Both spotlight payloads were effective in enhancing visibility in low-light situations, particularly when used to assist persons on the ground. However, using a spotlight payload in conjunction with a visual camera payload is not a substitute for a thermal camera when observing a scene in low-light conditions.

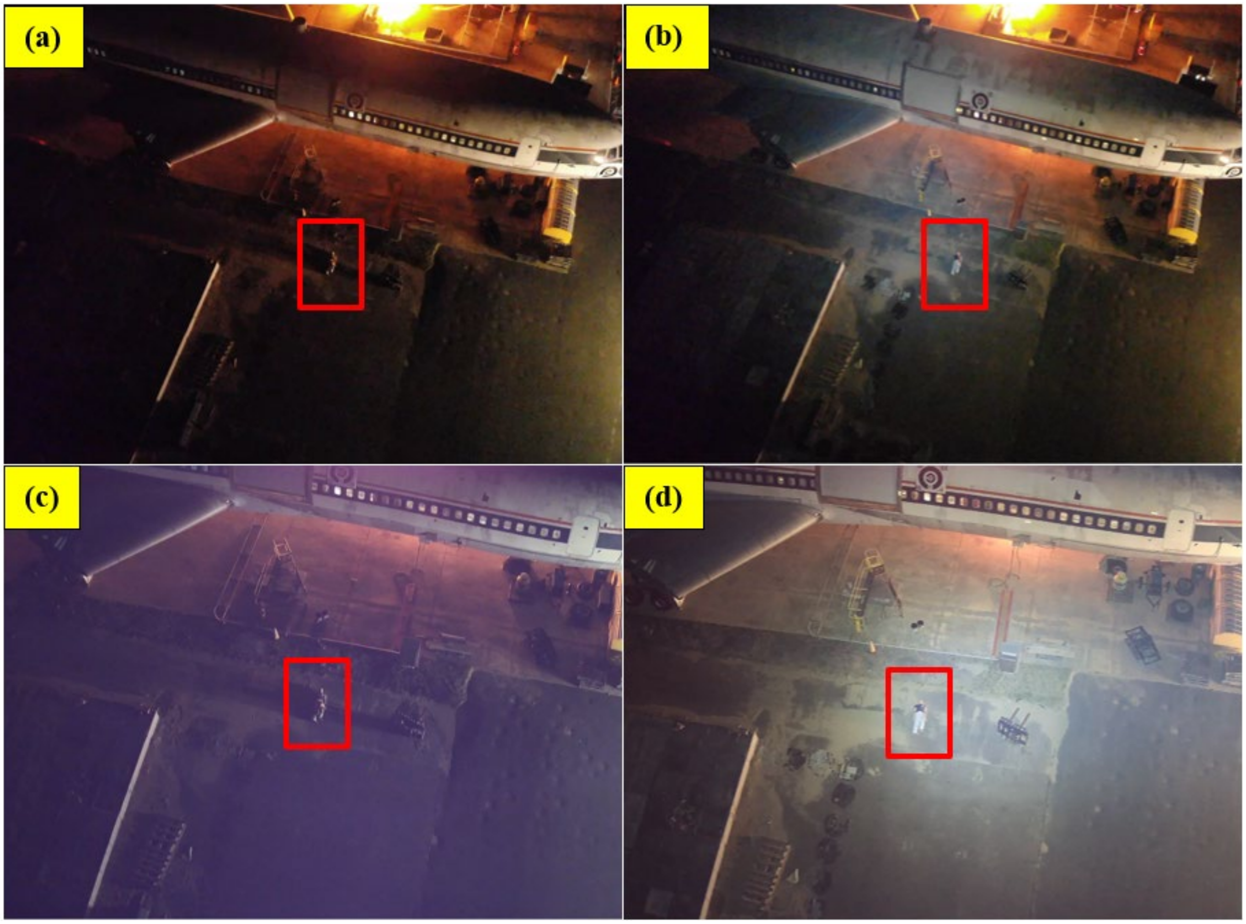

Figure 29. Comparison of Spotlight Payload Efficacy with Visual Camera (manikins are outlined in red): (a) M2ED, (b) M2ED with Spotlight, (c) XT2 13mm, and (d) XT2 13mm with Spotlight

While the spotlight payloads are not a substitute for a thermal camera payload, they can be of use to persons on the ground during an accident or incident, including ARFF responders and victims. Figure 30 shows the effect of each spotlight payload when viewed from the ground. The M210 spotlight payload was found to produce considerably more light than the M2ED spotlight, but both spotlights were found to significantly enhance visibility for personnel on the ground in low-light conditions.

Figure 30. Comparison of Spotlight Payload Efficacy from the Ground: (a) M2ED Spotlight Off, (b) M2ED Spotlight On, (c) M210 Spotlight Off, and (d) M210 Spotlight On

4.4 PHASE 2 FINDINGS SUMMARY

Below are the primary findings from Phase 2 UAS testing at ACY:

1. All visual cameras tested performed adequately in daylight, twilight, and night conditions.
2. 720p was confirmed to be an acceptable minimum resolution for live video feeds.
3. For recorded video, a resolution of 1080p was confirmed to provide the best combination of image quality and manageable file size.
4. 640 x 512 was confirmed to be the minimum acceptable resolution for thermal cameras, outperforming lower resolution thermal cameras (160 x 120, 320 x 256, and 336 x 256).
5. Payloads capable of blending visual and thermal camera feeds improved the clarity of thermal camera footage, but this capability did not provide an adequate substitute for a higher resolution thermal camera in low-light conditions.
6. Spotlight payloads provided enhanced visibility for personnel on the ground in low-light conditions, supplementing ARFF vehicle spotlights and other external lighting sources, but were not an adequate substitute for a thermal camera when observing a scene in low-light conditions.
7. Visual cameras with optical zoom capability allowed the IC to inspect small details from a distance without compromising resolution.

8. A 1500-nit monitor provided sufficient brightness for outdoor viewing in daylight conditions.

5. PHASE 3 TESTING: DFW FTRC

During Phase 3, FAA researchers conducted flights during the DFW FTRC Advanced Strategies and Tactics for Aviation Incidents class's live-fire, scenario-based exercises. These flights were intended to validate findings from Phases 1 and 2 and evaluate the benefits and limitations of using UASs to provide enhanced situational awareness to ARFF responders.

DFW is a towered airport certificated under Title 14 C.F.R. Part 139 and located in Class B airspace. A Google Earth™ image of DFW depicting the location of the FTRC is shown in Figure 31.

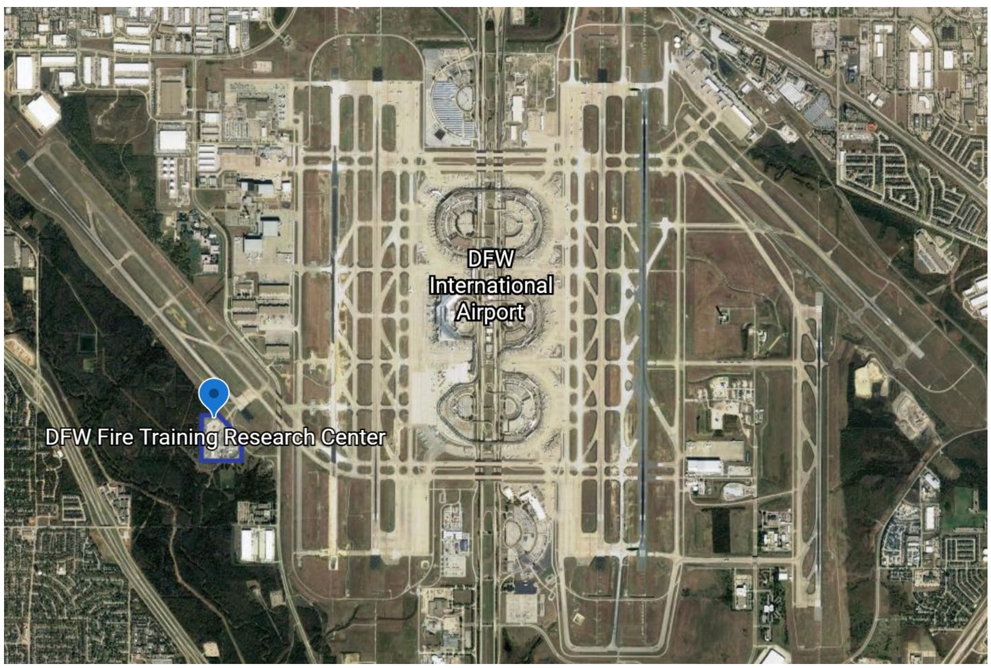

Figure 31. Facility Map for DFW

The DFW FTRC, pictured in Figure 32, is an ARFF research and training facility located along the western border of the air operations area (AOA) at DFW. The FTRC has a Boeing 737 specialized aircraft fire trainer (SAFT), as well as the nation's only Airbus A380 SAFT. In addition, the FTRC features classrooms, a three-dimensional (3D) liquid hydrocarbon fuel pit used to simulate engine fires, an off-road course for ARFF-vehicle driver training, and a structural tower for building fire training. The FAA's Airport Research and Development Branch and DFW FTRC have a Cooperative Research and Development Agreement in place to provide a mechanism for conducting ARFF technology research and development efforts at the DFW FTRC. The objectives of this agreement are to advance technology in ARFF, including the use of UASs, through shared resource investment by both the FAA and the DFW FTRC. UAS operations at DFW were performed within a designated operations area over the DFW FTRC as shown in Figure 33.

Figure 32. The DFW FTRC

Figure 33. The DFW UAS Operating Area

5.1 UAS AND PAYLOADS

Sections 5.1.1.1–5.1.1.4 describe the UAS platforms, payloads, GCSs, and additional equipment used to conduct Phase 3 testing at DFW FTRC.

5.1.1.1 UAS Platforms

The following UAS platforms were utilized during Phase 3 UAS flight testing at DFW FTRC:

- DJI M210
- Parrot Anafi USA

UAS flight testing at DFW FTRC was primarily conducted with the DJI M210, while the Parrot Anafi USA was limited to use as a backup. The M210 was the only UAS platform that could carry a thermal camera payload that met the resolution recommendations developed during testing at ACY. The Parrot Anafi USA was chosen as the backup because it met the initial visible camera specification; however, the thermal camera resolution was below the initial thermal specification. The M2ED's thermal camera was not found to be suitable for ARFF live monitoring during testing at ACY and was not included in flight testing at DFW. It was, however, included in the deployment demonstrations for students to evaluate its form factor.

The UAS platforms used in Phase 3 are shown in Figure 5 in Section 3.1.2. A comparison of key specifications for these UASs is presented in Table 1 in Section 3.1.2, and detailed specifications for each platform are presented in Appendix B.

The GCSs included during Phase 3 flight testing were the DJI Cendence controller with CrystalSky tablet and the Parrot Skycontroller 3 with iPad Mini tablet. Both GCSs were also included in the deployment demonstration tests and the DJI Smart Controller. Photographs and specifications of each GCS are presented in Section 3.1.2.

5.1.1.2 Payloads

The following camera payloads were used to capture footage during UAS testing at DFW FTRC. Payload photographs and a comparison of key specifications are presented in Section 3.1.3. Detailed specifications for each payload are presented in Appendix C.

- DJI Zenmuse XT2 13mm (Visual and thermal camera)
- DJI Zenmuse Z30 (Visual camera)
- Parrot Anafi Triple (Dual visual cameras and one thermal camera)

5.1.1.3 Video Streaming and Display Equipment

FAA researchers used the following additional equipment during Phase 3 testing: DroneSense streaming software, Dell Latitude 7220 Tablet, and Verizon MiFi® wireless hotspots. This equipment is described below.

- DroneSense streaming software

  DroneSense is a software package that allows for wireless live streaming of a payload camera feed to any device that has an internet connection. Figure 34 shows DroneSense displaying a payload feed during the DFW FTRC Advanced Strategies and Tactics for Aviation Incidents class.

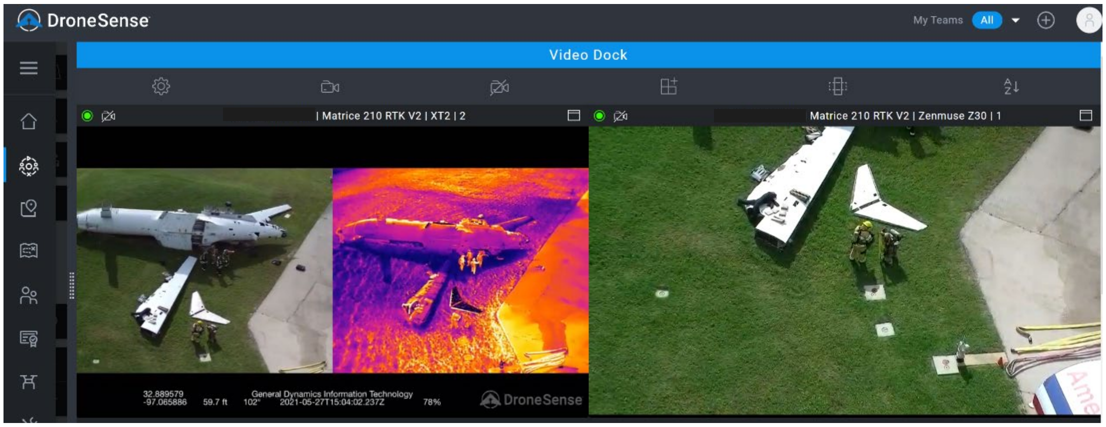

Figure 34. Screenshot of DroneSense Taken During DFW Advanced Strategies and Tactics for Aviation Incidents Class

- Dell Latitude 7220 Tablets

  Dell Latitude 7220 Rugged Tablets were used by the IC and FAA researchers to remotely view the live payload feed from the UAS during testing using the DroneSense software. This tablet is designed for commercial field use, featuring a durable enclosure and a 12-inch, 1000-nit brightness screen capable of being viewed in direct sunlight. The Dell Latitude 7220 Rugged Tablet is shown in Figure 35.

Figure 35. Dell Latitude 7220 Tablet Displaying DroneSense Software

- Verizon MiFi® wireless hotspots

  FAA researchers used Verizon MiFi® hotspots to connect the UAS and Dell tablets to DroneSense to allow for wireless streaming of the payload feed. The UAS operator had one MiFi® to upload the data feed, while the IC had the second hotspot and used it to download the feed.

5.2 TEST METHODS AND PROCEDURES

Testing was conducted during two Advanced Strategies and Tactics for Aviation Incidents classes. Each class was a 5-day event composed of 2.5 days of classroom instruction followed by 2.5 days of live-fire training exercises. During these scenarios each student took a turn as IC. Each scenario lasted approximately 30 minutes, followed by a 15-minute debrief in which students and instructors talked through the scenario and evaluated their performance. Between the two classes, a total of 23 students attended. These students came from airports of various sizes from across the country.

5.2.1 UAS Demonstrations and Evaluations

Prior to conducting flight operations, DFW FTRC staff allotted time for FAA researchers to brief the participants of the class. The purpose of this briefing was to familiarize the participants with the research program, including the UAS ARFF live-monitoring CONOPS, the testing conducted thus far, and how UASs would be implemented during the class. The parties also established a basic set of commands that the ICs could use to direct the UAS during the exercises.

Following the initial briefing, FAA researchers conducted deployment demonstrations of each UAS platform to allow the students to observe and evaluate the hardware. These demonstrations included the entire preflight procedure, including unpacking and assembling the UAS and GCS. Once the UAS was fully assembled and energized (but locked out of flight), students were given the chance to handle each controller and evaluate the GCS and interface. During these demonstrations, students provided feedback regarding various hardware considerations for each UAS platform, including portability and deployment time, and GCS screen size and brightness.

5.2.2 Test Scenarios

Contracted personnel conducted manually flown UAS operations during each scenario. A list describing each scenario including instructor notes is provided in Appendix D. Rather than using these flight operations to evaluate the technical capabilities of different UAS and payloads, the primary goal of this flight testing was to study how the UAS was being utilized and assess the value the UAS footage provided to ARFF responders. Figure 36 shows the UAS monitoring a large-scale fuel fire exercise.

Figure 36. The UAS Monitoring a Fuel Fire Exercise During DFW FTRC Advanced Strategies and Tactics for Aviation Incidents Classes

During each scenario, the student acting as IC had direct access to the UAS live payload feed via a tablet and could direct the UAS to view various elements of the scene at their discretion. After each exercise, FAA researchers recorded notes of how the UAS was used and obtained feedback from the IC. Following the completion of each class, the recorded payload footage was analyzed to develop a comprehensive understanding of specific functions the UAS could perform during the response, and the benefits they could provide to ARFF personnel. In addition, FAA researchers conducted deployment demonstrations of each UAS platform for the students and collected feedback regarding each UAS platform and GCS.

Over the course of both training classes, UASs were used during 17 of 20 scenarios. A low cloud ceiling and visibility (instrument meteorological conditions) prevented UAS operation during two scenarios, and technical difficulties prevented operation during another scenario. Flight operations took place only during daylight conditions, at altitudes up to 110 ft AGL. During each scenario, contracted personnel deployed the UAS, and the FAA researchers provided the IC with a Dell Latitude 7220 tablet mounted in their vehicle displaying the live camera feed from the UAS payloads. This live camera feed was streamed to the tablet using the DroneSense software and Verizon MiFi® Hotspots. Figure 37 shows the Dell Latitude tablet displaying a live payload feed using DroneSense while mounted in the IC vehicle.

Figure 37. Tablet Mounted in IC Vehicle Displaying Payload Feed

Each IC used the UAS differently and to varying degrees. The DFW FTRC Advanced Strategies and Tactics for Aviation Incidents Class's training curriculum extends beyond the UAS, and therefore Ics were not required to use it during the response. Only one IC chose not to use the UAS in some capacity. Some Ics preferred to have the UAS orbit the scene, searching for walking wounded or bodies thrown from the aircraft, while others instructed the UAS to remain stationary and monitor a blind spot, allowing assets to focus on a specific section of the scene. While many Ics monitored the live feed directly from the tablet, others chose to ask the RPIC to provide verbal reports over the radio to inform the IC of various elements of the response, including asset positioning, search and rescue status, or the presence of heat signatures. Following each scenario, the IC provided feedback regarding the usefulness of the UAS footage, and how this tool can be best leveraged to enhance the safety and effectiveness of the response.

5.2.3 Safety and Coordination

Phase 3 UAS testing followed all the safety and coordination procedures from Phase 1 described in Section 3.2.5. All UAS operations at DFW FTRC were conducted in accordance with the regulations of Title 14 C.F.R. Part 107 and FAA-approved airspace authorization.

5.3 RESULTS AND DISCUSSION

Sections 5.3.1–5.3.2 summarize the results from Phase 3 UAS testing at DFW FTRC.

5.3.1 Scenario-Based Test Summaries and Results

Using feedback from the ICs as a starting point, FAA researchers analyzed the recorded payload footage to identify the benefits UASs provided during each response. Sections 5.3.1.1–5.3.1.5 provide analysis of each type of incident presented during the classes, including a false alarm, an engine fire, a cabin/engine fire, an aircraft accident on the airfield, an aircraft accident into a structure, and a fuel spill fire.

5.3.1.1 Scenario Type 1: False Alarm

During this scenario, firefighters responded to a call reporting light smoke coming from the aft portion of a Boeing 737. While unknown to firefighters at first, there was no fire during this exercise and no victims. While no fire was present during this scenario, the UAS still provided the IC the benefit of enhanced and simultaneous visibility on both sides of the aircraft.

This scenario represents the most common ARFF response at an airport. Most aviation emergency responses are precautionary or investigative rather than scenarios involving actual crashes or fires. The approach that an IC takes for this type of call can range from sending in an interior team with a thermal camera and a fire extinguisher, to instructing ARFF crews to bring firefighting handlines into the aircraft.

Upon arriving at the scene, the IC conducted an initial 360° assessment from his vehicle by driving around the aircraft before parking approximately mid-ship on the port side. Figure 38 shows the IC's view of the incident from this position. Figure 39 shows the view of the incident from the UAS, including the position of the IC.

Figure 38. View of Incident from IC Position

Figure 39. View of Incident from UAS

Firefighters made entry from both sides of the aircraft through the forward doors (L1 and R1). The firefighters entering through L1 brought in a charged handline. During this scenario the UAS provided a view of the entire right side of the aircraft as well as the top of the fuselage, which the IC did not have a visual of from his position. The view from the UAS, shown in Figure 40, allowed the IC to monitor the entire scene, including the firefighters entering the aircraft through the R1 door, while remaining stationary and mitigating the potential risk that comes with driving around a developing incident scene at an airport.

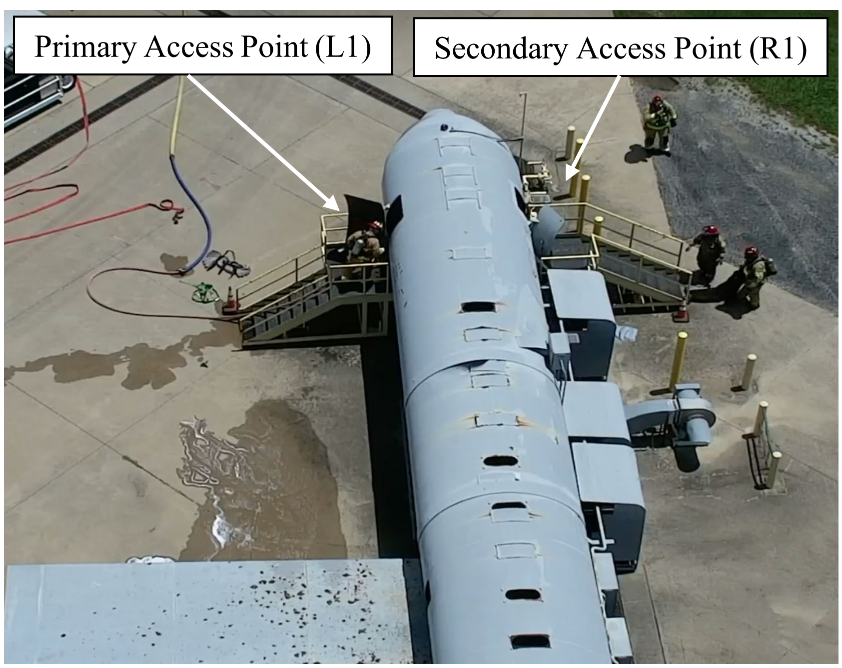

Figure 40. View of Aircraft Access Points from UAS

5.3.1.2 Scenario Type 2: Engine and Cabin Fires

During this scenario, firefighters responded to a call involving a Boeing 737 experiencing fire and heavy smoke in three areas: the left main gear, #1 engine, and passenger cabin. The fire in the #1 engine is shown in Figure 41. During this scenario, the UAS provided several benefits to the IC, including enhanced monitoring of turret streams, mitigation of the loss of visibility due to smoke, and persistent monitoring of the opposite side of the aircraft.

Figure 41. Scenario 2 Incident Scene upon Arrival

Upon arrival at the scene, the first action taken was to extinguish the engine fire using the primary turret on an ARFF vehicle. From the position of the turret operator and the IC, the dispersed stream of water blocked their view of the effectiveness of the firefighting stream. From the position of the UAS, shown in Figure 42, the view was unobstructed, enhancing the IC's ability to monitor the turret stream, confirm it was hitting its mark, and subsequently confirm the fire was extinguished.

Figure 42. View of Turret Stream from UAS

Once the exterior fires were under control, an interior fire attack team began stretching handlines and opening doors. As soon as the doors were opened, ventilation began. As shown in Figure 43, during ventilation the IC's visibility of the scene from ground level was severely limited due to the smoke. The view from the UAS, shown in Figure 44, significantly improved the IC's situational awareness of the scene.

Figure 43. View of Scenario from IC Position

Figure 44. View of Scenario from UAS

During this scenario, the IC was positioned on the port side of the aircraft, where the engine fire and entrances were located. The view from the IC's position is shown in Figure 45. During the initial 360° assessment of the scene and just prior to firefighters making entry into the aircraft, the IC had ARFF resources position themselves so they could briefly check the starboard side of the 737.

Figure 45. View of Incident from IC Position

As part of the ventilation strategy, both starboard doors (R1 and R2) were opened. During a real-world incident, if the escape slides were not disarmed by the firefighters they would have inflated. These deployed slides would serve as emergency exits for firefighters or maintenance workers still on board. As shown in Figure 46, the UAS allowed the IC to clearly monitor both doors and slides. In a typical ARFF response, the IC would need to dedicate resources to monitor this side of the aircraft; however, during the remainder of the scenario, the starboard side of the aircraft was only monitored by the UAS. This served as a force multiplier, allowing the IC to utilize all their resources for firefighting and ventilation.

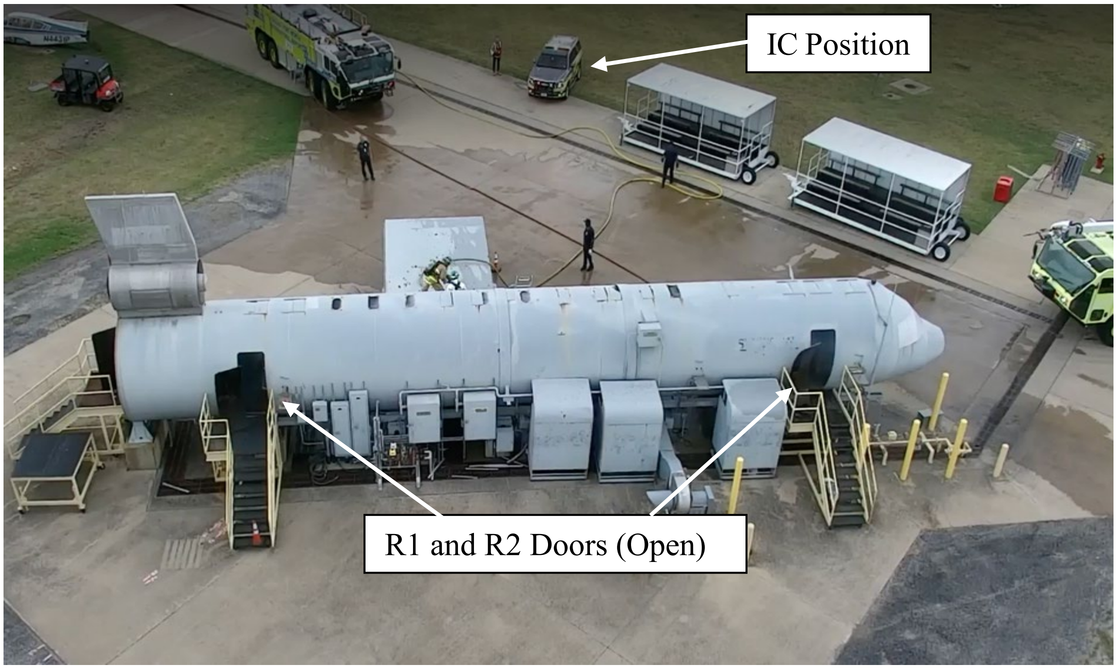

Figure 46. View of Incident from UAS

5.3.1.3 Scenario Type 3: Aircraft Accident

In this scenario, firefighters responded to a crash involving a Gulfstream that aborted takeoff, coming to rest on its side near the crest of a hill off the departure end of the runway. The aircraft broke up during the crash, leaving a debris field along the hill and ejecting several passengers. Heavy smoke was coming from the interior of the aircraft, and several victims were trapped inside. During this scenario, the UAS benefited ARFF responders by enhancing the initial size-up of the scene, enhancing the IC's ability to monitor agent application to the fuel spill, expediting the search for victims, and enhancing the monitoring of crew member exertion using the payload's zoom capability.

This scenario was enacted in both class sessions, with slight differences to highlight the varying benefits of UASs. In the first session, water was used to simulate a fuel spill on the end of the runway surface, and during the second session the scene included additional victims ejected from the aircraft.

Upon arriving at the scene during the first session, the IC was presented with a particularly complex environment. The combination of terrain, a debris field, ejected passengers, and a fuel spill prevented the IC from performing a 360° assessment from their ground vehicle.

The IC needed to position the command vehicle in a position that was:

- out of the way of firefighting operations,

- upwind of smoke,
- provided the best vantage point of the operation, and
- remained clear of the simulated fuel spill area.

Having accounted for each of these considerations, the IC had to select a position that provided a limited field of vision, requiring them to depend on radio reports from others positioned around the scene. The IC's position relative to the aircraft is shown in Figure 47, and the IC's view of the incident is shown in Figure 48.

Figure 47. Overview of Gulfstream Scenario

Figure 48. View of Incident from IC Position

The UAS provided an opportunity for the IC to gain situational awareness of the entire accident scene, something they were unable to achieve from their vehicle's position. The UAS is immediately able to inform the IC on the size of the fuel spill and debris field and report the location of two victims ejected from the aircraft, who were outside the field of vision of the IC or arriving ARFF vehicles. The smoke coming from the open L1 door indicated an interior fire, and the direction the smoke was traveling identified the wind direction. The view of the scene from the UAS and these initial observations are shown in Figure 49.

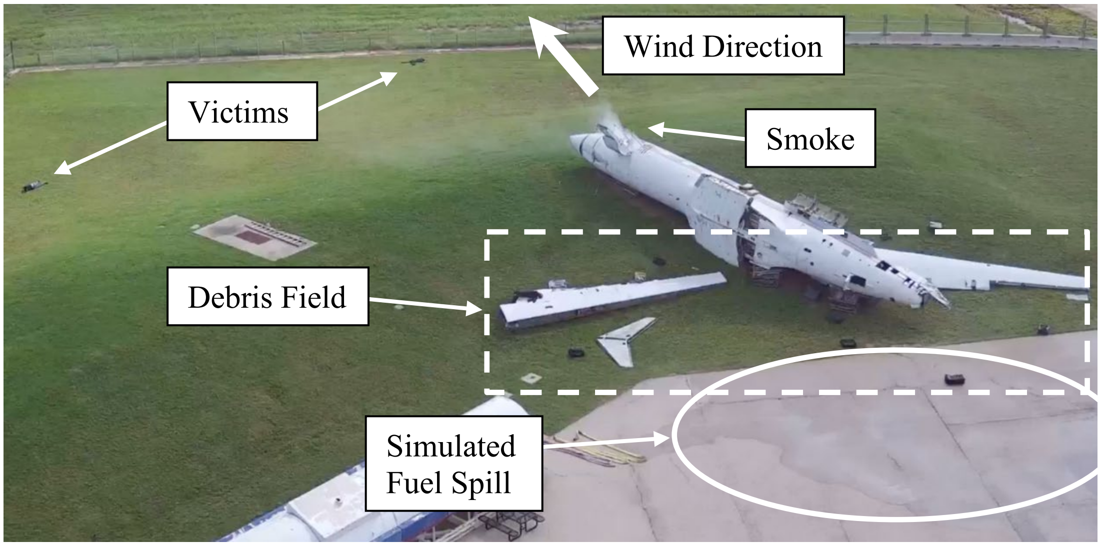

Figure 49. Initial Assessment from UAS

The first ARFF vehicle to arrive at the scene applied water (used to simulate foam agent) to the simulated pooled fuel underneath and adjacent to the fuselage to reduce the likelihood of ignition. The UAS allowed the IC to monitor the application of water on the fuel spill, ensuring thorough coverage while also increasing efficiency and conserving agent. The UAS view of this simulated foam application is shown in Figure 50.

Figure 50. View of Water Application on Simulated Fuel Spill from the UAS

During the exercise, the instructors at the DFW FTRC placed a total of seven manikins in the surrounding area, most of which were on the opposite side of the hill by the aircraft. From the IC's position, only a single manikin could be seen. The UAS identified all seven within seconds of becoming airborne, allowing the IC to dedicate the proper number of resources to rescue these ejected passengers. This process was faster than conducting a similar search on foot. The view from the UAS identifying the victims is shown in Figure 51.

Figure 51. View of Victims Ejected from Aircraft from the UAS

During this scenario, the IC made multiple requests for the UAS to zoom-in on specific aspects of the scene. By identifying areas with no visible casualties, the IC could focus their resources on other tasks. The zoom capability enhanced the efficiency of the operation by allowing the IC to see the level of effort of teams engaged in various tasks. This helped in decision-making regarding the need for additional resources. It allowed for a rotation of rescuers for rehabilitation earlier than planned, based on a first-hand view of an exceedingly difficult rescue. An example of a zoomed-in view of a rescue in progress is shown in Figure 52.

Figure 52. Zoomed-In View of ARFF Responders Rescuing a Victim

5.3.1.4 Scenario Type 4: Aircraft Accident and Structural Fire

During this scenario, firefighters responded to a report of a small, single-engine aircraft that crashed into a warehouse on the airport property. There were three people onboard the aircraft when it crashed, and an additional three (unknown to the firefighters) workers in the building. During this scenario, the UAS benefited the response by providing an enhanced initial assessment of the scene, and by using its thermal camera payload to identify hot spots and potential ventilation points on the building.

Upon reaching the scene, firefighters found the fuselage inside on the ground floor of the building. The first floor was engulfed in fire, and the second floor was full of dense smoke. The crashed aircraft inside the burning building is shown in Figure 53.

Figure 53. Firefighters Responding to Crashed Aircraft and Fire in Warehouse

The UAS provided a great deal of information to ICs during the initial assessment. During an ARFF incident, the IC will position themselves out of the way of the ongoing operation in a location that provides a good vantage point of the incident. During the initial period of a major event, the IC could be the only person at the command post allowing them to relocate to get a better look at part of the operation. Later in the event, there might be multiple people at the command post, which generally will restrict further movement. Without the ability to reposition, the IC's situational awareness can be hindered. With the UAS providing an overview, moving the IC around is no longer necessary. From a single hover position in this example scenario, the IC can see the accident site, all their assets, and even small details such as the water supply line being charged to the pumper and victims that have been removed. Figure 54 shows a view of the incident from the UAS, as well as the various information provided that could benefit an IC.

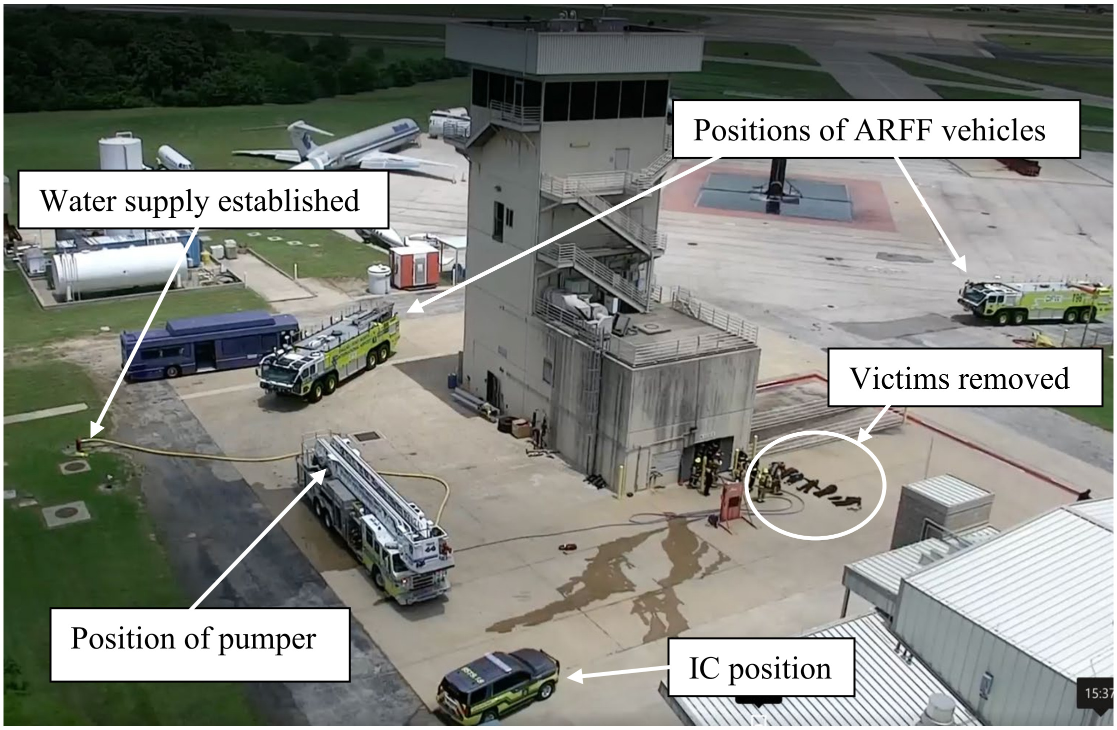

Figure 54. Initial Assessment Information Provided by the UAS

While the UAS could not show what was inside the building, it was able to provide reports on heat signatures on the exterior. Using a thermal sensor, the UAS was able to report there were no heat signatures on the upper floors of the building. Upon arrival, the UAS showed a metal rollup door on the side of the warehouse with a heat signature near the top. As shown in Figure 55, the size and intensity of the heat signature grew in 7 minutes. Using this information, the IC identified this as a potential ventilation location.

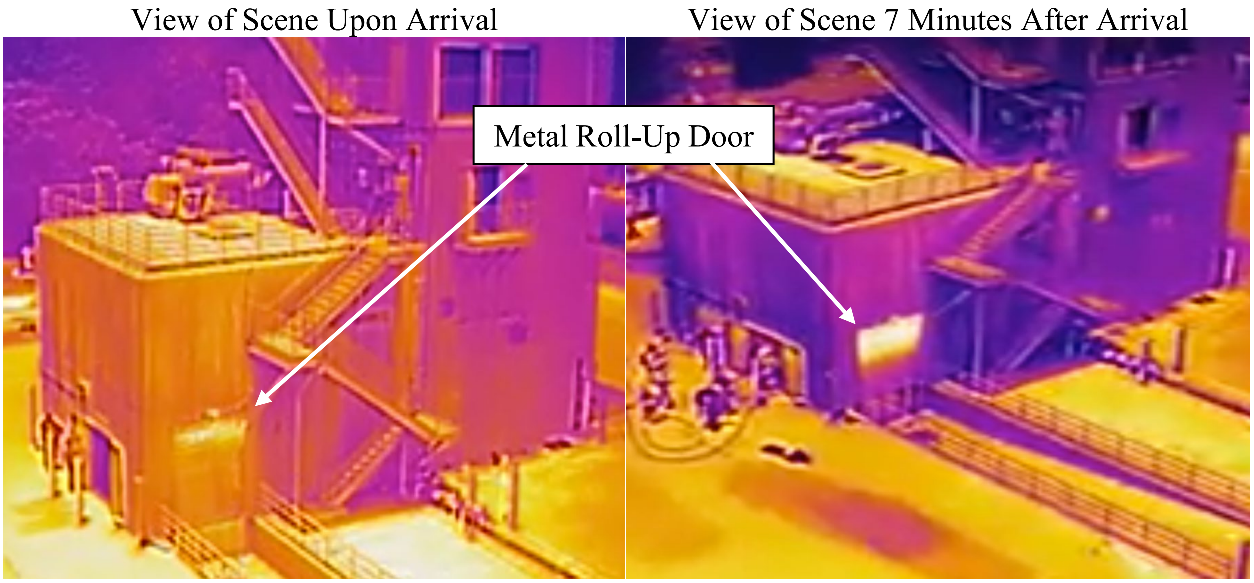

Figure 55. Intensifying Heat Signature on Warehouse Door Detected by UAS
(XT2 13mm 640 x 512)

5.3.1.5 Scenario Type 5: Fuel Spill and Cabin Fires

During this scenario, firefighters responded to a reported fuel spill involving a Boeing 777. Shortly before arriving on scene, the fire ignited into a large blaze alongside and underneath the entire starboard side of the aircraft, which spread to the interior main cabin. There were five victims onboard the aircraft. During this scenario, the UAS benefited the response by enhancing the IC's ability to monitor turret streams by continuously orbiting the scene to observe multiple activities occurring simultaneously, and by detecting and monitoring hot spots on the aircraft using its thermal camera payload.

The first arriving ARFF vehicle immediately began fighting the fuel fire with its primary turret. The footage provided to the IC by the UAS was used to evaluate the turret technique, pattern, and range of the agent being applied. This information gives the IC the information they need to help the turret operator extinguish the fire as quickly as possible. A screenshot of this footage is provided in Figure 56.

Figure 56. View of Turret Stream from the UAS

While the top priority when fighting a large-scale fuel fire with a turret is rapid extinguishment, the second priority is agent conservation. The UAS benefits this goal as well by ensuring accurate deployment of agent and by giving the IC an ideal vantage point to determine when the extinguishment is complete so they can call for a halt to discharge. This may allow the ARFF vehicle to stay in position longer before having to be resupplied with additional foam and water.

After extinguishing the exterior fuel fire, ARFF crews focused on preparing for interior firefighting and search and rescue. Firefighters made entry using stairs at the L1 door, while an ARFF vehicle used its HRET to pierce the hull on the starboard side to spray agent into the interior. Once firefighters made entry, they began opening doors on both sides of the aircraft to aid with ventilation. The IC was positioned off the nose of the aircraft, which provided a limited view of these activities. To compensate for this, the IC instructed the UAS to continuously orbit the aircraft, which provided a wider view of a multitude of activities. Typically, the IC must closely monitor the interior firefighting progress through radio reports, including the status of the ventilation strategy in progress and the overall condition of the aircraft.. The ability to monitor and record all these activities and conditions utilizing UAS were force multipliers for the IC. The UAS view of exterior firefighting activities is shown in Figure 57.

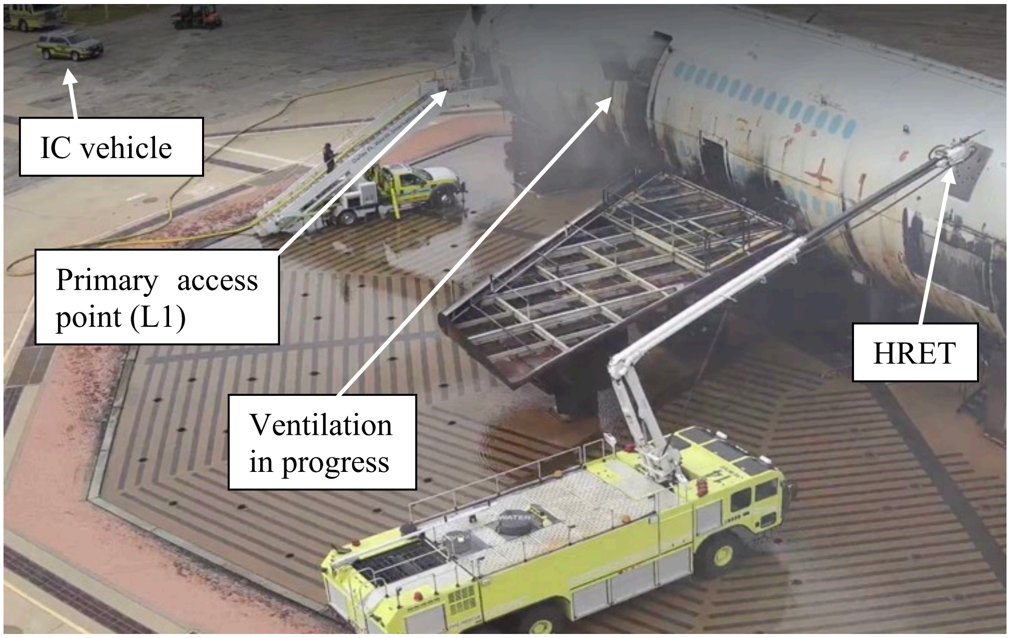

Figure 57. View of ARFF Response from the UAS

During its orbits, the UAS also provided the IC with thermal video of the aircraft. These images allowed the IC to monitor the level of heat inside the aircraft, as well as the location and size of the fire. Without the UAS, the IC would have to rely on a thermal camera mounted on an ARFF vehicle or handheld thermal cameras firefighters can carry as they walk around the aircraft. The view from the UAS thermal camera is faster, better quality, and can be directed from any vantage point.

As shown in Figure 58, the seat of the fire appeared to be on the port side of the aircraft just above the wing root. The rising heat was indicated by the yellow portions on top of the fuselage.

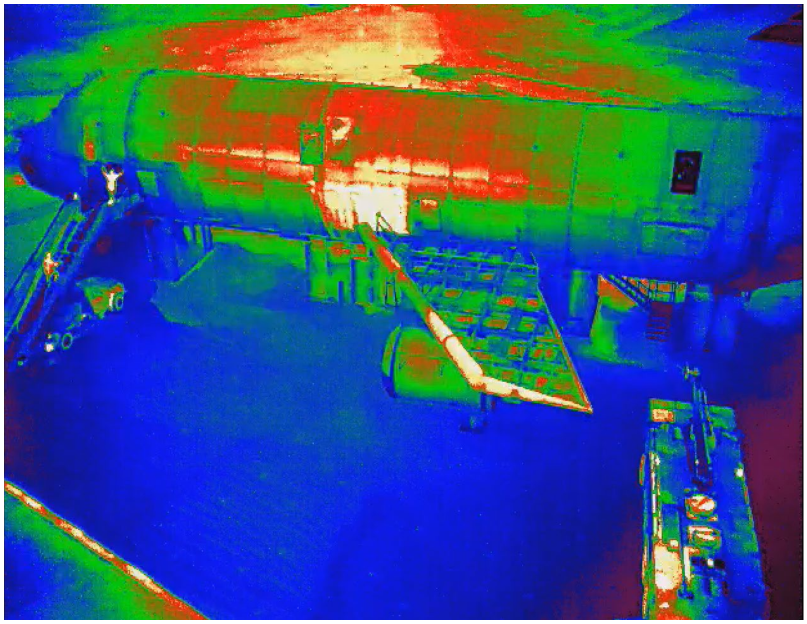

Figure 58. Thermal Image of the Port Side of the Aircraft (XT2 13mm 640 x 512)

As shown in Figure 59, the heat from the fire on the port side of the aircraft transmitted across to the starboard side. Using the UAS, the IC was able to monitor all sides of the aircraft.

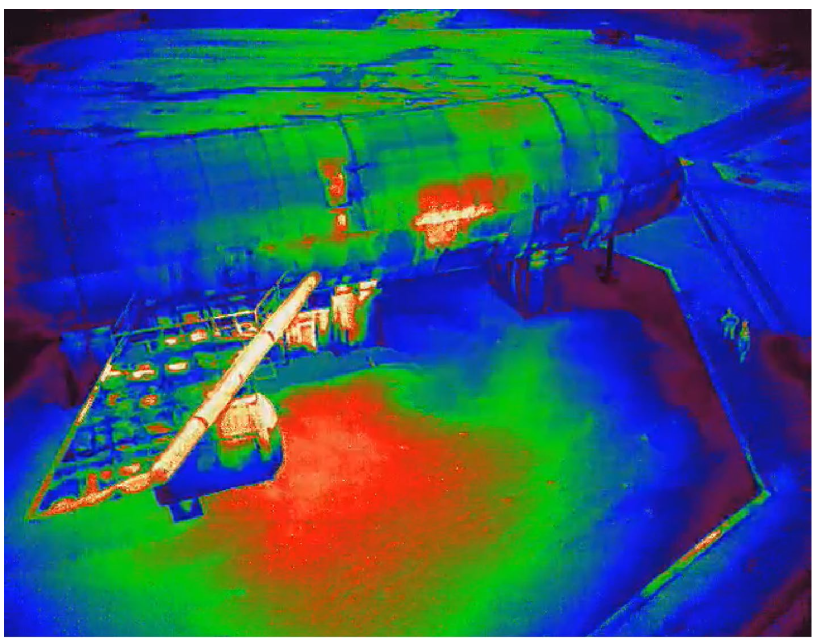

Figure 59. Thermal Image of the Starboard Side of the Aircraft (XT2 13mm 640 x 512)

5.3.2 UAS Platform Evaluations

During the deployment demonstrations, students evaluated each UAS platform regarding their ease of deployment and portability, GCS screen size and brightness, and overall practicality for supporting ARFF live monitoring. Following the demonstrations, participants were given the option to provide comments regarding each UAS. Sections 5.3.2.1–5.3.2.3 summarize the feedback received during these evaluations.

5.3.2.1 Ease of Deployment/Portability

With regard to ease of deployment and portability, participants found the DJI M2ED to be the simplest and the quickest to deploy. This can be attributed to its fold-out airframe that requires no assembly prior to flight. In addition, the M2ED used the DJI Smart Controller, which integrates the GCS screen and controller into a single unit, negating the need for assembly. When asked for comments regarding the M2ED, participants responded with:

- “I liked the simplicity.”
- “Easiest use and deployment of the units demonstrated.”
- “I liked the one-piece setup.”
- “Ease of deployment was very quick and case is easy to carry and [is] compact.”

Participants also found the Parrot Anafi USA to be capable of rapid deployment due to its fold-out airframe that does not require any assembly prior to flight. However, they found its deployment to be more complicated than the M2ED due to the need to connect the iPad used for the GCS screen to the Parrot Skycontroller. Participants provided the following comments regarding the deployment of the Anafi USA:

- “The extra iPad needed for the screen can add time for deployment. Just another piece of equipment needed to be turned on and connected.”
- “Too many pieces.”
- “The controller appeared fragile comparatively and was the cumbersome item of setup.”

Participants found the DJI M210 took significantly longer than the other systems to deploy, due to the need to assemble the airframe and GCS prior to launch. This process included attaching the landing gear, propellers, and payload, and connecting the CrystalSky GCS display to the DJI Cendence controller.

- “Drone took longer to deploy because of its size in comparison to the others. Portability is good but case can be more cumbersome [than the other UAS platforms demonstrated].”
- “Too long for setup.”
- Complete setup [time] of 5 minutes [is] too long for being effective in initial fire attack with ARFF trucks.”
- “This would require a dedicated person on staff.”
- “User would need to be well practiced to be efficient in setup.”
- “I work at a small department and would not have additional personnel to setup the drone when arriving on scene.”

- “During a large scale incident I see this being a problem to get up in the air in a timely manner. Lots of parts to assemble.”
- “Would give excellent rating with a larger case with drone already assembled and ready to launch with minimal assembly.”
- “Seems straightforward and pretty easy to deploy.”

5.3.2.2 GCS Screen Size/Brightness

Participants generally deemed all GCS screens evaluated to be satisfactory for viewing the live payload feed. The DJI CrystalSky was the most preferred display due to its size and brightness.

The DJI M210 received the following comments regarding its GCS screen size and brightness:

- “[The screen is] very clear.”
- “Clear split screen, good optics.”

The DJI M2ED was also received positively due to its bright screen, but several participants expressed concern regarding its smaller screen size relative to the other UAS platforms demonstrated. The comments received included the following:

- “Clear image and seemed like a better controller [than the other UAS demonstrated].”
- “[It would be] nice to plug the controller into a bigger screen.”
- “[The] Screen [is] small [and] not as clear as [the] others.”

While the majority of participants found the Parrot Anafi USA GCS to be satisfactory, it received considerably more negative feedback regarding its screen brightness than the other UASs. Comments received regarding the Parrot Anafi USA regarding its GCS included:

- “Could use [a] bigger [and] brighter screen.”
- “Not as clear image.”

5.3.2.3 Overall Ratings

The overwhelming majority of participants found each UAS to be satisfactory for use supporting ARFF live monitoring. Despite its longer deployment, the M210 received the most positive feedback due its GCS screen, its capability to view both the visual and thermal camera payload feeds simultaneously in split-screen mode, and its interchangeable payloads. Participants provided the following comments regarding the M210:

- “Split screen essential.”
- “[The] ability to add [multiple] payload[s] and [a] zoom lens is a plus. [Its] resolution [and] abilities [receive] positive marks.”
- “Cannot wait to see it in action.”
- “For the product and [its] capabilities, setup and portability are not bad at all. The benefits definitely outweigh the cons.”
- “In the application of [providing an] overall crash scene visual it would work great.”

- “Great drone.”
- “A super beneficial piece of equipment.”

The M2ED also received mostly positive feedback from participants due primarily to its ease of use, quick deployment, and portability. The comments received regarding the overall performance of the M2ED during the demonstration include:

- “I would be most likely to use this one.”
- “Overall, I thought this drone was [the] most effective and efficient.”

While most found it to be satisfactory for ARFF live monitoring, the Parrot Anafi USA received the most critical feedback from class participants during the demonstration. Participants expressed concerns regarding its durability and the inability to view the thermal and visual payloads separately in a split-screen mode. The Parrot Anafi USA received the following comments during the demonstration:

- “[The] all-in-one camera and inability to add payload options puts this item back a step.”
- “I would not use this one.”
- “Compared to [the] others [I] would not purchase.”
- “[The] controller appeared fragile.”

5.4 PHASE 3 FINDINGS

Following are the primary findings from Phase 3 UAS testing at DFW FTRC:

1. UASs provided a significant situational awareness benefit to ICs in a variety of ARFF response scenarios.
2. sUASs provided the most benefit for complex scenarios requiring a larger area to be monitored.
3. The primary uses for UASs in these scenarios included performing initial 360° assessments of incidents, detecting hot spots, searching for victims, and monitoring areas outside the view of the IC for situational awareness purposes.
4. Optimal UAS positioning depended on the incident—the UAS was positioned to avoid smoke plume, while keeping as much of the incident in a single frame as possible.
5. Participants validated previous visual- and thermal-camera payload resolution recommendations.
6. Evaluators preferred the larger (7-inch), brighter GCS monitor of the M210.
7. Evaluators preferred the portability and ease of deployment of smaller UAS platforms that are compact in size and required minimal assembly.
8. The DroneSense video streaming solution performed satisfactorily overall, but experienced connectivity issues at times during testing, indicating the need for a more robust wireless network connection. Live streaming the live payload feed to a device other than the GCS is dependent on the quality of the wireless connection. This could be an issue in a complex radio frequency (RF) environment such as an airport, where many users are communicating over wireless networks. During testing at DFW, this connection experienced periods of

disruption that prevented the IC from viewing the video. Under these circumstances the IC had to rely on traditional methods of viewing the scene, or radio reports from the RPIC.

6. SUMMARY

Sections 6.1–6.3 summarize the findings regarding the benefits and limitations of UASs for ARFF live monitoring, recommended performance specifications, and additional technical and operational considerations.

6.1 BENEFITS AND LIMITATIONS

Sections 6.1.1 and 6.1.2 summarize benefits and limitations of deploying UASs for ARFF response.

6.1.1 Benefits

UASs were found to provide a significant situational awareness benefit to ICs in a variety of ARFF response scenarios. UASs provided the most benefit for complex scenarios requiring a larger area to be monitored. The primary uses for UASs in these scenarios included performing an initial assessment, detecting aircraft heat signatures/hot spots, searching for victims, monitoring agent application, and monitoring areas outside the view of the IC for situational awareness purposes.

- UASs benefited the ARFF response by allowing for more efficient allocation and positioning of resources, including ARFF vehicles and personnel.
- UASs enhanced safety by negating the need for the IC to drive around the scene, which can be particularity hazardous in the presence of debris, areas blanketed by foam agent, or passengers who have evacuated or have been ejected from the aircraft.
- UASs significantly reduced the amount of time needed to search for passengers outside of the aircraft.
- UASs helped to improve efficiency when applying agent to fires by providing an ideal vantage point from which ICs could monitor the turret stream to ensure accuracy.

6.1.2 Limitations

There are currently several regulatory and technical limitations that could limit the deployment of an UAS for ARFF live incident/accident monitoring:

- The ability to deploy a UAS may be limited by the available staffing at the incident/accident scene. Many airports operate with minimal ARFF personnel on duty at a single time and would lack the staffing required to support UAS operations in addition to fulfilling existing ARFF requirements. UAS operations generally require at least one individual serving as RPIC, who is responsible for the safety of the operation and maintaining visual line-of-sight of the UA in accordance with 14 C.F.R. Part 107.31. The RPIC will likely be prevented from carrying out any other duties during the ARFF response.

- UAS operations may also be limited by weather conditions at the time of the operation. The RPIC must consider the operating limitations of the UAS and the weather they will be operating in, including the temperature, precipitation, and wind speed, to ensure operations can be safely conducted (refer to section 6.3.6 for additional information regarding UAS environmental tolerances). Also, 14 C.F.R. 107.51 requires no less than 3 SMs of visibility and 500-ft vertical/2,000-ft horizontal separation from clouds (Operating Limitations for Small Unmanned Aircraft, 2017), limiting the ability to legally conduct UAS operations in these conditions. However, it is possible to obtain an operational waiver of this requirement from the FAA.

- Operations may be limited by ATC and airspace restrictions. The ATC facility may disapprove, restrict, or delay UAS flight operations covered by an airspace authorization at any time. Additionally, UAS operations may be limited by temporary flight restrictions (TFR). RPICs are required to check the airspace they are operating in and comply with all restrictions that might be present in accordance with 14 C.F.R. §107.45 and §107.49 (a)(2), such as a TFR. A TFR defines an area restricted to air travel due to a hazardous condition, a special event, or a general warning for the entire FAA airspace.

6.2 RECOMMENDED PERFORMANCE SPECIFICATIONS

Based on the findings derived from testing conducted at ACY and DFW FTRC, and analysis of the capabilities of current technologies, FAA researchers created recommended UAS performance specifications for ARFF live monitoring. These performance specifications address general UAS platform (features and capabilities), payload, and visual and thermal camera payloads. Appendix E presents these performance specifications in table format.

6.2.1 UAS Platform

Following are the recommended minimum requirements for the UAS platform:

- The UAS must be capable of stable and predictable flight behavior, including the ability to maintain a stationary hover without input from the RPIC. This minimizes the task load on the operator.
- The UAS must be capable of streaming real-time video via a compatible software application or external device.
- The UAS must have the capability of restricting horizontal and vertical flight boundaries, such as a tether or a programmable geofence.
- The UAS must include a return-to-home failsafe feature in case of control link loss.
- The UAS must have an anti-collision light visible from at least 3 SMs. This lighting requirement is based on Title 14 C.F.R. § 107.29, Paragraph (b) (Operation at Night, 2022).
- When stored, all components of the UAS must be resistant to the typical shocks and forces an ARFF vehicle may be subjected to, including off-road driving.

6.2.2 Payload

Sections 6.2.2.1–6.2.2.3 contain the minimum payload requirements.

6.2.2.1 General

Following are the recommended requirements for the required payload sensors and gimbal:

- The UAS payload(s) must include both visual and thermal camera sensors.
- The payload gimbal must have 3-axis stabilization (yaw, pitch, and roll) and a vibration dampening mount to ensure the video remains as steady as possible.
- The gimbal must have a controllable vertical range of motion of -90 to 0 degrees, and a horizontal range of motion of 360 degrees to allow viewing in all directions below the UAS.

6.2.2.2 Visual Camera

Following are the recommended minimum visual camera requirements. The visual camera payload must:

- transmit live footage with a minimum resolution of 720p (1280 x 720),
- record footage with a minimum resolution of 1080p (1920 x 1080),
- record footage with a minimum frame rate of 30 frames per second (fps),
- be capable of automatically focusing to minimize the task load on the operator,
- be capable of automatically adjusting the exposure.

6.2.2.3 Thermal Camera:

Following are the recommended minimum thermal camera requirements. The thermal camera payload must:

- detect long-wave infrared (LWIR) energy (8 µm to 12 µm). This is the most effective wavelength for firefighting and human detection and is the predominant type of thermal sensor available for UASs. This is also the same requirement for a forward-looking infrared (FLIR) device discussed in AC 150/5210-19(FAA, n.d.). Because LWIR sensors do not require internal cooling, they have low size, weight, and power characteristics.
- have a minimum resolution of 640 x 512. During testing, this resolution provided a superior level of performance compared to the lower resolution thermal camera payloads, allowing ARFF personnel to identify details in the scene, including distinguishing ARFF personnel close to the fire.
- have a minimum refresh rate of 30 Hz. A 30-Hz refresh rate provides smoother video of objects and people in motion than a lower refresh rate, such as 9 Hz. A refresh rate of 30 Hz will also ensure that the thermal video is visually in sync with the visual camera video.
- include automatic focus and gain control to ensure clarity and the ability to detect details, such as people and vehicles, as temperatures in the frame change.
- have a high-contrast filter that will show low-contrast objects in a dynamic thermal scene.

6.3 TECHNICAL AND OPERATIONAL CONSIDERATIONS

In addition to performance specifications, FAA researchers made the following recommendations regarding technical and operations considerations for the use of UASs to enhance ARFF situational awareness. These include general UAS characteristics, UAS operation, payloads, wireless video transmission, GCS and user interface, and UAS environmental tolerances.

6.3.1 General UAS Characteristics

Following are general considerations for selecting an UAS:

- Rapid deployment of the UAS is critical to maximizing its situational benefit for ARFF live monitoring. Operators should consider the size, portability, and ease of deployment of an UAS when selecting a platform for ARFF live monitoring. Compact UAS platforms with integrated payloads and fold-out airframes requiring minimal assembly (e.g., fold-out airframe, integrated payload, integrated GCS and controller) were the easiest and fastest to deploy.
- An UAS in its case should be able to be stored in a compartment on an ARFF vehicle for maximum protection and ease of transport. Some airport operators may choose to deploy the UAS from other types of vehicles, such as pick-up trucks or SUVs.
- Operators should consider the flight endurance (i.e., the length of time a UA can remain airborne before needing to replace batteries) when selecting an UAS. These typically range from 20–40 minutes. The actual amount of flight time will be less than the specified flight time due to the presence of wind, use of external payloads, and the need to maintain enough reserve power for emergency purposes (typically 20%). Tethered UAS typically can remain airborne as long as the ground power source is available.

6.3.2 UAS Operation

Following are considerations for the operation of an UAS:

- Optimal UAS positioning and altitude will vary with the nature of each incident. An UAS should be positioned to avoid updrafts and smoke plumes, while keeping as much of the incident in a single frame as possible.
- Incidents with debris fields or large areas covered by foam agent may benefit most by having the UAS orbit the scene to allow the IC to remain stationary. Responses with less manpower may benefit most from having the UAS monitor a single area, allowing resources to be dedicated to higher priority tasks.
- Lower altitudes provide footage with greater detail. Operators should seek to balance capturing detail with avoiding obstacles and minimizing areas occluded by the aircraft.

6.3.3 Payloads

Following are considerations regarding the payload and sensors:

- The capability to blend visual and thermal video helped enhance the clarity of lower resolution thermal cameras, but this benefit was significantly degraded in low-light conditions. Blending visual and thermal video does not provide a suitable replacement for higher resolution payloads.
- It is recommended that the visual camera payload should be capable of optical zoom with a minimum of 10x magnification. Visual camera payloads with optical zoom outperformed those without this feature. Optical zoom allows the IC to inspect small details from a distance, allows for a greater standoff distance from the incident/accident, and aids in maximizing visibility while avoiding flight over nonparticipants.
- Resolution significantly effects the file sizes of recorded video. The files sizes of 4K resolution video can be up to four times greater than 1080p.

6.3.4 Wireless Video Streaming

Following are considerations for the video streaming systems:

- Wirelessly streaming video is an effective means to immediately distribute the UAS camera payload footage and enhance the situational awareness of multiple parties involved with the emergency response during an incident/accident.
- Access to video streams should be password-protected and limited to authorized personnel.
- Operators should ensure that the video streaming service is compatible with their UAS and payload.
- The effectiveness of a wirelessly streaming system is dependent on the strength and stability of the connection between the streaming provider's network, the UAS capturing the footage, and the device(s) streaming the footage.
- If using mobile hotspots for wireless connectivity, it is recommended that the user carry one from each of the major wireless network providers and select the network with the strongest and most stable connection at any given time or location.
- Prior to wirelessly live streaming UAS payload video in an operational setting, it is recommended that users test wireless connectivity at locations across the airport to ensure there are no "dead zones." Should these exist, users should consider employing contingencies, such as utilizing the airport's wireless network or using a priority first-responder network to minimize the chance of losing connection.

6.3.5 Ground Control Stations and User Interface

Following are considerations for selecting a GCS:

- The minimum recommended size for the GCS monitor should be 7-inches (diagonally) to ensure ease of UAS operation and viewing payload footage.
- The minimum recommended GCS monitor brightness should be 1500 nits to be visible in direct sunlight. The brightness level should be adjustable by the user.
- The graphical user interface should be capable of providing simultaneous visual and thermal video feeds in a side-by-side or picture-in-picture format.
- The user interface should provide full pan-tilt-zoom controls of the visual and thermal payloads.

- The GCS should have the capability to display the live payload feed on an external monitor(s) either wirelessly or through a direct connection.
- The live display on the GCS should display the UAS altitude, speed, system health, global positioning system (GPS) signal strength, and GPS coordinates. Altitude should be displayed in feet AGL.
- The GCS should include a function to capture a screenshot of the on-screen content.

6.3.6 Environmental Tolerances

Following are considerations regarding the environmental tolerance of the UAS:

- It is recommended that UAS used to support live monitoring of ARFF incidents/accidents have a minimum ingress protection rating of IP-43. This IP-rating would provide protection from the effects of dust and other solid particles, and protection from water spray up to 60 degrees from vertical.

  The International Electrotechnical Commission (IEC) has established a rating system to categorize a device's ability to resist dust and water known as an IP rating. An IP rating contains two digits, with higher numbers indicating a higher level of protection. As shown in Table 4, the first digit specifies the level of resistance to dust and solid objects, from 0 (no protection) to 6 (dust tight). The second digit specifies resistance to water, from 0 (no protection) to 9 (protected from high pressure and temperature water jets from all directions).

Table 4. The IP Rating Matrix (IEC, n.d.)

Dust (First Number)	Moisture (Second Number)
IP 0x – No Protection	IP x0 – No protection
IP 1x – Objects ≥ 50mm	IP x1 – Vertically falling water
IP 2x – Objects ≥ 12mm	IP x2 – Vertically falling water when enclosure tilted up to 15 degrees
IP 3x – Objects ≥ 2.5mm	IP x3 – Sprayed water (up to 60 degrees from vertical)
IP 4x – Objects ≥ 1mm	IP x4 – Splashed water (from all directions)
IP 5x – Dust Protected (Vacuum)	IP x5 – Low-pressure water jets (from all directions)
IP 6x – Dust Tight	IP x6 – Powerful water jets (from all directions)
	IP x7 – Temporary immersion
	IP x8 – Indefinite immersion
	IP x9 – High-pressure and temperature water jets (from all directions)

- The operator should select an UAS with an operating temperature range that encompasses all conditions a specific airport is likely to experience. Based on market research, two recommended operating temperature range targets were identified: 32 °F -110 °F for warmer climates, and -40 °F to 110 °F for colder climates that require winterization. These ranges are based on the operating temperature range for ARFF vehicles specified in AC 150/5220-10E, *Guide Specification for Aircraft Rescue and Fire Fighting Vehicles*.

However, because no UAS platforms are currently capable of operating at -40 °F as stated in AC 150/5220-10E, the minimum recommended operating temperature for colder climates was raised to 14 °F (FAA, 2011).

- The UAS should be able to operate in sustained winds as specified by the manufacturer and should provide an on-screen alert if wind conditions exceed operating limits.

7. CONCLUSION

The Federal Aviation Administration (FAA) Airport Technology Research and Development Branch conducted a research effort to explore the use of small unmanned aircraft systems (UASs) to improve the situational awareness and effectiveness of aircraft rescue and firefighting (ARFF) personnel when monitoring the response to an ongoing ARFF accident/incident. The purpose of this effort was to develop minimum recommended performance specifications and technical/operational considerations for the use of UASs to aid ARFF response.

This research effort was conducted in three phases. During Phases 1 and 2, UAS test flights were conducted during daylight, twilight, and nighttime hours at Atlantic City International Airport (ACY) over simulated aircraft accident scenarios to evaluate the capabilities of various UAS platforms and payloads to enhance the ARFF response. Based on this testing, preliminary UAS and payload minimum performance specifications were developed, as well as other findings and lessons learned regarding best practices. Phase 3 testing was conducted at the Dallas/Fort Worth International Airport (DFW) in conjunction with the facility's ARFF classes. For this testing, UASs were flown by contracted personnel during 17 live-fire training scenarios. FAA researchers observed the ARFF response while providing the Incident Commander (IC) with a tablet displaying the UAS payload video feed. The payload video collected during each exercise was analyzed alongside feedback from each IC to develop the benefits and limitations of utilizing UASs, as well as additional operational and technical considerations regarding using UASs to support an ARFF response.

Based on analysis of footage and feedback collected during testing, FAA researchers found that, when equipped with thermal and visual cameras, UASs provided a significant situational awareness benefit to incident commanders in a variety of ARFF response scenarios. UASs provided the most benefit for complex scenarios requiring a larger area to be monitored. The primary benefits UASs provided in these scenarios included enhanced initial 360° assessments, detecting heat signatures/hot spots, searching for victims, and monitoring areas outside the view of the IC for situational awareness purposes. Limitations for the deployment of UASs included the availability of staffing required to operate the UASs, weather, air traffic control (ATC), and airspace limitations.

Minimum recommended performance specifications were also identified to ensure the effectiveness of the live payload video, including minimum video resolutions of 720p (1280 horizontal pixels x 720 vertical pixels) for visual cameras and 640 horizontal pixels x 512 vertical pixels for thermal camera payloads. This thermal resolution is in line with previous research on thermal imaging cameras (640 x 480) for (ARFF) Driver's Enhanced Vision System, which is discussed in FAA Report DOT/FAA/TC-17/27, *Thermal Imaging for Aircraft Rescue and Fire Fighting Applications* (Short, Torres, & Kreckie, 2017), and Draft AC 150/5210-19B, *Driver's Enhanced Vision System (DEV*S) (FAA, n.d.).

FAA researchers also developed technical and operational guidance to maximize the benefits of UASs for ARFF live monitoring. This guidance addresses technical aspects such as the UAS, ground control stations, and payloads, as well as the wireless video transmission. In addition, this guidance addresses operational considerations regarding using UASs to monitor an ARFF incident.

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APPENDIX A—UAS PLATFORM SPECIFICATIONS

A.1 INTRODUCTION

This appendix provides the specifications for the unmanned aircraft system (UAS) platforms used during this research effort. Table A-1 shows the specifications for the Da-Jiang Innovations (DJI) Matrice 210 RTK v.2 (DJI M210); Table A-2 shows the specifications for the DJI Mavic Enterprise Dual System (M2ED); and Table A-3 shows the specifications for the Parrot Anafi USA platform.

Table A-1. Specifications for the DJI M210 (DJI, 2020)

DJI Matrice 210 RTK v2	
Type	Rotary aircraft (4)
Wingspan	25.3″ motor-to-motor cross measurement
Weight	10.83 lb with batteries only
Maximum flight time	± 25 minutes
Average speed of flight during image capture	± 15 mph
Operating temperature range	-4 °F–122 °F
Transmitter range	5 miles (unobstructed)
Communication with transmitter	Radio (2.4000–2.4835 GHz; 5.725– 5.850 GHz)
Maximum sustained wind speed limit for safe flight	Up to 27 mph
Lost link procedure (if > 3 seconds)	Autonomous return-to-home at predetermined AGL with manual override available once link has been reestablished.
Low-battery procedure	Autonomous return-to-home if no action taken by the pilot after 10 seconds. If battery critically low, the UAS will initiate autonomous landing.
Operational area procedure	Onboard, preprogrammed flight area prohibits flying outside of predetermined geofence.
Obstacle avoidance	Forward, Down, Above, DJI AirSense (ADS-B Receiver)
Ingress protection rating	IP43

ADS-B = Automatic Dependence Surveillance-Broadcast
AGL = Above ground level
IP = Ingress Protection

Table A-2. Specifications for the DJI M2ED (DJI, 2021)

Mavic 2 Enterprise Dual	
Type	Rotary Aircraft (4)
Wingspan	13.9″ motor-to-motor cross measurement
Weight	1.98 lb (without accessories)
Maximum Flight Time	31 minutes
Operating Temperature Range	14 °F–104 °F
Transmitter Range	6.2 miles (unobstructed)
Communication with Transmitter	Radio (2.400–2.483 GHz; 5.725–5.850 GHz)
Maximum sustained wind speed limit for safe flight	Up to 23.6 mph
Lost link procedure (if > 2 seconds)	Autonomous return-to-home at predetermined AGL with manual override available once link has been reestablished.
Low-battery procedure	Autonomous return-to-home if no action taken by the pilot after 10 seconds. If battery critically low, the UAS will initiate autonomous landing.
Operational area procedure	Preprogrammed flight area prohibits flying outside of predetermined geofence.
Obstacle avoidance	Omnidirectional – Forward, Backward, Upward, Downward, Sides, DJI AirSense (ADS-B Receiver)

ADS-B = Automatic Dependence Surveillance-Broadcast
AGL = Above ground level

Table A-3. Specifications for the Parrot Anafi USA (Parrot, 2020)

Parrot Anafi USA	
Type	Rotary Aircraft (4)
Wingspan	14.6″ motor-to-motor cross measurement
Weight	1.0 lb
Maximum flight time	± 32 minutes
Average speed of flight during image capture	± 15 mph
Operating temperature range	-32 °F–122 °F
Transmitter Range	2.5 miles (unobstructed)
Communication with Transmitter	Radio (2.4000–2.4835 GHz; 5.725–5.850 GHz)
Maximum sustained wind speed limit for safe flight	Up to 33 mph
Lost Link Procedure (if > 3 seconds)	Autonomous return-to-home at predetermined AGL with manual override available once link has been reestablished.

Parrot Anafi USA	
Low-battery procedure	Autonomous return-to-home if no action taken by the pilot when there is only enough battery for return-to-home. If battery critically low, the UAS will initiate autonomous landing at current position.
Operational area procedure	No built-in limitation for NFZ, On board, preprogrammed flight area prohibits flying outside of predetermined geofence – radially limited.
Obstacle avoidance	Down
Ingress protection rating	IP53

AGL = Above ground level
IP = Ingress Protection
NFZ = No-fly zone

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APPENDIX B—PAYLOAD SPECIFICATIONS

B.1 INTRODUCTION

This appendix provides the payload specifications for the small unmanned aircraft system (UAS) platforms used in the current research. Table B-1 shows the specifications for the Da-Jiang Innovations (DJI) Zenmuse XT2; Table B-2 shows the specifications for the DJI Zenmuse Z30; Table B-3 shows the specifications for the M2ED Visual and Thermal Cameras; and Table B-4 shows the specifications for the Parrot Anafi Triple payload.

Table B-1. Specifications for the DJI Zenmuse XT2 (DJI, 2018)

DJI Zenmuse XT2	
Gimbal control (3D Stabilized)	Tilt: +45° to -130° Pan: ±330° Roll: -90° to +60°
Visual camera sensor	1/1.7″ CMOS, 12 MP
Visual camera resolution	4K; 1080p
Visual camera frame rate	29.97 fps
Visual camera FOV	57.12° × 42.44°
Digital zoom	Thermal - 1x, 2x, 4x, 8x Visual - 1x, 2x, 4x, 8x (Live view only)
Thermal camera sensor	FLIR Tau2 Uncooled VOx Microbolometer
Thermal camera resolution	9mm: 336 x 256 13mm/19mm/25mm: 640 x 512
Thermal camera frame rate	30 Hz
Thermal camera FOV	9mm: 35° x 27° 13mm: 45° x 37° 19mm: 32° x 26° 25mm: 25° x 20°
Thermal camera temperature range	High gain: 640 × 512: -13 °F to 275 °F 336 × 256: -13 °F to 212 °F Low gain: -40 °F to 1022 °F
Thermal camera spectral band	7.5–13.5 µm
Thermal camera sensitivity	< 50 mK
Photo formats	Thermal - JPEG, TIFF, R-JPEG Visual - JPEG
Video format	Thermal - 8 bit: MOV, MP4 14 bit: TIFF Sequence, SEQ** Visual - MOV, MP4

FLIR = Forward-looking infrared
FOV = Field of view

Table B-2. Specifications for the DJI Zenmuse Z30 (DJI, 2019)

DJI Zenmuse Z30	
Gimbal control (3D Stabilized)	Pitch: -120° to +30° Pan: ± 320° Roll: +90° to -50°
Visual camera sensor	1/2.8″ CMOS, 2.13 MP
Visual camera resolution	1080p
Visual camera frame rate	30 Hz
Visual camera FOV	63.7° (wide) to 2.3° (max zoom)
Digital zoom	6x
Optical zoom	30x
Photo format	JPEG
Video formats	MOV, MP4

FOV = Field of view

Table B-3. Specifications for the M2ED Integrated Payload (DJI, 2021)

M2ED Thermal/Visual Camera	
Gimbal control (3D Stabilized)	Tilt: -135 – +45° Pitch: -90-+30 ° Pan: -100 – +100°
Visual camera sensor	1/2.3" CMOS, 12MP
Visual camera resolution	4K; 2688 × 1512; 1080p
Visual camera frame rate	30 fps
Visual camera FOV	85°
Digital zoom	3x
Thermal camera sensor	FLIR Lepton Uncooled VOx Microbolometer
Thermal camera resolution	160 x 120
Thermal camera framerate	8.7 Hz
Thermal camera FOV	57° Horizontal
Thermal camera temperature range	High gain: 14 °F to 284 °F Low gain: 14 °F to 752 °F
Thermal camera spectral band	8–14 µm
Thermal camera sensitivity	< 50 mK
Photo Formats	JPEG
Video Formats	Thermal/Visual:MP4, MOV (MPEG-4 AVC/H.264)

FLIR = Forward-looking infrared
FOV = Field of view

Table B-4. Specifications for the Parrot Anafi Triple (Parrot, 2020)

Parrot ANAFI Triple	
Gimbal control (3D Stabilized)	Pitch: -140° to +110°
Visual camera sensors	(2) 1/2.4″ CMOS Wide: 21MP Rectilinear: 16MP
Visual camera resolution	4K; 1080p
Visual camera frame rate	24/25/30/48/50/60fps
Visual camera FOV	Wide: 84° Rectilinear: Up to 75.5°
Digital zoom	32x
Thermal camera sensor	FLIR Boson
Thermal camera resolution	320 x 256
Thermal camera frame rate	9 Hz
Thermal camera FOV	Not specified.
Thermal camera temperature range	-40 °F to 302 °F
Thermal camera spectral band	7.5–13 µm
Thermal camera sensitivity	< 60 mK
Photo formats	JPEG, DNG
Video format	MP4

FLIR = Forward-looking infrared
FOV = Field of view

B.2 REFERENCES

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APPENDIX C—ATLANTIC CITY INTERNATIONAL AIRPORT LIVE-MONITORING TEST PARAMETERS

This appendix provides the test parameters utilized during Phases 1 (Table C-1) and 2 (Table C-2) small unmanned aircraft system (UAS) testing for live monitoring of airport rescue and firefighting at Atlantic City International Airport.

Table C-1. Phase 1 Test Parameters

Flight #	UAS Platform	Payload	Altitude (ft)	Orbit Radius (ft)
1	DJI M210	XT2 9mm	75	300
2	DJI M210	XT2 13mm	75	300
3	DJI M210	XT2 19mm	75	300
4	DJI M210	XT2 25mm	75	300
5	DJI M210	Z30	75	300
6	DJI M2ED	Integrated EO/IR Payload	75	300
7	DJI M2ED	Integrated EO/IR Payload	100	300
8	DJI M2ED	Integrated EO/IR Payload	125	300
9	Parrot Anafi USA	Anafi Triple	75	300

Table C-2. Phase 2 Test Parameters

Flight #	UAS Platform	Payload	Lighting	Altitude (ft)	Hover Location
1	DJI M210	XT2 9mm	Daylight	100	1
	DJI M210	XT2 9mm	Daylight	100	2
3	DJI M210	XT2 13mm	Daylight	100	1
4	DJI M210	XT2 13mm	Daylight	100	2
5	DJI M210	Z30	Daylight	100	1
6	DJI M210	Z30	Daylight	100	2
7	DJI M2ED	Integrated EO/IR Payload	Daylight	100	1
8	DJI M2ED	Integrated EO/IR Payload	Daylight	100	2
9	Parrot Anafi USA	Anafi Triple	Daylight	100	1
10	Parrot Anafi USA	Anafi Triple	Daylight	100	2
11	DJI M210	XT2 9mm	Twilight	100	2
12	DJI M210	Z30	Twilight	100	2
13	DJI M2ED	Integrated EO/IR Payload	Twilight	100	2
14	Parrot Anafi USA	Anafi Triple	Twilight	100	2
15	DJI M210	XT2 9mm	Night	100	1
16	DJI M210	XT2 9mm	Night	100	2
17	DJI M210	XT2 13mm & Spotlight	Night	100	1
18	DJI M210	XT2 13mm & Spotlight	Night	100	2
19	DJI M210	Z30 & Spotlight	Night	100	1
20	DJI M210	Z30 & Spotlight	Night	100	2

Flight #	UAS Platform	Payload	Lighting	Altitude (ft)	Hover Location
21	DJI M2ED	Integrated EO/IR Payload & Spotlight	Night	100	1
22	DJI M2ED	Integrated EO/IR Payload & Spotlight	Night	100	2
23	Parrot Anafi USA	Anafi Triple	Night	100	1
24	Parrot Anafi USA	Anafi Triple	Night	100	2

APPENDIX D—DALLAS/FORT WORTH INTERNATIONAL AIRPORT ADVANCED STRATEGIES AND TACTICS FOR AVIATION INCIDENTS CLASS SCENARIO DESCRIPTIONS

This appendix provides a transcription of the scenario descriptions and instructor notes utilized by staff of the Dallas Fort Worth International Airport Fire Training Research Center during their Advanced Strategies and Tactics for Aviation Incidents classes in May and October 2021. These descriptions provided instructors with pertinent details regarding each incident, including which specialized aircraft fire trainer (SAFT) to use, the number of persons on board (POB), and the locations of smoke and fire.

May 2021

- False Alarm

  Exercise – Alert 1, Gate B 30, Engine 1/Engine 2/EZ42/T44/Stair 48, responding to light smoke coming from aft section of a 737 aircraft, unknown cause

  No POB), unknown fuel, aircraft has been at the gate for the past hour.

  (Instructor notes: Light smoke, no fire. Narrow body (NB) SAFT. No victims.)

- Engine Fire and Cabin Fire

  Exercise – Alert 1, Maintenance Ramp, Engine 1/Engine 2/EZ42/T44/Stair 48, respond to engine fire on a 737. Maintenance personnel onboard, unknown number, not responding to tower. Unknown fuel.

  (Instructor notes: Left main engine and cabin fire, heavy smoke. NB SAFT. 3 victims)

- Cabin Fire

  Exercise – Alert 1, Engine 1/Engine 2/EZ42/EZ96/T44/Stair 48, respond to a reported fire on the flight deck of Airbus (A)380 aircraft.

  Two mechanics reported onboard doing maintenance and unaccounted for unknown fuel onboard.

  (Instructor notes: Heavy smoke and fire in flight deck, two victims – one in flight deck and one in mid-cabin)

- Cabin Fire

  Exercise – Alert 1 Terminal D Hardstand for Engine 1/Engine 2/EZ42/EZ96/T44/Stair 48, respond to reported APU fire on a 767. Fire called in by ramp personnel. Three airline ground crew unaccounted for.

Three POB and 60,000 gal. of fuel on board

(Instructor notes: heavy smoke and fire in lower cargo, three victims in the cargo hold)

- Cabin Fire

  Exercise – Alert III spot 111, Engine 1/Engine 2/EZ42/T44/Stair 48, respond to outbound flight at spot 111, 737 aircraft. Pilot reports heavy smoke in the cabin with evacuation taking place at this time.

  Unknown POB reported, 20,000 lb of fuel.

  (Instructor notes: Heavy smoke and fire in main cabin NB SAFT, five victims)

- Aircraft Accident

  Exercise – Alert III off the departure end of 36L Engine 1/Engine 2/EZ42/T44/Stair 48 respond to a Gulfstream that aborted takeoff.

  (Instructor notes: Heavy smoke, debris field, eight SOB – three ejected outside and five inside, spray water out in front of the Gulfstream to look like fuel spill)

- Aircraft Accident in Warehouse

  Exercise – Alert III off the south side of 13R. Small aircraft crashed into warehouse building. Engine 1/Engine 2/EZ42/T44/Stair 48 respond. three POB aircraft, unknown number of victims in warehouse.

  (Instructor notes: Smoke and fire in warehouse /smoke only upstairs. Six total victims: three victims in plane and three in building—two downstairs and one at top of stairs.)

- Engine Fire & Cabin Fire

  Exercise – Alert 1, Airbus A380 at spot location 1. Engine 1/Engine 2/EZ42/EZ96/T44/Stair 48 respond to reported engine fire A380, five POB

  (Instructor notes: #1 Engine fire – A380 w/extension to main mid cabin. five victims scattered.)

- Fuel Spill Fire & Cabin Fire

  Exercise – Alert 1, Airbus A380 at spot location 1. Engine 1/Engine 2/EZ42/EZ96/T44/Stair 48 respond to reported fuel spill on 777 at Terminal hardstand

(Instructor notes: Wait to light the spill fire once they are dispatched, full half-pit fire, no victims)

- Cabin Fire

  Exercise – Alert III 737 and MD80 collision - Engine 1/Engine 2/EZ42/EZ96/T44/Stair 48 respond to the area of Terminal A and EJ. 737 has flames showing from left side of aircraft, aircraft was parked. The MD80 was taxiing. No contact with the MD80.

  (Instructor notes: 737 – Smoke, three victims in 737, McDonnell Douglass (MD) 80 – Smoke, eight victims)

October 2021

- False Alarm

  Exercise – Alert 1, Gate B, Engine 1/R4/T44/T2 respond to light smoke coming from aft section of a 737 aircraft, unknown cause

  No SOB, unknown fuel, aircraft has been at the gate for the past hour.

  (Instructor notes: light smoke, no fire NB SAFT. No victims.)

- Engine Fire and Cabin Fire

  NB SAFT Landing gear, engine, and cabin fire

  Exercise – Alert 1, Maintenance ramp, Engine 1/Engine 2/EZ42/T44/Stair 48, respond to wheel fire on a 737. Maintenance personnel onboard, unknown number, not responding to tower. Unknown fuel.

  (Instructor notes: Left main gear and left main engine and cabin fire, heavy smoke. Three victims)

- Cabin Fire

  Exercise – Alert 1, Engine 1/Engine 2/EZ42/T44/Stair 48, respond to reported fire on the flight deck of A380 aircraft.

  32 mechanics reported on board doing maintenance and unaccounted for, unknown fuel on board.

  (Instructor notes: Heavy smoke and fire in flight deck, two victims – one in flight deck and one in mid-cabin.)

- Engine Fire and Cabin Fire

NB SAFT Landing gear, engine, and cabin fire

Exercise – Alert III, Runway 13R, Engine 1/Engine 2/EZ42/T44/Stair 48 respond to main cabin fire on a 737. Unknown souls onboard, unknown fuel, not responding to tower.

Stairs are slides

(Instructor notes: cabin fire, heavy smoke, three victims)

- Aircraft Accident

  Exercise – Alert III, departure end of Runway 13R, Engine 1/Engine 2/EZ42/T44/Stair 48 respond to a Gulfstream that aborted takeoff. Unknown POB, unknown fuel, not responding to tower.

  (Instructor notes: Heavy smoke, fuel spill, debris field, six POB—two ejected outside and four inside)

- Fuel Spill Fire and Cabin Fire

  Exercise – Alert III, terminal ramp, Engine 1/Engine 2/EZ42/T44/Stair 48 respond to reported unignited fuel spill A380, unknown SOB, unknown fuel.

  (Instructor notes: Fire lit after dispatch. Heavy smoke, spill fire on west side, three victims in the main cabin.)

- Aircraft Accident in Warehouse

  Exercise – Alert III off the south side of 13R. Engine 1/Engine 2/EZ42/T44/Stair 48 respond to small aircraft that crashed into a warehouse building. three POB aircraft, unknown number of victims in warehouse.

  (Instructor notes: smoke and fire in warehouse, smoke only upstairs. Five total victims: three in plane and two in building – one downstairs and one at top of stairs.)

- Aircraft Accident

  Exercise – Alert III, departure end of Runway 13R, Engine 1/Engine 2/EZ42/T44/Stair 48 respond to a Gulfstream that aborted takeoff. Unknown POB, unknown fuel, not responding to tower.

  (Instructor notes: heavy smoke, five victims scattered inside.)

- Cabin Fire

Exercise – Alert III MD80, Engine 1/Engine 2/EZ42/T44/Stair 48 respond to MD80 that crashed short of Runway 13R. No contact with the flight crew. Evacuation is in progress. Unknown POB.

(Instructor notes: Manifest shows 100 POB reported later)

- Aircraft Accident

  Exercise – Alert III, departure end of Runway 13R, Engine 1/Engine 2/EZ42/T44/Stair 48 respond to a Gulfstream that aborted takeoff. Unknown POB, unknown fuel, not responding to tower.

  (Instructor Notes: Heavy smoke, fuel fire, debris field, unknown POB)

APPENDIX E—RECOMMENDED MINIMUM PERFORMANCE SPECIFICATIONS

This appendix presents the minimum performance specifications for unmanned aircraft systems (UASs) in the context of live monitoring during airport rescue and firefighting operations. Minimum performance specifications are presented for general UAS use (Table E-1), live streaming (Table E-2), visual camera payload (Table E-3), thermal camera payload (Table E-4) and payload gimbal (Table E-5).

Table E-1. General UAS Performance Specifications

Item	Criteria
Payload	The UAS must be equipped with both visual and thermal camera payloads.
Flight performance	The UAS should be capable of stable and predictable flight behavior, including the capability to hover in a fixed position at a commanded altitude with no control input.
Geofence	The UAS must be equipped with a programmable geofence capable of restricting the horizontal and vertical flight boundaries.
Return-to-home failsafe	The UAS must include a return-to-home failsafe feature.
Anti-collision beacon	The unmanned aircraft (UA) must be equipped with anti-collision lighting visible at a distance of at least 3 statute miles.

Table E-2. Live Streaming Performance Specifications

Item	Criteria
Resolution	The UAS must live stream payload footage at a minimum resolution of 720p.
Frame rate	The UAS must live stream payload footage at a minimum frame rate of 30 fps.

Table E-3. Visual Camera Payload Performance Specifications

Item	Criteria
Resolution	The visual camera payload must record footage with a minimum resolution of 720p.
Frame rate	The visual camera payload must have a minimum frame rate of 30 frames per second.
Autofocus	The visual camera payload must include auto focus.
Autoexposure	The visual camera payload must include auto exposure.

Table E-4. Thermal Camera Payload Performance Specifications

Item	Criteria
Spectral Range	The thermal camera payload must detect LWIR (8 μm–12 μm) energy.
Resolution	The thermal camera payload must have a minimum resolution of 640 x 512.
Frame rate	The thermal camera payload must have a minimum refresh rate of 30 Hz.
Focus/Gain Control	The thermal camera payload must include automatic focus and gain control.
Filters	The thermal camera payload must include a high-contrast filter that will show low-contrast objects in a dynamic thermal scene.

Table E-5. Payload Gimbal Performance Specifications

Item	Criteria
Gimbal	The payload gimbal must have 3-axis (yaw, pitch, roll) stabilization and a vibration dampening mount.
Vertical Range of Motion	The gimbal must have a controllable vertical range of motion of -90 to 0 degrees.