Final Report
ASSURE A28: Disaster Preparedness and Response Using UAS
Appendix B: Case Studies – Historical Disaster Characterization Report

June 1, 2022

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NOTICE

LEGAL DISCLAIMER

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ACHS	Amherst County High School
AFD	Auburn Fire Department
AFD RED	Austin Fire Department Robotic Emergency Deployment
AGL	Above Ground Level
BLM	Bureau of Land Management
BPRW	City of Burlington Department of Parks, Recreation, & Waterfront
BSEE	Bureau of Safety and Environmental Enforcement
BVLOS	Beyond Visual Line of Sight
CAP	Civil Air Patrol
CDC	Centers for Disease Control and Prevention
CDRP	Center for Disaster Risk Policy
COA	Certificate of Waiver or Authorization
COW	Cell-On-Wings
CRASAR	Center for Robotics Assisted Search and Rescue
CTU	Command Tactical Unit
DEM	Digital Elevation Model
DHHC	Digital Heritage & Humanities Center
DOA	Division of Aviation
DOI	Department of the Interior
DSM	Digital Surface Model
ERMA	Environmental Response Management Application
FAA	Federal Aviation Administration
FBCOEM	Fort Bend County, TX Office of Emergency Management
FEMA	Federal Emergency Management Agency
FSU CDRP	Florida State University Center for Disaster Risk Policy
GCP	Ground Control Point
GPR	Ground Penetrating Radar
IMT	Incident Management Team
LiDAR	Light Detection and Ranging
LPD	Lakeview Police Department

NASC	Navmar Applied Sciences Corporation
NCDOT	North Carolina Department of Transportation
NGI	Northern Gulf Institute
NOAA	National Oceanic & Atmospheric Administration
NTSB	National Transportation Safety Board
NUPO	National UAS Project Office
NWS BVT	National Weather Service Burlington, VT
NWS RFC	National Weather Service River Forecast Center
OAS	Office of Aviation Services
ODOT	Oregon Department of Transportation
OEM	Office of Emergency Management
PIC	Pilot in Command
RFRL	Raspet Flight Research Laboratory
RTK	Real-time Kinematic
RWB	Roboticists Without Borders
SAL	Spatial Analysis Laboratory
SAR	Search and Rescue
SfM	Structure-from-Motion
SGI	Special Government Interest
TEXSAR	Texas Search and Rescue
TFR	Temporary Flight Restriction
TLS	Terrestrial LiDAR Scanners
TXTF1	Texas Task Force 1
USF	University of South Florida
USFS	United Stated Forest Service
USGS	United States Geological Survey
UVM	University of Vermont
VLOS	Visual Line of Sight
VO	Visual Observer
VRT	Verizon Response Team
WFD	Wimberley Fire Department

WSDOT	Washington State Department of Transportation
WSFR	Windsor-Severance Fire Rescue
WSP	Washington State Patrol

1. CASE STUDIES - HISTORICAL DISASTER CHARACTERIZATION REPORT

1.1 Wind & Storm – Hurricanes

1.1.1 Hurricane Harvey –TX& LA, 2017

Location: Texas and Louisiana

Year: 2017

FEMA Declared: Yes (DR-4332-TX, EM-3382-LA, FEMA-4332-DR)

Estimated Cost: $125 billion

Figure 1. Severe flooding following Hurricane Harvey in Port Arthur, TX (Wikipedia Contributors, 2019).

Hurricane Harvey initially made landfall in Texas on August 25th, 2017, and in Louisiana on August 2nd, 2017 [1]. The Category 4 hurricane stalled near the Texas-Louisiana coast, leading to disastrous flooding, destruction, and many deaths [1]. The Houston area and other parts of Southeast Texas saw upwards of 40 inches of rain within a four-day period [1]. The resulting damage, primarily due to flooding from the extremely heavy rainfall, cost an estimated $125 billion [1]. Hundreds of thousands of homes were damaged, leading nearly 780,000 Texans to evacuate [1], [2]. The preparation, response, and recovery to Hurricane Harvey and its impacts lasted from August 23rd to September 15th, 2017 [1]. From August 26th to September 4th, UAS were integrated into the response [3]. UAS deployment enabled faster, more efficient, and safer rescue operations [3]. In addition, UAS allowed emergency response teams to perform damage and debris assessments more efficiently, which contributed to restoration of services, cleanup, and recovery more quickly [3]. This application marked the largest known organized response of UAS by public officials for a federally declared disaster in the country [4]. The benefits that this technology provided throughout the Hurricane Harvey response helped establish public and governmental support for similar use(s) of UAS in the future [4].

The Federal Emergency Management Agency (FEMA) declared Hurricane Harvey a major disaster on August 25th, 2017 [2]. This designation initiated collaborative disaster preparedness and response efforts from non-government organizations, volunteers, private actors, and local, state, and federal agencies across the country [2]. To prepare for the impact that the hurricane would have on the community, the Fort Bend County, TX Office of Emergency Management (FBCOEM) attained the help of the Center for Robotics Assisted Search and Rescue (CRASAR) [3], [4]. CRASAR led the UAS response, part of which involved mobilizing the Roboticists Without Borders (RWB) initiative [4]. RWB coordinated resources and personnel from universities, industry partners, and individual experts who had experience and training in disaster response [4]. The UAS response team, put together by RWB, was comprised of 13 UAS pilots, four data managers, and one unmanned marine vehicle operator [4]. Support and resources were supplied by industry partners and institutional members including the Florida State University Center for Disaster Risk Policy (FSU CDRP), Kovar Associates LLC, GroundVu, Hydronalix, the Texas A&M University-Corpus Christi Lone Star UAS Center of Excellence & Innovation (Lone Star UASC), the United Services Automobile Association, and Intel [4]. Public officials from Fort Bend County provided the UAS response team with invaluable local knowledge of the disaster area [3]. Throughout the response, flights were conducted by teams consisting of one or two CRASAR UAS pilots and a Fort Bend County official who identified objectives in real-time and instructed pilots on where to collect data [4]. Prior collaboration between FBCOEM and CRASAR allowed for smooth integration of non-local pilots into the operation [3]. In addition to UAS activity, CRASAR also managed air traffic for both manned and unmanned aircraft in Fort Bend County [4]. The company AirMap adapted their UAS air traffic application to allow organizations like CRASAR to view which of their platforms were airborne and track nearby airspace traffic [1]. CRASAR was able to fly missions without prior authorization from the Federal Aviation Administration (FAA) because there was not a Temporary Flight Restriction (TFR) issued for the county [5]. The lack of a TFR, although beneficial to CRASAR, meant that the airspace was heavily trafficked and therefore dangerous for UAS response personnel to operate [5]. In addition, amateur pilots who did not report their flight plans with Air Operations and CRASAR posed further risk to emergency response in the area [6]. Although the FAA warned amateur pilots to avoid flying in the Harvey Disaster Area and interfering with organized operations, new businesses brought in untrained, unprepared UAS teams that self-deployed throughout the disaster area and Fort Bend County [5], [6]. The absence of strict airspace regulation and enforcement from the FAA during the response elicited criticism from experienced responders due to the additional risk that it posed to operations and personnel [6].

RWB and their member institutions supplied 25 UAS and two unmanned marine vehicles that were made available to the UAS response team [4]. Ultimately only 10 of those platforms (both multirotor and fixed wing) were used [4]. Multirotor models included the DJI Inspire, DJI Mavic Pro, DJI Phantom 3 Pro, DJI Matrice 600 Pro, DJI Phantom 4 Pro, Intel Falcon 8, and the 3DR Solo [4]. The Insitu Scan Eagle, Parrot Disco, and Precision Hawk Lancaster 5 fixed-wing platforms were deployed as well [4], [6]. All platforms were outfitted with true-color cameras, including a DJI Zenmuse Z30 camera [4]. Multirotor platforms were utilized more heavily prior to the hurricane, during the incident, and in the response phase, compared to the fixed-wing platforms, which were employed more frequently in the disaster recovery phase [3]. All multirotor flights that took place in the first three response phases (preparation, incident, and response) were conducted using first person view [3].

UAS deployment commenced on August 25th [2]. Fort Bend County requested four types of missions: damage assessment, infrastructure inspection, situational awareness for the public, and situational awareness for response teams [3]. In the first week of flying, imagery and video data collection served to provide damage, flood, and debris assessments, infrastructure inspection, and aided local rescue teams on the ground with situational awareness [3], [6]. UAS-collected data were requested by county officials following their incident command procedures [4], [7]. A total of 112 UAS missions were flown and consisted of 64 inspections and 39 damage assessments, including five for public situational awareness and four informed response personnel situational awareness [3]. As a result of limitations posed by visual line of sight (VLOS) and battery life, many missions required multiple flights [3]. A week after initial UAS deployment, FBCOEM utilized fixed-wing platforms to survey larger areas and subsequently generate orthomosaics [3]. Throughout the entire UAS response, over 150 GB of data were collected, 85 GB of which were produced with the DJI Mavic pro [3]. Using collected imagery and knowledge of local conditions prior to the hurricane, local experts were able to quickly estimate and assess conditions on the ground [3]. As the need for immediate visual assessments and situational awareness diminished, data collection shifted to focus more on mapping and monitoring infrastructure, like river levees [3]. Data managers supported post-processing data and file backups, as well as organization [3]. UAS footage from the response was made publicly available online and included details about imagery collection [8].

This response to Hurricane Harvey benefitted greatly from Fort Bend County's previous involvement in utilizing UAS for similar applications and their existing relationship with CRASAR [3]. The county had previously employed UAS for two FEMA declared disasters prior to Hurricane Harvey, which provided the agency with valuable experience that contributed to this successful response [6]. In addition, FBCOEM had practice in managing and operating their own fleet of UAS, which served to inform decisions around platform selection, logistics, and mission goals pertaining to Hurricane Harvey [3]. The deployment of UAS in response to Hurricane Harvey allowed for more efficient, faster, and safer rescue operations and damage assessments which benefited local communities [3]. Additionally, data collected by UAS informed planning for future, comparable events [3].

1.1.2 Hurricane Irma –FL, 2017

Location: Florida

Year: 2017

FEMA Declared: Yes (DR-4337-FL)

Estimated Cost: $3.5 billion

Figure 2. Power restoration work in Florida is documented with UAS following Hurricane Irma, (Knight, 2018).

On September 10th, 2017, Hurricane Irma made landfall in the Florida Keys as a Category 4 hurricane, and in southwestern Florida as a Category 3 hurricane [1], [2], [3]. Irma caused severe storm, wind and rain damage, and flooding across the state [3], [4]. The incident period stretched from September 4th to October 18th, 2017, with UAS flights occurring from September 12th- 15th of the same year [2], [5]. Collier County experienced severe wind and flooding damage from the Category 3 hurricane when it passed over the area on September 10th [4]. Initially, a UAS team from the FSU CDRP worked closely with Florida Task Force 8 to assist with Putnam County Search And Rescue (SAR) operations by providing situational awareness from above [2], [3], [4]. The aerial perspective not only helped search crews determine where to focus their efforts, but also enabled better coordination of SAR operations overall [2], [3], [4]. After concluding SAR operations in Putnam County, the FSU CDRP UAS team worked with the Collier County Office of Emergency Management to perform damage assessments on more than 1,500 critical pieces of infrastructure throughout the county [3], [4]. Utilizing UAS for these assessments proved to be more efficient and detailed, especially given that multiple infrastructure elements could be inspected in a single flight [4]. Reductions in inspection time and cost from employing UAS furthered the region's goals for restoration and economic reconstruction [4].

Hurricane Irma was officially declared a major disaster by FEMA on September 10th, which initiated disaster preparedness and response efforts from several federal, state, and local agencies [5]. In preparation of Irma making landfall, FSU CDRP assembled teams comprised of UAS pilots and platforms, data managers, and the RESPOND-R mobile lab [4], [6]. Missions were conducted in teams of two and were made up of personnel from FSU, Kovar and Associates LLC, and Texas A&M's CRASAR [4], [6]. These teams supported emergency response operations and collaborated with the local Office of Emergency Management (OEM) while they were deployed in both Putnam and Collier counties [2], [4]. Coordination between organizations (in the form of daily briefings and planning) created an environment in which personnel were prepared for post-disaster operations, given resources (so as to not deplete those from affected communities), and were made aware of regulations in the operating area(s) [6]. The FAA did not issue TFRs for the area because both counties were rural and therefore rarely saw heavy air traffic or busy airspace [4].

Eight UAS models were made available to the response teams, including the DJI Inspire, DJI Mavic, DJI M600 Pro, DJI Phantom 3 Pro, DJI Phantom 4 Pro, and Intel Falcon 8 multirotor UAS, and the fixed-wing Parrot Disco and PrecisionHawk Lancaster 5 [4]. Ultimately, only the DJI Mavic Pro and the DJI Inspire 1 with visual camera payloads were used in operations [2], [4]. In addition to multiple UAS platforms, the teams had access to the RESPOND-R mobile lab from Texas A&M University to assist with post-deployment data management [7], [8]. The RESPOND-R mobile lab served to automatically log and classify UAS, imagery, sensor, and human-imputed data for emergency and disaster responses [7], [8].

FSU CDRP UAS flight operations concluded on September 15th and demobilized on September 16th [4]. Flight logs compiled by RESPOND-R showed that on average, flights took 16 minutes on-site to inspect two infrastructure targets [2]. Throughout the five-day mobilization, 247 imaging flights were conducted in which, 491 infrastructure targets were evaluated [4]. Critical infrastructure evaluations were performed on structures like airports, bridges, power and fire stations, prisons, and water treatment facilities [9]. Inspections were prioritized by their importance for restoration and economic recovery [6]. Assessment data collection adhered to a standardized format created by CRASAR and FEMA that included five still images (nadir and elevation views of all sides) as well as an overview video of each inspection target [6].

Severe wind damage from the storm heavily shaped post-disaster response capabilities and needs. Downed trees unpredictably blocked transportation routes, which made route clearing operations imperative [4]. Non-operational and unreliable cellular systems made mission management and communication challenging, especially once teams had deployed in the field [9]. The loss of cellular networks limited personnel and system management as well as data sharing and organization [9]. Data had to be transferred between computers using internal Wi-Fi networks or USB drives, which was far less efficient than sharing data across mobile networks [9]. UAS teams frequently had to deliver data to local OEM GIS personnel at the end of each day [9]. Data were also distributed to FEMA through an online sharing service once cellular and internet access were restored [6]. As part of a National Science Foundation (NSF) grant, data collected by the FSU CDRP UAS team were made publicly available online in 2018 [3].

The 247 successful flights carried out during the Hurricane Irma response set a record for the highest number of mission flights conducted by public officials for disaster response [4]. This value surpassed the previous record set during the 2017 Hurricane Harvey response [4]. Teams utilized the knowledge and experience gained from the UAS disaster response to Hurricane Harvey for the response to Hurricane Irma [4]. Lessons learned from Hurricane Harvey were applied during the Hurricane Irma response in order to improve rapid inspection and mission planning, situational awareness, and data sharing and management [4]. Although certain aspects of the Hurricane Harvey UAS response translated to the Hurricane Irma response days later, Hurricane Irma had its own challenges, particularly with communications and cellular network access [2], [6]. The successful utilization of UAS for the Hurricane Irma disaster response aided recovery in the region by improving SAR situational awareness and increasing infrastructure inspection efficiency and cost-effectiveness [2], [3], [4].

1.1.3 Hurricane Florence–NC, 2018

Location: North Carolina
Year: 2018

FEMA Declared: Yes (DR-4393-NC, EM-3401-NC)

Estimated Cost: $24 billion

Figure 3. Aerial image of post-hurricane damage (NCDOT, 2019).

Hurricane Florence caused severe flooding across the Carolinas in September 2018. North Carolina Governor Roy Cooper declared a state of emergency on September 7th, 2018, in anticipation of arrival of Hurricane Florence [1]. Hurricane Florence made landfall on the Carolina coast as a Category 1 storm on September 14th, 2018 [1]. The slow speed of the storm as it passed over North Carolina resulted in record rainfall with some areas receiving 30 inches of rain, and eight trillion gallons spread across the state. More than 2,400 roads, including major interstates, were closed due to widespread flooding [2]. The North Carolina Department of Transportation (NCDOT) began operating UAS to collect photos and videos of the disaster area on September 15th [3].

The planning around how the NCDOT UAS team was going to utilize UAS started over a week prior to Florence making landfall at the North Carolina coast [1]. A team consisting of state agencies and private contractors was created to establish a chain of command and manage the UAS teams involved in the response. The state agencies involved were NCDOT, North Carolina Department of Public Safety, North Carolina State Highway Patrol, NC State University, and North Carolina Public Safety Drone Academy. The private contractors were from senseFly, Drone Scape, North State Engineering, Precision Hawk, and SM&E. All contracted UAS teams operated under Part 107 waivers unless given further authorization, while NCDOT teams operated under the department's Certificate of Authorization (COA) [4]. All UAS operations were managed by the NCDOT Division of Aviation (DOA) [1]. A command center staffed with NCDOT employees, State Highway Patrol troopers, emergency management staff and private contractors was established at the DOA office [1].

NCDOT formed 15 UAS teams to be deployed by drawing upon pilots from the state agencies and contractors involved in planning the operation. The flight teams were provided with Viper Radios and unlocked WiFi hotspots to upload images and videos [5]. All pilots were FAA Part 107 certified [5]. Additionally, the FAA allowed the UAS team from senseFly to conduct operations Beyond Visual Line of Sight (BVLOS) under NCDOT's COA [5]. Pilots were updated on TFRs and given tasks each morning by a phone call from the command center. In the days before the landfall, NCDOT deployed the UAS teams and positioned them in areas of North Carolina expected to be the hardest hit, including Ocracoke Island, Wilmington, Jacksonville, Fayetteville, Lumberton and other nearby communities [6]. Pre-storm flights were conducted to assess conditions of key roads and coastal regions to provide a baseline for post-storm assessment [6]. The teams would report traffic conditions, road closures and flooded areas to the command center [7]. They were also able to authenticate incoming reports of flooding and other roadway hazards from submissions by the general public. All UAS operations were coordinated with the FAA, Emergency Management, FEMA, National Guard, and other federal and state agencies to ensure no interference with manned response.

The UAS used in the operations included several models from DJI and an eBee X from senseFly. All DJI models used were small quadcopter UAS flown within visual line of sight [1]. The DJI UAS platforms had geofence and airspace restrictions programmed into their flight software, requiring the DOA to contact DJI to request the removal of the restrictions [1]. DJI accepted their request and removed the restrictions [1]. The eBee X is a fixed-wing UAS which has a longer flight time than the DJI models, was flown BVLOS to collect mapping data [5]. The eBee X was outfitted with senseFly's AeriaX photogrammetry camera [5].

To enhance airspace management capabilities, NCDOT DOA deployed for the first time a new UAS tracking and management system, developed with industry partner AIRMAP for North Carolina's FAA UAS Integration Pilot Program (IPP) [6]. This allowed the DOA and other responding agencies to identify where UAS were flying and how they could avoid contact with manned aircraft, including helicopters performing search and rescue missions. In addition, a social media campaign alerted the public about "No Drones in Disaster Zones" – aiming to keep hobbyists from interfering with air response efforts. No incidents of civilian UAS interfering with response and recovery operations occurred during this event [6].

After Hurricane Florence made landfall, NCDOT used UAS technology to complement the state and federal manned response teams, with a focus on launching UAS during and after the hurricane to monitor and inspect the state's transportation infrastructure by collecting digital images [7]. Once the winds died down, UAS operators searched for people in need of help and delivered medical supplies. Afterward, with high-resolution sensors and the ability to fly low and close to facilities, UAS were used by utilities and governmental agencies to identify powerline or infrastructure damage [7]. As floodwaters dissipated and communities could begin returning to their homes, UAS were used to monitor the congestion along the detour route as it navigated secondary and minor roads to avoid damaged sections of the major highways [7].

In the immediate response, the FAA established an unusually large TFR surrounding Wilmington's ILM airport effectively grounding all UAS flights within 200 miles [7]. This was shortly amended to a restriction at or below 200 ft Above Ground Level (AGL), with just a 30-mile radius around ILM [7]. UAS operators were keenly watching the updates from the FAA to ensure safety and compliance with rapidly changing permissions as well as hazards on the ground. With so much flooding, not only were residents temporarily displaced from their communities, but the response teams also had trouble getting on location for certain areas of interest. Small communities with intact bridges and roadways became hot spots for traffic congestion, in some cases even limiting travel to emergency personnel [7]. In these cases, it was helpful to have direct communication via Viper Radio to the command center in Raleigh, who was co-located with officials from various agencies including State Highway Patrol to provide clearance for access [7].

In the week following landfall, NCDOT DOA conducted more than 260 UAS missions and captured more than 8,000 videos and images of roads, bridges and dams, helping state agencies assess conditions, deploy emergency responders and divert public movement away from endangered areas [6]. The data collected by NCDOT's UAS teams were shared with state and federal agencies who used it to inform real-time emergency response decisions [1]. Information was provided to emergency responders through a custom-designed ArcGIS online dashboard and to the public via traditional and social media [6]. All media were also uploaded to the NCDOT-UAS SharePoint site, where media were sorted into folders by mission location [4]. UAS enabled responders to bypass obstacles and hazards, which sped up assessment and repair efforts [8]. Public mobility, a critical issue as the storm progressed, was enhanced by UAS flights that monitored road conditions and traffic backups, enabling the Department of Public Safety to reroute traffic to support evacuations and alleviate congestion [6].

1.1.4 Hurricane Delta –LA& MS, 2020

Location: Louisiana and Mississippi

Year: 2020

FEMA Declared: Yes (DR-4570-LA, EM-3547-LA, EM-3548-MS)

Estimated Cost: $61 million

Figure 4. The TigerShark-XP3 collected aerial imagery along the banks of the Mississippi River following Hurricane Delta (Vierra, 2020).

Hurricane Delta made landfall in Louisiana as a Category 2 hurricane on October 9th, 2020 [1]-[3]. Soon after, the storm was downgraded to a Category 1 hurricane before travelling through Mississippi [1], [3]. Hurricane Delta caused heavy rain, flash flooding, and coastal storm surges in Louisiana and neighboring states, which led to considerable damage in the low-lying coastal region [1]-[3]. Following the storm, aerial imagery of flooded areas along the Mississippi River was gathered with UAS [1], [2]. The application of UAS allowed data to be shared quickly with weather forecasters and other decision makers, which in turn, informed and improved forecast accuracy [1]. This use of UAS technology was part of a larger body of research conducted by the National Oceanic and Atmospheric Administration's (NOAA) Oceanic and Atmospheric Research UAS program, the Northern Gulf Institute (NGI,) and regional National Weather Service River Forecast Centers (NWS RFCs) [1], [2]. The research focused on the utility and cost effectiveness of UAS-collected data to advance warning systems and forecasting for major flooding events [1], [2].

UAS operations following Hurricane Delta were carried out by NOAA and the NGI, a NOAA Cooperative Institute led by Mississippi State University [2]. Additional collaborators included regional NWS RFCs, the NOAA Remote Sensing Division, and the Mississippi State University Raspet Flight Research Laboratory (RFRL) [1], [2]. After the regional NWS RFC requested data on inundated land in the lower Mississippi River basin, the NGI team led by Dr. Robert Moorhead, worked with RFRL to gather UAS data [2]. The organizations coordinated to enable real-time data sharing with the NWS Lower Mississippi RFC office throughout UAS imagery collection [1]. Flights were organized out of Greenville, MS where in past operations, the UAS was launched from a municipal airport across the river in Arkansas [2], [4].

The Navmar Applied Sciences Corporation (NASC) TigerShark-XP3 fixed wing UAS from the Mississippi State University was used to acquire post-storm imagery [1], [2]. The TigerShark-XP3 was a large Group 3 UAS with a wingspan of over 21 feet and weighed approximately 500 pounds [1], [5]. With maximum flight time of eight to ten hours between refueling, the platform's endurance allowed researchers to collect data over the large area of interest as efficiently as possible [2], [5]. The platform was equipped with a Trimble Digital Sensor System for imagery collection and required a runway to launch and land [5], [6].

Individual flights lasted multiple hours, with the UAS collecting data at an altitude of 2,500 to 5,000 feet [2], [6]. Initially, cloudy weather delayed flight operations, but after several hours, the team was able to launch the TigerShark-XP3 and collect the necessary data [2]. The survey covered land on both sides of the river and along the Louisiana and Texas coasts, giving further insight into the impacts of flooding on the landscape [1], [2], [7]. Oblique and nadir imagery was captured with a ground sampling distance (GSD) between 15 cm/pixel and 30 cm/pixel [6]. Following collection, data were shared with the NWS Lower Mississippi RFC located in Slidell, LA, where they were used to augment existing flood data, give warnings, and improve prediction capabilities of future models [1], [2]. A goal of data collection and sharing during this event was that data were shared rapidly so that flood forecasts and warnings could be updated in as close to real-time as possible [1].

Ultimately, scientists determined that flooding caused by Hurricane Delta in the region where UAS imagery was collected was not as severe as initially predicted [1]. Utilizing UAS technology for data acquisition following Hurricane Delta offered an efficient and cost-effective solution to meet the time-sensitive needs of flood forecasters [1], [2]. Data collected by NOAA and NGI, combined with previous imagery that the team gathered in February and May of 2019, served to inform more accurate flooding forecasts and allow scientists/researchers to understand storm data from a broader perspective [1]. Other researchers are using UAS in similar events (following natural disasters and storms) to produce more accurate damage assessments and prediction models, as well as to communicate risks to the public [1].

1.1.5 Hurricane Ida –LA, 2021

Location: Louisiana

Year: 2021

FEMA Declared: Yes (4611-DR-LA)

Estimated Cost: $342 million

Figure 5. NOAA captures UAS imagery of flooding caused by Hurricane Ida in Barataria, LA (Mendoza, 2021).

Ida made landfall near Port Fourchon, Louisiana on August 29th, 2021 as a Category 4 hurricane and by next day, it had weakened to a tropical depression as it passed through Mississippi [1]. Maximum sustained winds reached up to 150 mph, making Hurricane Ida one of the strongest landfalls on record since 1856 [1]. Along with high winds, the hurricane caused storm surge, heavy rainfall, and flash flooding that resulted in dangerous conditions throughout Louisiana [1]. UAS were utilized by federal agencies, businesses, and other disaster response groups to capture and share the extent of the damage, as well as aid in response assessments and efforts.

The FAA played a key role in managing the safe usage of UAS by releasing a notice which informed remote pilots to take precautions and avoid flying in restricted airspaces or interfering with any emergency response [2]. President Biden also instructed the FAA to authorize the use of UAS for surveying damage to power lines to assess the scope of the downed infrastructure, identify locations most in need of repair, and expedite the time to get electricity back to citizens [3]. The FAA worked with electric companies across Louisiana and Mississippi to accomplish this without impeding other aerial flights, such as search and rescue missions [3], [4]. Numerous businesses including Verizon, AT&T, and State Farm utilized UAS to carry out response operations of their own, such as providing cellular coverage or inspecting storm damage. AT&T deployed UASs from their "Cell-On-Wings" (COW) fleet, to provide LTE coverage to areas where the hurricane had cut off electricity and cell communication [5]. Developed by AT&T's Network Disaster Recovery

Team, these specialized COW UAS were designed for extreme weather conditions with the ability to withstand winds up to 50 mph, heavy rain, and even sub-freezing temperatures and intense heat [5]. The UAS were connected to ground equipment through a cable tether, allowing them to hover at 300 feet and provide coverage over 40 miles [5]. Verizon Frontline, a platform of networks and technology for first responders, recently developed a UAS training program to get members of the Verizon Response Team (VRT) remote pilot certified and prepared to deploy UAS in emergency situations [6]. After Hurricane Ida, VRT members deployed a UAS that could provide cellular service for essential search-and-rescue missions and kept other UAS ready in case they were needed for monitoring or assessing storm damage [6], [7]. With these capabilities, UAS can be quickly deployed and easily relocated to provide coverage in an efficient way during emergency situations [2]. After conducting successful studies surrounding the use of UAS for damage-assessment, State Farm was the first company in the U.S to receive a national waiver from the FAA in 2019, granting them permission to conduct flights over people and beyond visual line of site [8]. In response to Hurricane Ida, State Farm utilized UAS to assess storm damage, collect aerial imagery, and perform inspections for its customers [9]. UAS were selected to aid insurance claim specialists because of their ability to reach inaccessible areas, operate more safely and efficiently than alternative options, and maintain social distancing efforts as well [9].

Florida State University's CDRP played a role in the response effort as well, sending their UAS team to assist with an urban search and recovery effort in Grand Isle, Louisiana [10]. CDRP belongs to Florida's State Emergency Response Team and utilizes UAS for a variety of tasks including search and rescue missions, support for law enforcement and first responders, and disaster response missions [11]. In Grand Isle, the UAS team was vital in providing real time data and informing response decisions, such as communities most in need of supplies and assistance [10]. An eBee fixed wing UAS was used for imagery collection, taking over 1,200 photos on just the first day which were stitched together to create a cohesive map of the area [10]. A fixed wing UAS was chosen for its longer battery life that allows it to collect data in the sky for over an hour, resulting in a much more efficient mission [10].

1.2 Wind & Storm – Tornadoes

1.2.1 Amherst County Tornado-VA, 2018

Location: Virginia

Year: 2018

FEMA Declared: No

Estimated Cost: N/A

Figure 6. An Amherst County High School student uses a UAS to survey tornado damage following the April 15 tornado (Faulconer, 2018).

A tornado traveled through Amherst County and Campbell County, Virginia on April 15th, 2018 [1]. With winds up to 150 mph, the EF3 storm caused significant damage to homes, businesses, and infrastructure in the town [1], [2]. UAS were utilized by students in the Amherst County High School (ACHS) Technology Club to document damage in the county and the town of Elon after the tornado and to record the community's recovery in the proceeding months [2]. The students' footage served to inform damage assessments and provide situational awareness for emergency response personnel [2].

Following the event, the ACHS Technology Club worked with the local Sheriff's Department, the Emergency Management Services (EMS), and utility providers to operate over areas that had experienced damage and to share the collected data [2]. Through the club's relationship with the Sheriff's Department, they also provided data to the NOAA and the National Weather Service (NWS) [2]. The club's UAS operations were led by Mike Cargill, who was an instructional technology teacher at the high school [2], [3].

Multiple platforms were used to collect imagery, including a DJI Phantom 4 and a DJI Mavic [3]. Students captured aerial photos and videos of the tornado and its effects from April to June 2018 [2], [3]. Imagery served to document the wreckage caused by the storm and to record the community's response and recovery efforts afterwards [2], [3]. The club also helped recover the personal effects of locals who had lost their homes [2]. The data were shared with the public on social media sites including Facebook, YouTube, and Twitter [2].

The ACHS Technology Club hoped that their documentation of the damage caused by the tornado and the subsequent reconstruction efforts of the area would preserve the history of the event [3]. The club also hoped to make a documentary within the year after the storm to showcase the changes and recovery that occurred in the community since the tornado hit [3].

1.2.2 Tescot Tornado–KS,2018

Location: Kansas

Year: 2018

FEMA Declared: No

Estimated Cost: N/A

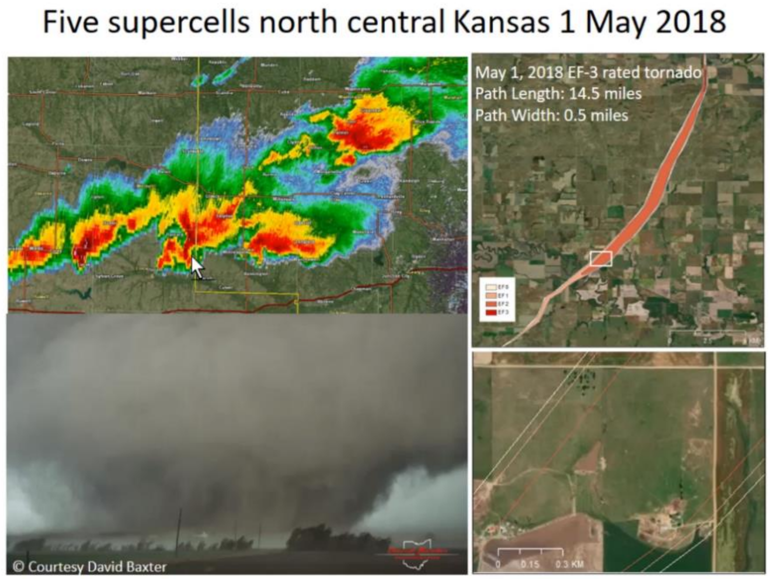

Figure 7. Clockwise from top left: Tornado radar, tornado path, terrestrial image of the storm cell(s), and aerial imagery after the storm (Wagner & Doe, Tornado Pathway Dynamics Using UASs, 2019).

An EF-3 tornado in north central Kansas on May 1st, 2018, caused a 14.5-mile-long path of destruction [1]. In the aftermath of the tornado, a research team was deployed to Tescot, Kansas to conduct a damage assessment of the area using UAS [1]. UAS were chosen to conduct damage surveys due to the technology's ability to access remote or inaccessible locations, provide detailed information during site investigations, and because of their low cost [2].

The research team and UAS operations were led by Melissa Wagner from the University of Arizona and Robert K. Doe from the University of Liverpool [1]. The UAS research team collaborated with the National Weather Service Forecast Office, Emergency Managers, and an Agricultural Extension Agent [2]. UAS activities were based out of a farm, on the top of a hill which was a local elevation maximum [1]. UAS had to be flown within visual line of sight, so basecamp was strategically established at a higher elevation to provide maximum line of sight [1].

A DJI Phantom 4 Pro and a DJI Phantom 3 Pro quadcopter UAS were used for data collection [1]. The Phantom 4 Pro was outfitted with a 4K true color digital camera and the Phantom 3 Pro was equipped with a custom multispectral camera which captured near-infrared and red band imagery [1]. Allen Instruments, an Arizona-based supplier of measurement products and positioning solutions, provided some of the equipment that the research team used for UAS data collection [1], [3]. Flight planning was conducted on site using DroneDeploy and UAS flying height ranged from

200-300 feet, with 75% front and side overlap between images [1]. Prior to the flight, a ground control survey was conducted using a Trimble Geo 7x for positional correction of the georeferenced images from the UAS [1]. After correction, the positional accuracy of the images was between 1 and 10 centimeters [1].

After data collection was complete, images were calibrated and georeferenced using Ground Control Points (GCPs) and then processed to generate Digital Elevation Models (DEMs) and orthomosaics [1]. The DEMs and orthomosaics were created in Maps Made Easy and AgiSoft, with the former also being used to generate a densified point cloud [1]. Orthomosaics, DEMs, and 3D models were analyzed by researchers to track the tornado's path and any associated damage [1]. Cloud Compare was utilized to perform geomorphic change detection between United States Geological Survey (USGS) Light Detection and Ranging (LiDAR) data and the point cloud created from the UAS data [1]. The high-resolution aerial imagery allowed researchers to study the impacts of topography on tornado behavior and intensity [1]. Data were shared using ArcGIS Online and a File Transfer Protocol site [2].

1.2.3 Lee County Tornado –AL, 2019

Location: Alabama

Year: 2019

FEMA Declared: Yes (DR-4419-AL, DR-4426-AL)

Estimated Cost: $5.5 million

Figure 8. Debris and remnants of houses were what remained after the March 3rd storm in Lee County (Chitwood, 2019).

A deadly EF-4 tornado touched down in Lee County, Alabama on March 3rd, 2019 [1], [2], [3]. The tornado touched down in Macon County, AL before travelling east through Lee County, AL (which experienced the most damage) and then into Georgia [1]. The cyclone's maximum wind speed was estimated at 170 mph, which destroyed homes, infrastructure, and tore down trees and electrical lines [3]. Along with the physical damage that Lee County sustained, 23 people were killed in the storm and associated destruction [3], [4]. The tornado was one of many severe weather events seen in the southeastern US in the beginning of March 2019 [5]. UAS provided a unique perspective during search and rescue operations that emergency responders would not have had otherwise and was less expensive than using manned aircraft [4].

Shortly after the tornado passed through, first responders from Lee County dispatched to the town of Beauregard, AL where the storm had caused massive destruction [2]. Hundreds of emergency response personnel, volunteers, and community members from the surrounding area aided in the removal of debris that had been carried into roadways [2]. Local officials started every day with a meeting, where daily plans and missions were assigned to each emergency response team [2]. The Lee County Police Department coordinated their UAS search efforts with crews on the ground to ensure that no one had been missed in their search [3], [4].

For search and rescue purposes following the storm, the Lee County Police Department utilized a UAS equipped with thermal sensors to search through the rubble of collapsed buildings and homes for survivors [3], [4]. UAS operations took place on the day of the storm during daylight hours as well as at nighttime, when victim's heat signatures would have been easier to locate amidst the cooler ambient temperature(s) [3]. When a heat signature was identified, search crews on the ground were dispatched to its location and inspected the scene further [3]. No survivors or victims were found using UAS on the night of March 3, although multiple animals and a hot water heater were found [3].

UAS technology played a critical role in the successful Lee County tornado disaster response. UAS had better maneuverability than ground search crews, were more cost-effective than manned aircraft, and when paired with infrared sensors, UAS provided emergency responders with greater search capabilities to look for survivors and victims [3], [4].

1.2.4 2021 Tornadoes, KY

Location: Arkansas, Illinois, Indiana, Kentucky, Mississippi, Missouri, Ohio, and Tennessee

Year: 2021
FEMA Declared: Yes (4630-DR-KY 3575-EM-KY, 3576-EM-TN, 3577-EM-IL, 4633-DR-AR)
Estimated Cost: $11.3 million (from KY+AR disaster declarations only)

Figure 9. Mayfield, Kentucky Candle Factory on December 13th, 2021. Low oblique image captured with a small multirotor UAS (FSU, 2021).

On December 10th and 11th 2021, a series of tornadoes and severe weather impacted eight states in the southern and central US. [1]. Although the most severe storms were seen in Kentucky, Arkansas, Tennessee, and Missouri, tornadoes were also reported in Illinois, Indiana, Mississippi, and Ohio [1]. As of December 21st, the National Weather Service had confirmed 66 tornadoes occurred over the two days, along with reports of hail and damaging winds across the affected area [1]. The storms caused the collapse of an Amazon warehouse in Illinois and a candle factory in Kentucky [2]. Over 100 people are estimated to have died because of the storms, with the majority of casualties occurring in Kentucky [3]. UAS were utilized after the storms to document and communicate the extent of the damage through imagery, video, and mapping products [3]- [5].

Organizations involved in the response included the FSU CDRP, Graves County, KY Emergency Management, the Kentucky Division of Emergency Management, and the FEMA Incident Support Team (IST) and the Urban Search and Rescue (US&R) Task Forces [6]. Other states' Emergency Management Agencies responded to the disaster and recovery efforts, along with multiple news organizations and individual commercial UAS pilots that helped document damage from the storms [3]-[10]. Brandon Clement, Whitney Westerfield, and Brian Emfinger collected drone imagery and videos that were utilized by news outlets to showcase the damage that many communities faced [3], [4], [9], [10]. Westerfield is a commercial UAS pilot and a Kentucky state senator [3]. Clement is an Emmy award winning UAS videographer known for storm chasing videos [10]. The Graves County Emergency Management and the Kentucky Division of Emergency Management requested CDRP to help with damage assessments and remote sensing efforts in Mayfield, KY following the disaster [6]. CDRP was deployed from December 12th through the 17th in Graves County, KY and collaborated with the FEMA Incident Support Team and US&R Task Forces to monitor search efforts, support searching collapsed infrastructure, record damage and areas of interest [6].

The CDRP team employed small commercial "off the shelf" multirotor and fixed-wing UAS and relied on past disaster response techniques and workflows to inform their operations [6]. Brian Emfinger collected UAS video and imagery in northeastern Arkansas on December 10th with a DJI Mavic 3 multirotor UAS [4].

FSU CDRP data served to inform county damage assessments and imagery and mapping deliverables supplemented response and recovery work [6]. The FSU CDRP team quickly mapped over 1,800 acres of damage in Mayfield, KY in under four hours [6]. CDRP generated two-dimensional mapping products and three-dimensional models that were utilized for search and rescue planning, damage assessments, and providing situational awareness [6]. Data was also used to estimate volumetric measurements of debris for cleanup and removal planning [6]. Following their work in Graves County, KY, the FEMA US&R Task Force flew multiple sorties to help search 155 acres near Bowling Green, KY for a missing child [6]. UAS imagery and video of the storm wreckage that was collected by various individuals was rapidly shared on social media and through news outlets [3], [4], [8], [9].

UAS deployment greatly enhanced the disaster response following the tornadoes and severe weather in the south-central US Public and emergency responder awareness benefited from the speed at which UAS imagery was shared. The combined efforts of the organizations involved in this response served to advance understanding around conducting more effective flight protocol for structural surveys and debris volume estimates [6]. UAS imagery and video coverage utilized by news outlets provided a broader perspective of storm damage and more accurately communicated the urgency and scale of the catastrophe than terrestrial media could portray [4]. This application of UAS technology demonstrates the value and capabilities of UAS to support future tornado and severe weather emergency responses.

1.3 Wind & Storm – Wind

1.3.1 Addison County Microburst –VT, 2017

Location: Vermont

Year: 2017

FEMA Declared: No

Estimated Cost: N/A

Figure 10. Images taken during a damage assessment following the microburst in northern Vermont (National Weather Service BTV, 2017).

Central and northern Vermont experienced severe thunderstorms and strong winds on May 18th, 2017 [1], [2]. There were three distinct areas where the severe weather was concentrated, including western Addison County, South Burlington and Williston, and the northeast Kingdom near the town of Barton [1], [2]. The National Weather Service Burlington, VT office (NWS BTV) conducted a damage assessment following the storm and found the storm had knocked down trees and power lines on a property on Potash Bay Road in Addison County [1], [2]. It was determined that a microburst with wind speeds up to 80 - 100 miles per hour caused the damage [1].

The University of Vermont Spatial Analysis Lab led UAS operations and collected imagery data in Addison County with a fixed-wing UAS on May 20th [1]- [3]. The flight path was pre-planned and covered an area of approximately 150 acres near Potash Bay Road, and the UAS flew autonomously while capturing images at regular time intervals [2]. Unlike outdated Google Earth satellite imagery, the UAS imagery was collected within 36 hours of the storm, therefore providing the most up to date aerial imagery for the area [1]. The UAS data served to inform investigations of the damage caused by the local microburst and was made publicly available as a web map application [1], [4]. In the web app, users can swipe between pre-storm satellite imagery and the post-storm UAS imagery to compare the storm damage [4]. Since the UAS gathered imagery over such a large area, the NWS BVT office was able to better understand the extent of the storm damage, especially in areas that were challenging for field crews to access [2].

1.3.2 August Derecho–IA, 2020

Location: Iowa

Year: 2020

FEMA Declared: Yes (DR-4557-IA)

Estimated Cost: $43 million

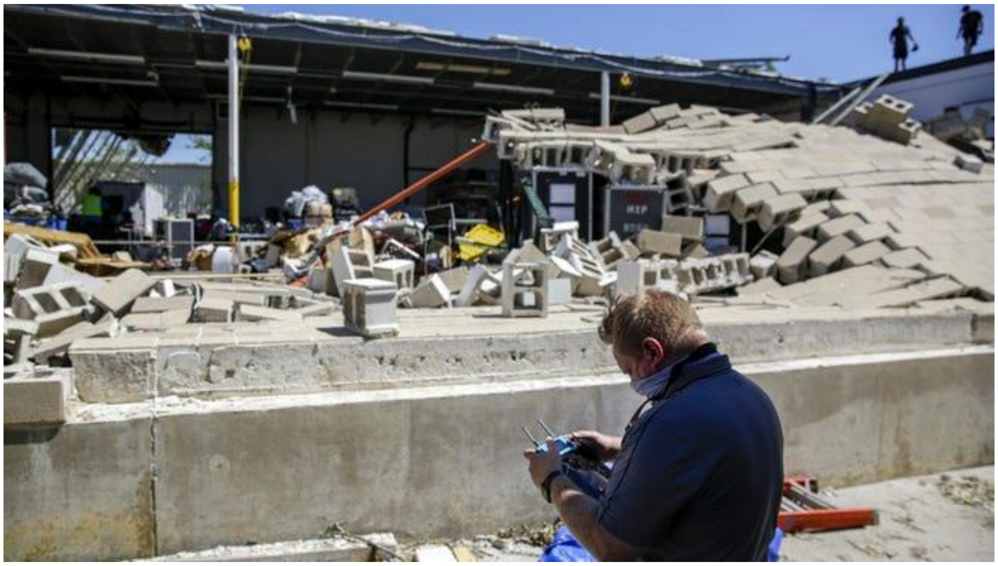

Figure 11. A Field Property Specialist from Grange/Integrity Insurance flies a UAS to document a damaged building and take measurements for an insurance claim (Jordan, 2020).

On August 10th, 2020, a derecho in Iowa with 100 mph winds destroyed a significant amount of agricultural land throughout the state, including nearly a million acres of corn and 600,000 acres of soybeans [1], [2]. Following the derecho, insurance agencies were overwhelmed with insurance claims from farmers in the state and region. By utilizing UAS in damage assessments, insurance claim adjusters were able to identify the location(s) of damage and where they needed to conduct appraisals far more quickly than if UAS were not used [1]. UAS also enabled insurance companies to access areas that were inaccessible after the storm and to have more accurate assessments- even in fields that would normally be difficult to evaluate without UAS technology [3].

Multiple insurance companies were involved in the damage assessments following the derecho, including State Farm Insurance, Grange Insurance, Integrity Insurance, and Zurich Insurance [1], [4]. Zurich North America, who insured crops in Iowa, had previously developed a UAS program to support and improve the insurance claim adjusting process for its Rural Community Insurance Services (RCIS) customers [1]. Zurich had over 20 licensed claim adjusters operating UAS in Iowa after the storm to speed up the process and to keep up with the volume of incoming claims [1], [3]. UAS were also used to compensate for the limited number of claim adjusters that were able to respond after the event due to the COVID-19 pandemic [4]. Claim adjusters from both State Farm and Integrity Insurance operated UAS as well, with the former having had FAA approval to operate over people [4].

Zurich claim adjusters utilized DJI Mavic quadcopter UAS with integrated digital cameras [1]. UAS operators in Zurich's RCIS division were certified as pilots through the FAA and had access to a fleet of 42 UAS platforms [1]. Between August and September 2020, Zurich deployed 19 UAS throughout the Midwest in response to the August derecho as well as nearby Hurricane Laura [1].

Aerial imagery of damaged crop fields was collected from various perspectives and angles, enabling the data to be used for vegetation health monitoring and understanding the damage extent [5]. In addition, the UAS imagery could be stitched together to generate imagery of entire fields [5]. The location of damage identified by UAS could also be annotated onto maps, which were provided to the farmers to inform their post-storm clean-up operations [5]. Aerial imagery collected by UAS and the processed outputs helped claim adjusters to identify areas of damage in each field in need of further inspection on the ground and allowed them to show farmers the location(s) of damage in real time [5], [1].

Employing UAS for damage assessments significantly increased the amount of land that a single claim adjuster could assess. In the six days following the derecho on August 10th, Zurich's team of UAS pilot-claim adjusters assessed 53,000 acres of cropland in Iowa, Illinois, and Arkansas [1]. In some situations, the company saw time savings as high as 66% with the help of UAS [1]. The use of UAS in this operation significantly reduced the time the farmers had to wait to be reimbursed by their insurer, which accelerated the region's recovery [1].

1.4 Wind & Storm – Flood

1.4.1 Blanco River Flood–TX, 2015

Location: Texas

Year: 2015

FEMA Declared: Yes (DR-4223-TX)

Estimated Cost: $225 million

Figure 12. FM 165 Bridge in Wimberley, TX after the flood (Wimberley Strong: 2015 Memorial Day Weekend Flood Wimberley Texas (2016).

On May 23rd, 2015, heavy rain in the Blanco River Basin caused massive flash flooding of the Blanco River in south-central Texas [1]. The town of Wimberley, Texas experienced severe and extensive damage to infrastructure and property from the flood [1]. During the event, eight people were confirmed missing, prompting search and rescue operations that covered nearly 100 miles around Wimberley [2].

The coordinated emergency response was a collaborative effort between the following actors: the Wimberley Fire Department (WFD), Blanco County Incident Command, Wimberley Valley Incident Command, Hays County Emergency Management, the National Guard, Texas Search and Rescue (TEXSAR), Texas Task Force 1 (TXTF1), the Austin Fire Department Robotic Emergency Deployment (AFD RED) Team, and emergency response personnel and volunteers from the surrounding communities [2], [3]. In anticipation of the extreme flooding, Hays County Emergency Management and WFD initiated a reverse 911 call system and door-to-door warnings to residents [3]. An Incident Command was set up at the Wimberley Central Fire Station; they managed and coordinated incoming resources [3].

Gene Robinson, from the WFD UAS operations unit, assumed the role of air boss for all manned and unmanned aircraft during the response [2], [3]. The UAS flight crew was comprised of Gene Robinson (WFD) as the Pilot in Command (PIC), Andrew Reyes (AFD RED) as the Pilot at Controls (PAC), and Coitt Kessler (AFD RED) as a Visual Observer (VO) [3]. UAS operations were unable to occur until May 26th due to crowded airspace [2]. Another challenge that delayed the UAS response was the long wait time to receive permission from the FAA, exacerbated by power outages and limited cell signal [2]. The Blanco Fire Department and Emergency Management office, the WFD UAS unit, TXTF1, and TEXSAR worked with Incident Command to lead search and rescue operations for eight missing people [3]. Simultaneously, a large search and rescue effort from volunteer civilians took place [3]. This effort was managed by a non-local family who had a connection to the missing people and consisted of ground and airborne search crews [3]. At the height of the search and rescue operations, the civilian response consisted of nearly 1,000 volunteers, dog teams, and 14 private helicopters operating in the vicinity [3]. The Wimberley Valley Incident Command, which was operating from a mobile incident command center, repeatedly tried to establish ongoing communication between the volunteer efforts and authorized responders, which ultimately proved unsuccessful [3]. Volunteer search activity posed major logistical challenges for authorized emergency response operations and personnel, especially since the volunteers were unfamiliar with emergency and disaster response protocols [3].

A COA had been previously obtained in December 2014 by WFD for local operations, but because UAS operation for this flood was outside the area defined by the pre-existing COA, applying for a separate, emergency COA was necessary [3]. Confining to the formal FAA application process proved to be technically impossible given that the emergency response was time-sensitive, and therefore, WDF worked with Air Traffic Control (ATC) to initially request and then adjust the emergency COA [3]. A TFR around Wimberley was initially put in place to enable Blackhawks to operate for search and rescue, but the TFR was canceled upon their departure [3]. Throughout the flood response, the WFD UAS unit aided in operations including conducting searches in Blanco County and then in Wimberly for the missing people, as well as mapping a seven-mile segment of the Blanco River as part of the damage assessment [3]. The WFD UAS unit, who worked closely with Incident Command, had daily Incident Action Plans (IAP), which established goals and tasks for the team [3]. On May 28th, the WFD applied for TFRs over a five-mile area along the Blanco River, though the FAA extended the area to 13-miles [3]. Gene Robinson obtained BVLOS permissions from the FAA for UAS flights to occur along the river for mapping purposes [2]. The FAA required that VOs were stationed along the flight path to retain visual line of sight with the UAS and that the flight crew constantly be in communication using radios [2]. Within and around the TFR, aircrews were responsible for air traffic de-confliction [3].

A DJI Inspire quadcopter was used early in the response for its ability to collect high-resolution imagery to supplement search and rescue efforts [3]. The multirotor UAS was flown at 100-200 feet AGL and imagery data were reviewed on a laptop by the WFD UAS team in a mobile command center [3]. Ground search and rescue personnel were then sent to investigate areas of interest that were identified by the UAS [3]. A fixed-wing Spectra UAS was used in the response as well, although the terrain made launching, landing, and maintaining visual line of sight challenging [3]. With a four-foot wingspan, long flight endurance, and the ability to fly at 400 feet AGL, the Spectra provided high resolution imagery over large areas [3]. A laptop was used as a ground station for fixed-wing operations to relay the automated flight plan to the platform [3]. The WFD UAS unit collected a total of 780 images in Wimberley and 590 in Blanco County over a four-day period spent mapping areas of the Blanco River [3]. Photogrammetric processing was used to generate an orthomosaic with a resolution of 1.77 inches/pixel from the UAS imagery [3]. In addition, search and rescue teams collected over 750 GPS data points, which were color coded and annotated with further information [4].

The data gathered by UAS, as well as imagery and mapping products, not only aided search and rescue operations, but also served to inform damage assessments and future disaster preparedness planning [3]. Recommendations for similar UAS responses in the future include establishing policies and procedures to inform future UAS responses; working to create a positive public attitude toward UAS; establishing a group that represents UAS assets and personnel that could respond to future disasters; participation of UAS operations in state, local, and Federal trainings; the separation of manned and unmanned assets within Incident Command; creating UAS technology specifically for emergency response; and providing education on UAS response and a list of contacts at the local, state, and Federal level [3].

1.4.2 Johnson County Floods –TX, 2015

Location: Texas

Year: 2015

FEMA Declared: Yes (DR-4223-TX)

Estimated Cost: $225 million

Figure 13. A UAS delivers lifejackets and a safety line to two civilians surrounded by water (Free, 2015).

In May 2015, severe storms and heavy rainfall in parts of northern Texas caused power outages and flash flooding, trapping many residents in homes and vehicles. Major flooding occurred from May 17th through May 29th. Amidst the flooding on May 17th, local emergency response agencies received many calls of high water and rescued over a dozen stranded people and animals [1]. UAS provided a unique aerial perspective that allowed emergency responders to locate people in need of help in a matter of seconds [2].

Involved in the response and rescue operations were the Johnson County Emergency Management, Mansfield Fire Department, Joshua Fire Department, and other local agencies [1], [2]. Garret Bryl, a volunteer with the Joshua Fire Department, utilized his UAS and piloting skills to supplement local emergency rescue operations [2], [3]. Bryl also served as a volunteer UAS Pilot with the North Central Texas Public Safety UAS Team. He had a FAA UAS Remote Pilot license and operated under public safety COAs [4].

Bryl played a key role in two SAR operations- one where a UAS was used to bring life vests and a safety line to two people whose home was surrounded by water, while the other involved locating people who were trapped in a truck that was swept away in the moving water [2]. The truck had been carried into a riverbed, making pinpointing the location of the vehicle challenging for search and rescue personnel [3]. A UAS was then utilized to find the truck through the tree canopy, and a spotlight onboard the UAS allowed SAR personnel to navigate to the truck's location and rescue the passengers [3]. In the case of the two people stranded in their house, after the UAS brought flotation devices, a National Guard helicopter was used to evacuate them because water rescue proved too dangerous [1], [2].

Bryl employed his personal UAS platform- a DJI Inspire 1 equipped with an onboard digital camera- for the emergency response [2], [3]. A spotlight payload was also used during search and rescue operations to help direct ground crews to the location of trapped civilians [3].

The ability of UAS to rapidly deploy and provide key information in time-sensitive situations, like the Johnson County flash floods, showcased the utility of this technology for similar search and rescue operations. Additionally, interacting with the UAS during rescue operations provided a unique opportunity for one resident to see UAS as more than just a military reconnaissance tool [2].

1.4.3 Little Androscoggin River Flood –ME, 2015

Location: Maine

Year: 2015

FEMA Declared: No

Estimated Cost: N/A

Figure 14. A UAS helped to deliver a life jacket to children stranded in the river (McFarland, 2015).

On June 30th, 2015, two children became stranded on a rock in the Little Androscoggin River in Mechanic Falls, Maine after a tubing accident [1]-[3]. They were surrounded by fast-flowing water and only one of the two boys was wearing a life jacket [1]-[3]. Floatation devices were crucial in case the boys slipped and fell into the river before or during the rescue [2]. A UAS was used to help deliver a life jacket to the stranded boys and determine the downstream river conditions prior to beginning the rescue [1].

The Auburn Fire Department (AFD) arrived at the scene first and had been called upon due to their knowledge with swift-water rescues [1]. AFD Fire Chief Frank Roma had his personal UAS at the scene, which was initially going to be used to observe conditions down river via live video feed from the UAS [1]. Using the live video feed, Roma saw that only one of the boys had a life vest on, and priorities shifted to use the UAS to get a life vest to the boys [1]. A rescue line was attached to the bottom of the UAS with Velcro and then flown over the river so that one of the boys could grab the line [1]. The boys were able to use the line to pull a life vest to them [1]. Two fire fighters used a raft to cross the river to the stranded boys and bring them back to safety [1], [2]. The platform utilized for the response, and to record the rescue, was a DJI Phantom 3 Pro [1].

1.4.4 Kīlauea Volcano Eruption–HI, 2018

Location: Hawai'i

Year: 2018

FEMA Declared: Yes (DR-4366-HI)

Estimated Cost: $139 million

Figure 15. UAS operations near Kilauea lava flows (Pix4D, 2019).

From May to September 2018, multiple eruptions and heightened volcanic activity occurred at the Kīlauea Volcano on the Big Island of Hawaii. Located approximately 10 miles inland from the southeastern shore of the Island of Hawaii, Kīlauea had been slowly erupting for decades prior to 2018. The 2018 event marked significant changes in Kīlauea's ongoing activity, as the decades long eruption in the Middle East Rift Zone ended and the volcano summit collapsed. The summit collapse was the largest to occur in over 200 years at Kīlauea [1]. Lava flows traveled towards the ocean, destroying houses, infrastructure, and ultimately creating 875 acres of new land along the island's coast [1].

UAS were chosen for this site for their rapid deployment and response time, ability to produce real-time monitoring data for scientists and emergency responders, and low cost [2], [3]. UAS served to collect eruption monitoring data and to support local emergency response efforts for hazard tracking, evacuation, and search and rescue. This implementation marked the first known use of UAS for disaster response to a volcanic eruption in the U.S [2]. In addition, this event demonstrates a successful collaborative UAS response effort from many organizations at the local, state, and federal levels.

Organizations involved in the UAS response included the US Department of the Interior (DOI) the Office of Aviation Services (OAS), the Bureau of Land Management (BLM), and the USGS National UAS Project Office (NUPO), the FAA, the University of Hawaii at Hilo, the UH Hilo Spatial Analysis & Visualization Lab, the National Park Service, the Hawaii Emergency Operations Center, Frontier Precision, and the CRASAR [2]-[5].

The DOI OAS UAS Team and skilled volunteers from CRASAR were deployed in May 2018. These organizations, along with USGS NUPO personnel, were responsible for UAS operation throughout the extended response. Coordination between groups was necessary to collect and process data, provide information to emergency responders, and assist with search and rescue efforts. UAS operators had specific training requirements depending on their employer. To operate UAS, DOI employees had to obtain a FAA Remote Pilot Certification and pass a DOI interagency UAS Basic Remote Pilot Course [7]. Although CRASAR did not offer specifics on how volunteers were trained, the organization currently offers UAS Response Technician training and a course on UAS for Emergency Management. [8]. The FAA, DOI, and local organizations established airspace authorizations for UAS operations over the extended response period [3]. Part 107 waivers were granted to the UH Hilo team from §107.29 – Daylight Operations and from §107.51 – Operating limitations for Small Unmanned Aircraft. This permitted for UAS operations at night and at altitudes greater than 400ft AGL, thereby allowing data to be captured more quickly and for the UAS to avoid airborne erupted material [4].

For data collection, platforms including the DJI Matrice 200, Inspire 1, and Inspire 2 were equipped with DJI Zenmuse XT and XT2 thermal infrared cameras and X5S and X4 visible cameras [4]. The USGS deployed platforms including a DJI Matrice 600 with the following payload options: MultiGas detection sensor, Differential Optical Absorption Spectroscopy sensor, Z30 video camera, thermal infrared FLIR camera, and Ricoh GR II camera [9]. The USGS also utilized the FireFly6 fixed-wing UAS with Sony RX1RII and Ricoh GR II cameras, and the DJI Mavic Pro for photogrammetry and situational awareness [9]. Additional hardware used in field operations included field computers for data processing and display, UAS-mounted lights with visibility of at least 3NM for night operations, GNSS systems, and fire radios, among others [4].

The application of UAS in response to this disaster had a major impact on the capabilities of emergency responders and scientists alike, as well as the community. UAS data increased situational awareness in a way that enabled responders to monitor hazards in real-time, allowed for hazards to be more closely monitored, and helped ensure field crew and civilian safety during evacuations. Data were gathered using UAS near the volcano's summit area, craters, around fissures that had opened in the East Rift Zone, and in areas where lava was predicted to flow.

Visible and thermal imagery, video, and gas emission measurements were collected [3]. Real-time data and video feeds helped emergency responders predict lava flow movement and monitor other hazards, which in turn, informed evacuation efforts. Scientists utilized the UAS-acquired data to calculate lava flow rates and to model and monitor volcanic activity and gas emissions in real-time [2], [3]. Pix4Dmapper software was used to process and generate 3D maps and models which were then displayed and shared using ESRI ArcMap [4]. In one instance, a UAS was used in search and rescue operations. The aerial perspective from the UAS helped to locate a trapped civilian and lead them safely away from nearby lava flows until a search team could make contact [5].

Volcanoes and volcanic eruptions hold cultural significance to some native Hawai'ians. In Hawai'ian folklore, the deity Pele is the goddess of fire (including volcanoes, lightning, and wind) and determines where lava flows [10], [11]. To some Hawai'ians, the belief that Pele is a destroyer as well as a creator offered some consolation amidst the disaster, and many saw the changing landscape as a fact of life [11]. Using UAS to monitor the altered landscape not only kept Hawai'ians safe, informed them of hazards and what had been destroyed, but also what new land was formed in the process. Monitoring and prediction information obtained from UAS data could allow local communities to better prepare for similar situations in the future. This utilization of UAS, while the first of its kind for volcanic disaster response, contributed greatly to emergency response and scientific efforts surrounding the Kīlauea eruption in 2018, and shows promise for comparable UAS application in the future.

1.5 Geohazards – Seismic

1.5.1 Earthquake-Puerto Rico, 2020

Location: Puerto Rico

Year: 2019-2020

FEMA Declared: Yes (DR-4473-PR, EM-3426-PR)

Estimated Cost: $319 million

Figure 16. Earthquake damage in Guayanilla, Puerto Rico (Mewse, 2021).

From December 2019 to February 2020, a series of earthquakes occurred in Puerto Rico. Two major events in the series included a magnitude 6.4 earthquake in early January 2020 and a magnitude 5.0 earthquake in February 2020 [1], [2]. UAS data collected by Civil Air Patrol (CAP) personnel were used to help FEMA prioritize emergency services and response where damage was most severe [3]. Images served to document damage to both individual structures and overall infrastructure. UAS and traditional manned aviation were used to collect imagery. UAS were chosen when weather conditions did not allow for manned fixed-wing aircraft and when ground team photos did not provide sufficient information for emergency managers [3]. In addition, UAS imagery was used to assess the impact of the earthquakes on communities' infrastructure and to identify sites for temporary housing and other emergency infrastructure [4]. This disaster response demonstrates successful UAS deployment for longer-term earthquake emergency response and post-disaster support.

Organizations involved in the response included private, local, and federal entities - the CAP, FEMA, UNAVCO, WaldoAir, Geoxphere, Voxel3D, and local emergency response organizations [2], [3], [4]. Coordination between organizations made the extended and broad UAS response possible. CAP and FEMA coordinated data sharing to inform management decisions [3]. CAP personnel operated UAS in teams consisting of a mission pilot and an UAS technician [3]. UAS flight elevation was limited to 400 feet AGL [3]. Imagery was also collected with manned aircraft and field infrastructure surveys, with the former being used for its ability to reach higher altitudes

[2], [3]. As of 2019, in the US and Puerto Rico, CAP owned and operated more than 1,500 UAS systems with access to mission capable UAS, making them the largest civilian owner of FAA-registered small UAS in the country [5].

During the course of this response, over 13,000 high-resolution photos and videos were gathered using UAS [3]. Following data collection, imagery was utilized by FEMA to establish where damage was most severe, where help was most needed, and to prioritize emergency response resources [3].

UAS deployment greatly enhanced the Puerto Rico earthquake disaster response. Due to the speed at which UAS data could be shared with response organizations, entities such as FEMA were able to rapidly document damages to homes and other important structures [3]. In addition, the UAS data allowed for the impacted community members to receive assistance more quickly, which was especially crucial given the recurring seismic activity in the area and the potential for further infrastructure collapse. Processed data from the field surveys allowed emergency managers to assess damage and calculate debris volumes [4]. Data also served to aid in identifying sites for temporary housing. This successful and valuable application of UAS technology demonstrates the utility and potential of UAS to help inform and support responders and communities in future earthquake responses.

1.5.2 SR 530 Mudslide-WA, 2014

Location: Washington State

Year: 2014

FEMA Declared: Yes (DR-4168-WA, EM-3370-WA)

Estimated Cost: $30.8 million

Figure 17. Aerial image of landslide (Washington State Department of Transportation and Snohomish County Public Works).

A mudslide occurred in Snohomish County, Washington State on March 22nd, 2014. The mudslide buried State Route 530 and debris disrupted the nearby Stillaguamish River and its flood zone. Heavy rainfall following the slide caused unpredictable flooding and additional landslide movement, threatening the lives of emergency responders and nearby civilians.

UAS were used to assess further landslide and flooding risk, collect supplementary hydrological and geological data, and provide low altitude, high-resolution imagery in areas inaccessible to helicopters and field crews. Another unique capability that made UAS valuable in this response was that UAS data could be processed faster and relayed to responders more quickly than traditional alternatives of using field crews [1]. This event marked the first known circumstance in the US where a UAS was used for a mudslide response and where a deconfliction plan permitted UAS to operate within the same airspace as manned aircraft during a disaster [1]. The abilities of UAS and post-processing software to fulfill technical mission objectives and produce high quality data and deliverables proved very successful. This response also signified the adaptation of UAS from solely collecting tactical data, to systems that can convert data into actionable information that is readily accessible and understood by decision makers in real-time.

Snohomish County emergency responders, the Washington State Department of Transportation (WSDOT), the Texas A&M Experiment Station's CRASAR, Insitu, PrecisionHawk, and community members were involved in search, rescue, and recovery efforts [1]-[3]. CRASAR was asked to collect UAS data on site. Through Roboticists Without Borders, Insitu and PrecisionHawk were invited to join the deployment as well. The County Sheriff's Office and Air Operation Branch created an Air Space Deconfliction Plan. The latter coordinated flights within the temporary flight restriction zone surrounding the mudslide area and more broadly coordinated with Air Traffic Control (ATC) through the Seattle Center [1].

Initially, the Insitu Scan Eagle and PrecisionHawk Lancaster fixed wing UAS were chosen for data collection, with the CRASAR AirRobot AR100B quadcopter selected as a back-up platform [1]. However, no UAS flights were conducted during the March 2014 mobilization due to environmental constraints on Insitu Scan Eagle operations, miscommunication about airspace deconfliction plans, and local concerns over privacy and safety. The Insitu Scan Eagle was not used due to coordination issues, lack of launch and landing space, and the risk of potential radio interference with search and rescue helicopters [1].

In April 2014, members from the involved UAS organizations returned to conduct UAS operations. For this operation, the PrecisionHawk Lancaster was not granted an emergency COA required for flights and therefore was not used. The AirRobot AR100B, equipped with a true-color camera, was flown by CRASAR personnel and gathered imagery and video data [1]. During the flights, real-time video imagery was also used to inform scientists on flood mitigation progress. Using Agisoft Photoscan and PrecisionMapper, PrecisionHawk rapidly processed UAS imagery to produce 3D models (including a 3D interactive model) and 2D orthomosaics [1], [4]. The deliverables were used by Snohomish County to inform decision making in the field and to plan flood mitigation operations [1]. From obtaining emergency COAs, to data sharing, processing, and planning efforts, coordination between organizations, local actors, and the FAA was present throughout the extended emergency response.

Concerns were brought up by families about UAS operators viewing personally identifiable information (PII) of people who had lost their lives in the mudslide. For this reason, UAS were very intentionally not used for search and rescue operations and instead were used only to monitor hazard risks, which allowed first responders to dedicate more attention and time on search and rescue [1]. The monitoring of hydrological and geological conditions with UAS helped keep responders safe and allowed scientists to adapt risk mitigation techniques as the situation evolved. The successful use of UAS for the SR-530 Mudslide emergency response demonstrated the utility of UAS in situations where extreme conditions, regulatory constraints, and negative societal perception were present. In future, similar applications, thermal sensors and LiDAR payloads could improve data collection and overall UAS capability [1].

1.5.3 West Salt Creek Landslide–Collbran, CO, 2014

Location: Colorado

Year: 2014

FEMA Declared: No

Estimated Cost: N/A

Figure 18. Aerial image of landslide debris (White et al., 2015).

A landslide occurred near the town of Collbran in western Colorado on May 25th, 2014. The landslide contained nearly 38 million cubic yards of material and traveled almost three miles at speeds between 40-85 miles per hour [1]. Along with extensive environmental destruction from the landslide, three lives were lost, and the surrounding community faced challenges from damaged irrigation ditches and subsequent access to water [1], [2].

Aerial imagery and topographical data were collected using UAS and were supplemented with terrestrial LiDAR data [2]. These data were used to map, model, and monitor the landslide and the land movement sequence. UAS were chosen for their ability to (i) quickly provide high resolution imagery at a relatively low cost; (ii) determine what areas were safe for ground crew entry; and (iii) provide heat-seeking equipment capabilities [1], [3], [4]. At the time, using helicopters for search and rescue could cost up to six hundred times more per hour than UAS, making it a cost-effective alternative [4]. Cooperation between organizations and local responders allowed for timely data collection, sharing, and processing, which improved understanding of future monitoring and mitigation techniques.

Organizations involved in the emergency and UAS response included USGS, US Forest Service, FAA, NOAA, Colorado Geographical Survey, Mesa County Sheriff's office, Colorado Mesa

University, Mesa County Public Works Department, Colorado School of Mines, and Falcon Unmanned, Inc. [1], [2], [5].

The day following the landslide, a UAS with thermal infrared capabilities was used by the Mesa County Sheriff's office to search for three missing men and to obtain low-altitude imagery [3], [4]. Knowledge from the 2014 Snohomish County, WA mudslide served to inform authorities on how to best carry out the search [3], [4]. Falcon Unmanned, Inc. and Mesa County Public Works collected post-landslide UAS imagery in May 2014, with the latter conducting three more flights in July 2014 [2]. Scientists from the USGS Geologic Hazards Science Center gathered post-landslide UAS data in the weeks and months following the slide as well [6]. For data collection, Falcon Unmanned, Inc. used one of their own Falcon fixed-wing platforms equipped with a Sony NEX7 camera, while Mesa County Public Works utilized a Trimble UX5 fixed-wing UAS and a customized (true color) Sony camera [2]. In addition to platforms and sensors, ground control points and catapult launch bungees (for UAS launches) served as supporting hardware in the field [2].

Over the collection periods in May and July, visible imagery of the entire landslide deposit was gathered. High-resolution orthomosaics, Digital Surface Models (DSMs), and DEMs were produced using Agisoft Photoscan and Trimble Business Center software [2]. Data, models, orthoimagery, and past datasets were shared between organizations for processing and to inform tasks like geologically mapping the landslide [1], [5]. The post-landslide models combined with pre-existing models (generated from LiDAR data) allowed scientists to estimate the volume of the deposit [2]. Understanding and monitoring the geologic movement so quickly after the initial landslide was important due to the potential risk of a second slide occurring. In addition to this hazard, a small lake had formed behind the remaining material at the top of the landslide, posing a possible threat to downstream residents if the water was released [5]. With these possibilities in mind, emergency response managers and on-site professionals limited ground crew work in order to avoid any further risk to community members and response personnel.

In this case study, the application of UAS for landslide disaster response demonstrated the technology's niche ability to enhance and inform emergency response. Utilizing UAS increased emergency response efficiency while lowering the cost to the community, increased responder safety, and furthered scientific understanding of the disaster. UAS allowed for relatively low risk, extensive search and rescue, which would not have been possible with field crews only. Additionally, UAS data collection greatly reduced the risk that would have otherwise been placed on field survey crews. Maps and models generated from UAS data served to increase scientific understanding of this landslide and as a result, monitoring and mitigation techniques and technologies were expedited and improved as well. The use of UAS in response to the West Salt Creek landslide demonstrated successful application of this technology for such events and supports seeking similar UAS response in the future for comparable disasters.

1.5.4 Transportation Corridor Landslide Assessments-AK, 2016

Location: Alaska

Year: 2016

FEMA Declared: No

Estimated Cost: N/A

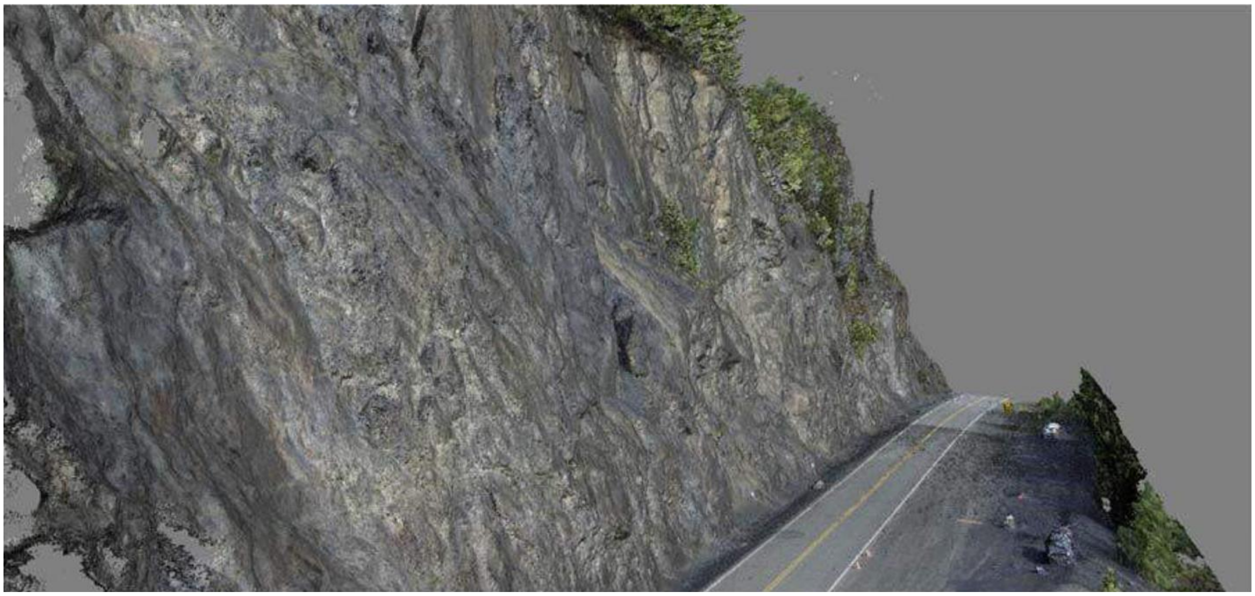

Figure 19. 3D model of rock slope generated from UAS imagery (Cunningham et al., 2016).

In 2016, the Pacific Northwestern Transportation Consortium (PacTrans) tested the utility of UAS for landslide, unstable slope, and transportation risk monitoring in Alaska. This study was part of a response to vastly increase landslide research by the US National Research Council following the 2014 Oso, Washington landslide disaster [1]. This study also served to investigate proactive slope management practices as a landslide mitigation and preparedness technique [1].

Two sites located along major highways in south central Alaska were studied in this assessment. UAS were chosen over alternative methods because UAS were able to capture more complete data compared to the Terrestrial LiDAR Scanners (TLS) deployed to the same areas [1]. UAS imagery was processed using Structure-from-Motion (SfM) photogrammetric modeling to then evaluate rock-slope stability and landslide risk near highly trafficked transportation corridors. Using TLS point cloud and DSM deliverables as a baseline for comparison, the study concluded that the SfM deliverables were capable of creating effective rockfall activity indicines (RAI) for landslide assessments [1]. In addition, the same study demonstrated that UAS are a safer alternative to using TLS due to the ability of UAS to launch and land remotely [1].

A handful of academic institutions, specifically PacTrans, the University of Alaska Fairbanks, University of Alaska Anchorage, Oregon State University, and University of Washington, were also involved in this assessment [1]. The UAS operator was from the University of Alaska Fairbanks and students from the University of Washington and Oregon State University assisted in image collection, processing, and analysis [1].

A DJI Phantom 3 Professional quadcopter was used for image collection at the assessment sites [1], with a built-in 12.4-megapixel image visible camera. Similar to the terrestrial images, the aerial photographs were shot in bright daylight and recorded in RAW image format. Supplemental imagery and data were gathered using a Reigl VZ-400 TLS and a handheld Sony Cyber-shot DSC-RX10 II digital camera [1]. All platforms collected still imagery in RAW format. Additional field equipment included the DJI GO UAS flight application, ground control points for the UAS flight, a Leica GS14 receiver, a Leica TS15 total station, and a wagon to transport the TLS platform [1]. The UAS data were processed in Agisoft Photoscan Professional v.1.2.5 to produce a DSM for each assessment site [1]. SfM and LiDAR derived surface models were evaluated using Maptek I-Site Studio 6.0, while SfM and LiDAR point clouds were compared using CloudCompare [1]. Additional software utilized for TLS data processing and visualization included Lecia Cyclone v.9.1 and GeoMat VR [1].

The results of these assessments furthered the successes from the 2014 Oso, WA landslide disaster response, which had established UAS as beneficial technology for emergency response. Through using UAS to perform rock slope hazard assessments, community members benefit from high-risk areas being better monitored and the people conducting assessments are safer than they would be using TLS methods. The successful application of UAS for landslide assessments along a transportation corridor showcased the technology's ability to effectively monitor unstable rock slopes and its potential in reducing landslide risk in the future.

1.6 Geohazards – Subsidence

1.6.1 Pasco County Sinkhole Collapse–FL, 2017

Location: Florida

Year: 2017

FEMA Declared: No

Estimated Cost: N/A

Figure 20. Aerial view of the sinkhole extent and damage (USF Digital Heritage & Humanities Collections, 2017).

On July 14th, 2017, a sinkhole collapsed in a residential neighborhood in Pasco County, Florida. The initial subsidence occurred over two hours, but erosion expanded the depression for several days after, destroying two homes and causing evacuation of seven others [1]. The sudden subsidence was partially attributed to historic land use, in which areas of an old lake underlying this area were filled in in the 1960s and 70s to allow for housing development [1]. In addition to land use change, a karst geologic feature contributed to the weakened ground structure and subsequent collapse [1]. Karst environments are a type of topography characterized by underground sinkholes and caves created by dissolving bedrock. Data were gathered following the subsidence using UAS, TLS, and Ground-Penetrating Radar (GPR) [1]-[6]. UAS SfM photogrammetry was used to monitor surface terrain changes and to inform stabilization efforts. UAS were chosen for their ability to rapidly and accurately map topography and because UAS data could be easily integrated with TLS and GPR data [1]. Coordination between UAS operating organizations and communication with the local scientific community improved understanding of the event and informed future best practices for subsidence-related disaster response.

The University of South Florida (USF) and Halo Imaging were responsible for data collection and monitoring [1]. USF conducted five UAS surveys during the seven weeks following the collapse until 10 months post-collapse [1]. The USF team of faculty and graduate students drew expertise from their Digital Heritage & Humanities Center (DHHC), School of Geoscience, and Water Institute [1], [2]. Garret Speed from the USF DHHC was responsible for the UAS SfM photogrammetry field work and subsequent data processing and other DHHC staff provided GIS analysis support [1]. In addition to the USF surveys, Halo Imaging flew five UAS flights in July 2017 in the two weeks following the initial subsidence [1].

Halo Imaging conducted flights using a senseFly eBee Real Time Kinematic (RTK) fixed-wing platform, while USF researchers collected still imagery and video with an unmodified DJI Mavic Pro quadcopter [1], [3]. The DJI Mavic Pro quadcopter was equipped with a sensor that produced 12-megapixel images [1]. Halo Imaging gathered true-color still imagery and used Pix4Dmapper to produce point clouds, DSMs, and orthophotos [1]. USF processed images photogrammetrically through Agisoft Photoscan Professional 1.4 and generated point clouds as well [1]. In addition, 3D models, an interactive GIS tool, and an imagery comparison analysis were created using the data and made accessible online [4]-[6].

Afterwards, the TLS and SfM point clouds were compared using Cloud Compare v.2 with qBroom plugin [1]. These products were used in conjunction with geotagged historic imagery and maps to document ground surface changes over time and to understand the underlying ground structure [1]. Structural data were used to inform stabilization, which commenced in August 2017 and included filling in the collapsed area and building up the rim [1]. Equipment used in field data collection included ground control points, a Trimble Geo7x GNSS system and Zephyr 3 antenna, a Trimble R10 rover, a FARO terrestrial LiDAR platform, and a MALÅ ProX GPR system [1]. Data processed by USF were made available online for others to view with the intent that it will help educate people, allow others to contribute additional data, and generally inform stake holders [3]. The UAS provided data with approximately 20cm horizontal and vertical resolution, the TLS produced data with 0.2cm resolution, and data collected with GPR consisted of 1cm horizontal and 5 – 17cm vertical resolution [1].

The use of UAS for this disaster response improved the capabilities and understanding of the scientific community, informed emergency response and mitigation efforts, and helped maintain safety of the local community and its residents. UAS imagery and processed deliverables provided valuable insight into the underlying causes of the sinkhole collapse, which were then communicated to the community. Following the monitoring and data collection, the USF team worked with Pasco County to establish a more efficient and rapid emergency response in the future [3]. This, along with greater understanding of areas that are at higher risk for subsidence could contribute to a more efficient emergency response in the future. The successful emergency response and monitoring of the Pasco County sinkhole using UAS shows promise for comparable use in future disaster events.

1.7 Geohazards – Avalanche

1.7.1 Avalanche Control Monitoring–WA, 2006-2007

Location: Washington

Year: 2006-2007

FEMA Declared: No

Estimated Cost: N/A

Figure 21. MLB BAT platform catapult launch (McCormack, 2008).

Between 2006 to 2007, WSDOT explored UAS applications along avalanche prone sections of State Route 20. WSDOT was interested in the utility of UAS to monitor and control avalanches on mountainsides above busy highways. The department was also curious about the economic feasibility for practical use of UAS and the potential to integrate UAS operations into existing practices. UAS were used to collect aerial imagery of avalanche prone areas and road conditions. UAS were chosen for their ability to identify avalanche hazard zones at lower costs than helicopters and because using this technology reduced risk for DOT workers who were responsible for avalanche prevention and therefore in higher risk situations [1]. This study found that there was potential for UAS as an avalanche control and monitoring technology and that effective application would benefit from further research and development. In addition, UASs were effectively utilized to collect aerial imagery that could be used for traffic monitoring and data collection [1].

WSDOT was primarily involved in this response, along with personnel from Georgia Institute of Technology (Georgia Tech) and MLB Company [1]. UAS platforms were owned and operated by both Georgia Tech and MLB, with WSDOT providing air traffic control support as needed [1]. WSDOT worked with Georgia Tech and MLB to test the applicability of two UAS for avalanche and traffic monitoring. The FAA granted a yearlong COA to WSDOT to fly the MLB UAS and after some delays, granted a COA for the UAS operated by Georgia Tech as well [1]. It was noted in the study that at the time, obtaining a COA online from the FAA was a new process that was complex, time consuming, and therefore caused multiple delays [1].

Both fixed-wing and multirotor platforms were flown for this assessment. The MLB BAT was a 25-pound fixed-wing UAS with a wingspan of 72 inches that carried a digital camera as well as a pan-tilt video camera [1]. This UAS was launched via a catapult that could be situated on top of a vehicle and after data collection, the UAS landed on a 100-foot segment of roadway [1]. Additional field equipment for this platform included field computers, a ground station, and an external antenna mounted on a tripod [1]. Poor visibility made the MLB BAT flights difficult, but the UAS successfully captured videos of avalanche risk areas and the roadway [1]. In addition to inclement weather, the landing requirements for this platform proved challenging. The second UAS used for this operation was the rotary wing Yamaha R-Max, which weighed 150-pounds and had a rotor span of 10-feet [1]. Operated by Georgia Tech, this platform was outfitted with pan-tilt cameras and portable computers [1]. External antennae fixed on tripods served as auxiliary field equipment [1]. During its flights, the Yamaha R-Max successfully navigated a path along predetermined waypoints, accurately dropped packages at specific GPS coordinates, and surveyed roadside terrain [1]. Issues with this platform included degraded flying ability due to high altitude and thin air and onboard GPS inaccuracies [1].

Despite challenges that arose, this study provided WSDOT with further understanding of the application of UAS for avalanche and traffic monitoring, and how this technology could be implemented in their agency. Incorporating UAS as an avalanche monitoring tool could mitigate risk to DOT personnel who may have been in harm’s way when using traditional monitoring methods. Additionally, faster, more efficient avalanche and avalanche hazard monitoring could reduce risk to nearby drivers and recreationists. WSDOT concluded that this technology demonstrated significant potential for UAS to constructively supplement the agency’s existing avalanche control operations and was interested in expanding future use of UAS [1]. Reservations that WSDOT had at the time concerning complexity of FAA authorization and platform operation have likely changed in the decade since this report was published.

1.7.2 Grand County Avalanche–CO, 2020

Location: Colorado

Year: 2020

FEMA Declared: No

Estimated Cost: N/A

Figure 22. View of the avalanche location from the bottom of the slope, looking up on the night of the event (Cooperstein, 2021).

On December 26th, 2020, an avalanche occurred in Grand County, CO near Berthoud Pass. Grand County is in north central Colorado, where backcountry skiing and avalanches are commonplace. A 911 call reported a missing skier who had been skiing alone in the area and had potentially been caught in the avalanche. When the skier didn't reconvene with their friends at the bottom of the pass, local authorities were alerted. A UAS was used during the search that night to evaluate the situation and aid in finding the body [1]. Locating the skier's body was made more challenging because he had not worn an avalanche rescue transceiver [2]. The skier was declared dead after his body was located. UAS gave search crews a better perspective than what could normally be seen from the ground and provided a faster response than more traditional aerial and field search methods, which can be extremely important in such time sensitive situations.

The Grand County Sheriff's Office and Grand County Search and Rescue responded to the 911 call and worked together to locate the skier's body [1]. The Colorado Avalanche Information Center (CAIC) published an avalanche report following the event [1]. According to a 2018 article from CBS Denver, the Grand County Sheriff's Office has UAS capabilities, including a DJI Matrice 210 with forward-looking infrared sensor (FLIR). The operator of the UAS for this avalanche response was not specified [2]. The Grand County Sheriff's Office was granted a waiver for 14 CFR § 107.29- Daylight operation, which allowed them to conduct UAS operations during nighttime for the search and rescue response [3]. The waiver, issued by the FAA, required that the mission use one or more VO and that the UAS be outfitted with anti-collision lighting [3]. Additionally, the waiver required the PIC and VO to complete additional night operation training and specified that the area of operation needed to be adequately lit to enable identification of any terrestrial obstacles [3].

The utilization of UAS for this avalanche response significantly impacted the capabilities of emergency responders. UAS increased situational awareness and efficiency of search and rescue. The local community also benefited from the rapid UAS response and search for the skier, as he was from a nearby community and had friends and family who were waiting for updates. A possible future application of UAS for avalanche disaster response could expand to include monitoring and prediction information. These data could supplement current practices and serve to better prepare and inform local authorities and winter recreationists of hazardous conditions. The use of UAS for avalanche emergency response contributed to the rapid and efficient search efforts in Grand County and shows promise for future UAS application in regions that experience avalanche threats.

1.8 Technological – Pandemic

1.8.1 COVID-19 Social Distancing Monitoring-VT, 2020

Location: Vermont

Year: 2020-Present

FEMA Declared: Yes (DM-4532-VT, EM-3437-VT)

Estimated Cost: $28.5 million

Figure 23. UAS imagery of Burlington public park (Brown, 2020).

In late March 2020, Vermont Governor Phil Scott issued a "Stay Home, Stay Safe" order to reduce the spread of COVID-19 and protect the state's residents [1]. Part of this directive involved practicing social distancing - maintaining a six-foot distance from others (excluding people from the same household) - along with other preventative actions to reduce the spread of COVID-19 [1]. According to the US Centers for Disease Control and Prevention (CDC), COVID-19 spreads predominately from people being within six feet of each other for extended periods of time [2]. For this reason, among others measures recommended by the CDC, social distancing was deemed critical in reducing further virus transmission.

The City of Burlington Department of Parks, Recreation, & Waterfront (BPRW) implemented measures to encourage social distancing following the "Stay Home" order to ensure that local park-goers were staying safe [3]. The University of Vermont's Spatial Analysis Laboratory (SAL), located in Burlington, has responded to disasters throughout the state of Vermont for years. The SAL's experience and UAS capabilities allowed them to provide decision makers with aerial video of park user's social distancing [4]. UAS were used to collect birds-eye view video at a few of the most trafficked parks in Burlington [4]. BPRW personnel used information from the UAS videos to understand how the larger parks were being used and how to navigate the new distancing measures [4]. This application of UAS provided city leaders with time-sensitive information about the use of public space that can be used to navigate the COVID-19 health crisis moving forward, especially in warmer seasons.

The University of Vermont (UVM) SAL UAS Team led the UAS response, with support and expertise provided by the lab's Director, Jarlath O'Neil-Dunne, the UAS Team Lead, Adam Zylka, UAS Pilot Kelly Shulze, and UVM undergraduate and GIS technician Jillian Joubert [4]. UAS operations required automated airspace approvals for flight up to 400 feet above ground level (AGL) in all locations due to proximity to the Burlington International Airport (BTV) [6]. BTV is LAANC enabled and successful requests and approvals were made on-demand as required in nearly real-time via the AirMap Web App [7].

UAS flights took place at some of the most popular Burlington parks, including Oakledge Park, A-Dog Skatepark, Leddy Park, and the waterfront bike path [4]. Six UAS flights were conducted between March 28th and April 24th, 2020 [5]. For all flights, a DJI Phantom 4 platform was used to capture video data [6]. Video durations (unedited) ranged from 5-15 minutes. Privacy of the general public was of utmost concern and flight locations and angles were chosen such that no personally identifiable information (PII) could be recognized in the videos and imagery. The majority of flight operations were conducted with the UAS hovering over Lake Champlain, in order to mitigate the risk of conducting a flight over non-participants. The collected videos were sped up and compiled into an accessible online web app that was made available to BPRW and the public [4], [5], [6].

This deployment of UAS for monitoring social distancing during the COVID-19 pandemic served to support BPRW by providing them with information on how parks were being used. Additionally, the UAS response enabled BPRW to navigate and enforce Governor Scott's orders in a more informed way while supporting continued public use of the parks. As a direct result of UAS data collection, BPRW increased signage and education about social distancing measures in public spaces. The utilization of UAS for this emergency response demonstrated the value that UAS data can have to decision makers and local stakeholders and showed vast potential for similar UAS applications moving forward.

1.8.2 COVID-19 Pandemic Prescription Delivery Service –FL, 2020

Location: Florida
Year: 2020
FEMA Declared: Yes (DR-4486-FL)
Estimated Cost: N/A

Figure 24. A Matternet M2 UAS platform was used to transport prescriptions to The Villages, FL (UPS, 2020).

Amidst the COVID-19 pandemic, United Parcel Service (UPS) partnered with Consumer Value Stores (CVS) to deliver prescriptions from a CVS Pharmacy to a retirement community in central Florida [1]. The retirement community, known as The Villages, is the largest in the US and was offered this service starting in May 2020 [1]. With the pandemic posing greater risks to seniors, the UPS subsidiary "UPS Flight Forward" offered prescription delivery to the community's 135,000 residents by flying a UAS from the nearby pharmacy to a designated spot at The Villages [1]. This utilization of UAS could reduce the health and exposure risk(s) to The Villages' residents by decreasing human contact and therefore, potential spread of COIVD-19 [1].

The delivery system was carried out with the Matternet M2 UAS platform and operated by UPS Flight Forward [1]. The Matternet M2, a quadrotor UAS has a 12.5-mile range and can carry up to five pounds [2]. Matternet is a California-based company that has had experience working with UPS operating a delivery service to a Raleigh, NC hospital [2]. UPS Flight Forward has an FAA Part 135 Air Carrier certification and conducted delivery service operations at The Villages under Part 107 regulations [1], [3]. The UAS were launched from the CVS Pharmacy parking lot and flown to a drop off location that was under a half a mile away [1], [3]. Once dropped off by UAS, a driver delivered the prescriptions to The Villages' front doors [1]. After the initial test flight, prescription pickup and delivery at The Villages location was to be conducted by UPS personnel [1], [3]. Through reducing close contact that the community's residents would experience from picking up prescriptions in-person at CVS, this application of UAS technology decreased the risk of residents contracting COVID-19 [1]. Additionally, prescription delivery could reduce certain accessibility barriers standing in the way of residents receiving prescriptions.

1.9 Technological – Oil Spill

1.9.1 Refugio Oil Spill –CA, 2015

Location: California

Year: 2015

FEMA Declared: No

Estimated Cost: N/A

Figure 25. Oil on the Refugio State Park beach, CA (NOAA, 2017).

An oil pipeline near Refugio State Beach, California ruptured on May 19th, 2015, spilling over 100,000 gallons of crude oil [1]. Given the pipeline's proximity to the beach, much of the oil reached the ocean [1]. A team from the NOAA, in collaboration with other agencies, launched a UAS to map Refugio State Beach and capture imagery of the spilled oil in the ocean [2]. The data also served to inform damage assessments of the contaminated area [2]. The process of collecting UAS data helped involved agencies better understand what technology and processes needed to be developed further and improved upon for future responses [2]. NOAA's response to the event garnered public interest in the technology, and shortly after, a workshop hosted by the National Academies of Science, Engineering, and Medicine, also saw increased interest in expanding UAS capabilities for future oil spill response [2], [3].

The UAS response to the oil spill included NOAA's UAS Program, the NOAA Office of Response and Restoration, NOAA National Geodetic Survey, NOAA Office of National Marine Sanctuaries, the Department of Interior Bureau of Safety and Environmental Enforcement (BSEE), the Coast Guard Marine Environmental Response, and the California Office of Spill Prevention and Response [2]. UAS operations were led by a team from NOAA, which had access to a variety of UAS platforms through the mentioned programs and offices [2]. One of the primary goals of the response was to display how UAS technology could be applied to NOAA's Environmental Response Management Application (ERMA) [2]. ERMA, a mapping application used by natural resource advisors and responders, shows real time and historical data [4]. Other goals included increased planning, speed, and data processing for accessibility in ERMA [2]. The second goal was successful, although the UAS had to be flown a second time because the first flight did not capture high enough resolution imagery [2].

The platform employed for this response was NOAA's PUMA fixed wing UAS [5]. With a nine-foot wingspan and 13-pound weight, the PUMA could be hand launched, land on water, and had a maximum range of 50 square miles with a two-hour battery life [5]. The UAS was equipped with a true color digital camera that could be swapped with a thermal infrared sensor; both could livestream video to the operator [2]. UAS imagery data served to document the extent of the oil spill in the ocean and were used to generate orthoimagery of Refugio State Beach [2]. The orthomosaic produced from this operation was put into the Southwest Region ERMA map [2].

The NOAA team worked with the BSEE to detect oil on the water using both the RGB and thermal data [2]. Improving thermal sensor calibration to better understand thickness and volume of oil was suggested as an area for future development following the response [2]. Another issue that arose was that testing technology used for oil spill responses was challenging due to how uncommon they are and a staged spill is not viable because it acts drastically different than a real spill [2].

NOAA, as well as the other organizations involved, had several key interests for applying UAS in preparation for future, similar events. NOAA expressed interest in applying SAR (synthetic aperture radar) in data collection efforts and the need to improve thermal sensors [2]. Two factors limiting SAR integration at the time were the cost and that SAR would require a different UAS platform than what NOAA already had [2]. The National Academies of Science, Engineering, and Medicine workshop had several goals and interests including: training programs for remotely operated vehicles, determining what assets and equipment first responders need, using decommissioned oil rigs as platforms to deploy response resources, increasing capabilities for nighttime operations and monitoring, standardizing data collection and processing across different locations, addressing private property and jurisdictional issues, incorporating new technologies like UAS, finding more effective ways to share data across all forms of organizations, and increasing interdisciplinary projects [3]. Some of these goals were stated expressly in the context of UAS, but most remained broad and focused on a variety of needs for future disaster response.

1.10 Technological – Terrorism

1.10.1 Nashville Bombing –TN, 2020

Location: Tennessee
Year: 2020
FEMA Declared: No
Estimated Cost: N/A

Figure 26. Downtown Nashville, TN streets after the bombing (Alund, et al., 2020).

A bomb went off in downtown Nashville that killed the bomber, injured three people, and caused a building to collapse on December 25th, 2020 [1].

Nashville area news organizations NBC-WSMV and The Tennessean reported on the bombing and captured UAS imagery and video of the destruction [1], [2]. The data were then released onto the organizations' online sites [1], [2]. The Tennessean worked with Brian Siskind, a Part 107 licensed UAS pilot, to collect UAS imagery for them [1]. The FAA instituted a temporary flight restriction (TFR) zone with a 1.15-mile radius around the explosion that lasted from December 25th until the 30th, 2020 [3]. A second TFR with a half-mile radius was implemented from January 6th to 10th, 2021 because a helicopter flew too close to the scene and blew glass and debris into people working on the ground [3]. The short period without flight restrictions allowed NBC-WSMV and Brian Siskind to gather UAS imagery and video [1], [2].

The two UAS operations involved flying the UAS five to seven stories high to capture images and video above the blast as well as of the impact on surrounding buildings [1], [2]. The NBC-WSMV video shows the street from both afar and up close to show the scale of the incident [2].
In addition to the use of UAS by the media, there was an attempt by the Tennessee Bureau of Investigation's (TBI) Aviation Unit to deploy their UAS to assist with assessing the explosion site and locating possible victims [4]. The Aviation Unit consists of a full-time pilot, the Assistant Special Agent in Charge, as well as three supporting flight crew members and two contract pilots [5]. The UAS were found "nonoperational" during their attempted use at the Nashville bombing

site however, the TBI was able to deploy a fixed-wing aircraft instead to assess the aftermath [6]. Since this incident, TBI has replaced the UAS in its Aviation Unit and continues to encourage other local governments to explore the use of UAS, which can be a helpful tool for collecting information and monitoring situations [6].

1.11 Technological – Vehicular

1.11.1 Northfield Amtrak Train Derailment –VT, 2015

Location: Vermont

Year: 2015

FEMA Declared: No

Estimated Cost: N/A

Figure 27. Aerial view of the 2015 train derailment in Northfield, Vermont (O'Neil-Dunne, 2015).

On October 5th, 2015, an Amtrak train derailed in Northfield, VT. Of the 102 passengers and crew members on board, the derailment injured seven people [1]. An investigation led by the National Transportation Safety Board (NTSB) determined that a rockslide on the tracks caused the incident [2]. UAS were utilized in the emergency response to help state and local agencies document the incident and provide critical data about the derailment [3], [4], [5].

Many state and local agencies and organizations responded to the emergency, including the Vermont State Police, local law enforcement and emergency response personnel, the Vermont Agency of Transportation (VTrans), the New England Central Railroad, NTSB, and the University of Vermont SAL [1]-[5]. At the beginning of the response, VTrans requested that the SAL collect UAS imagery in Northfield, which could be quickly passed on to incident command (run by the Vermont State Police) [5]. Prior to UAS flight operations, the SAL checked with the Air Division of VTrans for clearance to fly at the site, although the lab had a Section 333 Exemption [3]. UAS operations were led by three SAL personnel, who had experience operating UAS and had recently taken part in federal disaster training [5].

An eBee fixed-wing UAS platform was used for data collection and operated via the eMotion flight planning computer application [1]-[5]. The eBee, produced by the company SenseFly, weighed 1.5 pounds, and was equipped with a high resolution RGB camera [3].

Within an hour of arriving at the incident, high resolution, geotagged UAS imagery was collected and delivered to the incident commanders as a KML file [5]. Geotagging allowed the 280 images to be viewed in Google Earth and enabled the SAL UAS team to create an orthomosaic and map after processing the data [5]. ArcMap was utilized to display the data and was published as a map on ArcGIS Online, where it was made publicly available [5]. Considerations for privacy and ethics were kept in mind when gathering UAS data so that the flights were conducted after the injured people were no longer on-site [5]. One UAS operator noted that while privacy concerns were valid, because the images were taken vertically, identifying people in the UAS imagery was not possible [4], [5].

Following the response, a member of the SAL team expressed hopes that the application of UAS for emergency and disaster response seen in Northfield proved the technology's capabilities and utility [3]. Notably, the NTSB did not use or mention the UAS data in their investigation documents [2].

1.11.2 DuPont Amtrak Train Derailment –WA, 2017

Location: Washington

Year: 2017

FEMA Declared: No

Estimated Cost: N/A

Figure 28. Aerial view of the DuPont, WA train derailment (Wagner, 2019).

An Amtrak train crashed in DuPont, Washington, killing three passengers and injuring 68 passengers and crew on December 18th, 2017 [1]. The train was on a curve and approaching an I-5 overpass when 11 of the 14 train cars derailed because the train went over the speed limit [1]. The accident caused debris to be spread over a 920 ft by 340 ft area, including on the nearby highway overpass, which blocked traffic and led to an immediate pileup [1]. The first hour of the accident response focused on rescuing people from the wreckage and getting them medical attention [2]. In this phase of the response, there was a lack of organization and communication about where the responders were and what tasks had already been completed [2]. Communication issues were attributed to the fact that radio communications systems had been in the process of upgrading prior to the incident [2]. UAS were utilized in two different instances- one by the Washington State Patrol (WSP) and the other by the Lakeview Police Department (LPD) [1], [3]. This accident highlighted the potential uses of UAS for responding to train derailments, as well as some of the potential drawbacks associated with a disorganized UAS response.

A variety of organizations responded to the incident including fire departments, the LPD, the WSP, the National Transportation Safety Board (NTSB), and paramedics [2]. The NTSB led the investigation into the accident. Radio communication issues between organizations, especially for responders who arrived at different times, led to some disorganization and confusion [2]. Two

UAS responses were led by LPD and WSP, respectively [1], [3]. The WSP detective that led one of the UAS responses had previous experience operating the organization's UAS and had access to the WSP's fleet of multiple UAS [1].

The LPD Police Chief dispatched two officers from LPD to fly their UAS Unit 1, a 3DR Solo multirotor UAS, to capture aerial photos and video of incident that could be used by incident command [1], [3]. The other UAS response was led by WSP detective Eric Gunderson and other officers from the force and involved a DJI Matrice 200 quadcopter UAS as well as four Trimble TX5s ground laser scanners to recreate the crash scene [1]. Following the successful and effective UAS response to this event, WPS planned to increase the number of small UAS in their fleet and allow more investigators access to the technology [1].

The DJI Matrice 200, with a 20MP camera payload, was flown at 200 ft with 70% frontlap and 50% sidelap and then again for a second pass at 100 ft, and finally between 15 ft and 50 ft to collect some oblique imagery [1]. In under one-and-a-half hours, over 600 images were captured with the UAS [1]. WSP UAS data were photogrammetrically processed, while data from the TLS were processed in RealWorks to create a 3D point cloud of the scene [1]. The TLS and UAS point clouds were merged using RealWorks and provided investigators with a detailed 3D model of the entire crash scene that could be used to measure objects, make more detailed observations, and virtually navigate the scene [1]. UAS data allowed for more complete recreation of the scene by providing data of areas that TLS could not access [1]. Point cloud editing allowed excess points, primarily of people and vehicles, to be removed from the model and helped ensure clear data and reduce potential privacy concerns [1]. WSP data and models were shown to and shared with NTSB personnel, and although it was unclear of how NTSB utilized the data for this event, the organization is currently developing a process to further integrate UAS technology into their investigations [1], [4].

Although communication in the early phases of the emergency response to the DuPont train derailment was disorganized and poorly coordinated, the UAS response to the event was successful and provided valuable information to decision makers [1]-[3]. Having the ability to generate a detailed, 3D model of the crash scene not only enabled investigators to make more informed decisions, but also allowed for documentation of the event [1].

1.12 Technological – Biohazard

1.12.1 Permian Basin Methane Leaks–TX & NM, 2018

Location: Texas & New Mexico

Year: 2018-2020

FEMA Declared: No

Estimated Cost: N/A

Figure 29. A UAS inspects pipelines in the Permian Basin (Magill, 2018).

From 2018 to 2020, the companies Shell and Avitas tested the ability of UAS to detect methane leaks at over 500 Shell facilities across the Permian Basin, an area in western Texas and southeastern New Mexico [1]. Shell facilities experienced methane leaks, which the company needed to stop in order to reduce their greenhouse gas emissions [1]. Shell had used UAS for inspections at facilities in other areas of the world and wanted to integrate that at US facilities [1]. Avitas, a General Electric subsidiary, operated the UAS for Shell and was developing a framework and AI for autonomous facility inspection [1]. The two companies tested their methods over a two-year pilot program before Shell decided to employ small fleet of UAS [1]. The goal was to make the inspection processes fully autonomous [1].

The UAS operation was conducted by Avitas, who got permission from the FAA to fly the UAS beyond visual line of sight (BVLOS) during the initial phase of the project [1]. With the BVLOS waiver, the company tested two different UAS [1]. It was decided that the BVLOS certification would not be used for their current implementation and that operations would be kept within line of site [1]. Long term, BVLOS could be useful to Avitas due to the large area that Shell has facilities in and if the inspection process becomes automated [1].

The DJI Matrice 600 Pro and the AeroVironment VAPOR 55 UAS platforms were tested for their abilities to monitor facilities for methane leaks, but the program only utilized the DJI Matrice 600

Pro after the initial testing [1]. Matrice 600 Pro, a multirotor UAS, was equipped with an optical gas imaging camera and a laser-based detection system [1]. The AeroVironment VAPOR 55 had the same payload, but was a helicopter UAS [1]. The platforms were used in combination with AI software platforms and data collection configurations- the systems that would enable autonomous inspections [1].

1.13 Technological

1.13.1 Lincoln County Helicopter Crash –NV, 2020

Location: Nevada
Year: 2020
FEMA Declared: No
Estimated Cost: N/A

Figure 30. A UAS operator flies an EVO II Pro UAS following the helicopter crash (McNabb & Eagle, 2020).

A EuroStar 350 helicopter crashed in Lincoln County, Nevada, killing the pilot and passenger on July 29th, 2020 [1]. This led to an extensive investigation in the rugged, forested, and remote area where the helicopter crashed [1], [2]. The county Sheriff's office as well as other organizations responded to the event [1], [2]. The crash investigators called in a team from the Sundance Media Group to lead UAS operations and assist in locating parts of the crash [1]. Products created from the UAS data helped investigators determine the extent of the crash and recover debris [1]. UAS operations increased the investigators' safety and decreased the time that would've otherwise been allocated to search the difficult terrain [1].

The Lincoln County Sheriff's Office, the FAA, and NTSB responded to the incident [1], [2]. The NTSB led the investigation [1], [2]. UAS operations were conducted by a team from the Sundance Media Group LLC that consisted of three, FAA Part 107 licensed pilots who had a lot of experience in flying UAS [1], [3]. The operators' roles in Sundance Media Group were UAS operations instructors, and training others to become instructors themselves [3]. The company provided UAS instruction, consulting, and operations from multiple locations in Nevada and Utah, with staff from a variety of backgrounds [3]. The company obtained a 107.29 waiver for daylight operations valid until June 30th, 2021. The UAS operations did not extend into nights [4].

Two Autel Robotics Evo II Pro UAS were deployed for this response, along with seven Hoodman GCP discs, two tablets, and a computer [1]. The Evo II Pro quadcopters were equipped with high resolution cameras, as well as strobe lights to facilitate potential night operations [1]. The Hoodman GCPs were placed in a variety of locations throughout the approximately 70-acre mapping area and were used for RTK corrections and later as manual tie points during image processing [1]. These points served as markers to increase the accuracy of the imagery data [1].

Tablets were used to create preplanned flight paths in the Autel Mission Planner software, where one UAS covered the area in a north-south pattern, while the other flew from east to west [1]. Preplanning was especially important to avoid collisions and collect the highest quality data possible [1]. The UAS were operated simultaneously to collect the data more quickly and avoid shadow distortion in the final product [1]. The UAS were launched from opposite sides of the area and at different times and one UAS was flown at a slightly higher altitude than the other [1]. The UAS were flown at low altitude with a high ground sampling distance at a speed of 11 miles per hour [1]. These settings enabled high resolution data collection without any issues such as blur or streaking, and it would allow investigators zoom in on the final product to identify parts of the helicopter [1]. UAS imagery was utilized to generate a point cloud and high-resolution imagery that was given to investigators so that they could recover the helicopter parts and determine extent of the crash [1]. The primary final products included a 3.5 GB GeoTiff map viewable through Google Earth, and a dense point cloud that could be viewed in Pix4Dmapper [1]. The map consisted of nearly 7,000 images with many 2D and 3D points that investigators could use to identify locations of scattered aircraft parts amidst the dense vegetation [1]. Utilizing the detailed UAS imagery products was far more time efficient compared to manually searching the crash area [1].

1.14 Wildland Fires

1.14.1 Santa Rosa Wildfires –CA, 2017

Location: California

Year: 2017

FEMA Declared: Yes (DR-4344-CA)

Estimated Cost: $14.5 billion

Figure 31. UAS image of fire damaged building (DroneDeploy, 2018).

In 2017, the Santa Rosa wildfires in Sonoma County, CA, destroyed over 6,600 properties. Post-disaster, insurance estimators evaluated residences to process claims. Accurate Estimates Inc., a reconstruction insurance estimating company, utilized UAS data following the disaster to determine the damage to infrastructure [1]. The company was able to assess more homes with increased personnel safety with UAS [1]. Given the presence of debris, unstable structures, and other hazards, gathering the observational data for claims can be very dangerous for the estimators, particularly given that they are not always familiar with the area. These challenges can be significantly alleviated by employing UAS.

The application of UAS improved safety and efficiency of data collection in the Santa Rosa wildfires [1]. Following the fire, a small UAS was flown over each property and true color imagery was collected to create a high quality orthophoto map as well as a 3D model, the example above is from December 12, 2017 [1]. A key benefit to utilizing the UAS is that the estimator does not need to walk on dangerous piles of rubble unlike the typical process in which the estimator must carefully use a tape measure or laser measurement system to acquire the information in the rubble [1]. Integration of UAS into their workflow increased the estimators' efficiency compared to traditional damage assessments conducted in the field [1]. Safety issues arose during the emergency response to the fires due to hobbyist UAS flying in restricted airspace and over an airport [2]. The incursion of UAS into highly trafficked, restricted airspace meant that responding fire departments' aircraft had to remain grounded, and in turn, were not able to mitigate and manage the spread of fires [2].

A DJI Phantom 4 Pro multirotor and free flight UAS platform was used for data collection. The UAS was operated through the app DroneDeploy with either a tablet or computer [2]. The UAS acquired images of the property. These images were then processed to generate mapping products, such as an orthomosaic and digital surface models [1]. The imagery products and models were utilized to measurement features like building footprint dimensions, room sizes, and presence and size of pools [1]. In one example, mosaicked products used 115 images to build a true-color map of the destroyed property and surrounding landscape.

In the future, the president of Accurate Estimates Inc. wants to continue using UAS as well as expand its usage to perform pre-disaster assessments. He believes that assessing homes from the inside and outside with UAS before disasters could simplify the insurance claims process [1]. Although UAS and Global Positioning System (GPS) technologies were not advanced enough at the time to enable effective indoor assessments with UAS, recent and upcoming advancements could make doing so a viable option.

Emergency operators and airspace management personnel reported that from 2015 to 2016, the number of amateur UAS flights that interrupted wildfire fighting efforts and restricted airspace increased from 12 to 42 cases, respectively [4]. Cal Fire personnel hope that efforts to educate the public on the hazards of doing so will help ensure timely, safe, and uninterrupted responses to similar events in the future [4].

1.14.2 Parker 2 Wildfire –CA, 2017

Location: California

Year: 2017

FEMA Declared: No

Estimated Cost: n/a

Figure 32. DOI UAS Operator (Davis, 2018).

The Parker 2 wildfire burned a total of 7,697 acres in northeastern California between August 3rd and 28th, 2017 [1]. The fire occurred in Modoc National Forest. The event marked a significant point in the DOI use of UAS for wildland firefighting [1], [2]. The response demonstrated unparalleled cooperation between involved organizations and established unique UAS capabilities within DOI for deployment in future comparable events [2].

The FAA granted permission for DOI personnel to map a 500-acre area with potential spot fires using UAS [2]. The COA from the FAA for this work lasted for 24 hours and allowed UAS operation in the TFR zone, which would usually be reserved for other firefighting aircrafts [2]. Notably, for the first time, this COA allowed a waiver for operating UAS beyond visual line of sight (BVLOS), enabling much more expedient data collection and subsequent response [2].

The Firefly6 Pro, a fixed-wing UAS, was deployed for this mission and is manufactured by BirdsEyeView Aerobotics [3]. The platform can be equipped with a radiometric infrared camera, visible cameras, and a 10-band visible-near infrared multispectral sensor [3]. The UAS flight path was preprogrammed to fly over a 500-acre area of rugged terrain nearby, with a flight distance of 19 miles and a flight time of 34 minutes [2]. The UAS imagery was processed in GIS to generate a 3D topographical infrared model of the area, which was then used to determine and analyze characteristics of the fire [2].

The 3D infrared map served to identify remaining hotspots, the fire's perimeter, and to evaluate and quantify the number of acres burned from the wildfire [1], [2]. The fire occurred in Warner Mountains of northeastern California in the Modoc National Forest, which is managed by the US Forest Service [1]. The operators were prequalified by the National Wildfire Coordinating Group, enabling them to set their base station within the fire perimeter [2].

The ability for experienced personnel to operate UAS BVLOS saved time and increased safety for collecting data about the fire. The short flight time made data collection quick, especially when compared to traditional operations, which would require a team of 20 firefighters and several days to do the equivalent amount of field surveying [2]. Not only did this reduction in personnel benefit overall mission efficiency and cost, but it also enhanced safety by limiting the number personnel that needed to be in close vicinity to the wildfire. An important operational safety consideration for this mission was ensuring that the UAS operators were experienced. The DOI works closely with the FAA for purposes such as this. In addition to the UAS used in this case study, the DOI also has a large fleet of UAS that they use for other scenarios [2]. One example is the 3DR Robotics Solo Smart multirotor UAS, which fits into a backpack [2]. The UAS team also had this system with them at the wildfire as a backup [2]. Such a highly portable system could be utilized by appropriately trained fire crews in remote areas to perform future surveying work [1].

1.14.3 Weaver Dunes Fire –MN, 2017

Location: Minnesota

Year: 2017

FEMA Declared: No

Estimated Cost: N/A

Figure 33. The Nature Conservancy workers oversee the prescribed burning of a grassland (Restoring Fire to Native Grasslands, 2018).

The Weaver Dunes Preserve is a 320-hectare area of sand prairie in Wabasha County, Minnesota. On May 23rd, 2017, The Nature Conservancy (TNC) conducted a series of prescribed burns in the Weaver Dunes Preserve [1]. TNC carries out prescribed burns periodically in order to maintain a healthy sand prairie habitat. Three weeks following these burns, a team of personnel from the University of St. Thomas, MN, collected and analyzed UAS data for a 2.6-hectare portion of the previously burned area [1]. The data were analyzed to assess how terrain characteristics affected the distribution of ash post-fire [1]. The three-person team also provided an analysis on UAS practices [1]. UAS were chosen for this application over traditional methods like satellite imagery, manned aviation, and ground surveying due to their ability to produce high quality imagery, efficient and quick data collection capabilities, and relatively low cost [1]. Notable limitations of the UAS were predominately technological, such as battery size and flight time [1]. Variation in image resolution and clarity caused by changes in ground sampling distance and camera movement were identified as additional limitations of the platform [1].

The DJI Inspire 1, a quadrotor UAS, equipped with a DJI Zenmuse visible wavelength X3 camera was utilized in this mission [1]. The pilot was certified under Part 107 of the FAA and consulted the FAA app B4UFLY to determine possible airspace restrictions [1]. Flight path planning and UAS monitoring were carried out using the iPhone app Map Pilot [1].

Geotagged, true color imagery and elevation data were gathered by UAS and leveraged to create a DSM and an orthophoto mosaic [1]. The imagery data were processed in Drone2Map to generate a DSM and an orthophoto mosaic [1]. ArcGIS v.10.4 was used to map ash from the fires; the slope, elevation, and aspect of the terrain; and to export data tables [1]. Statistical Package for the Social Sciences (SPSS) software allowed researchers perform statistical analyses on environmental factors such as ash coverage and terrain characteristics [1]. From these products, slope, elevation, and aspect were evaluated in relation to ash coverage, and it was determined that low-lying areas and north-facing slopes were more likely to see ash accumulation following the May 2017 fires [1]. Steep slopes were determined to be less likely to have ash accumulation [1]. These findings were unexpected to land managers, who predicted different outcomes [1]. It was hypothesized that this result was due to north-facing slopes and low-lying areas experiencing greater moisture accumulation and therefore growing more vegetation, which ultimately provided more fuel for the fires [1].

1.14.4 Taylor Creek and Klondike Wildfires –OR, 2018

Location: Oregon

Year: 2018

FEMA Declared: Yes (FM-5256-OR)

Estimated Cost: $128 million

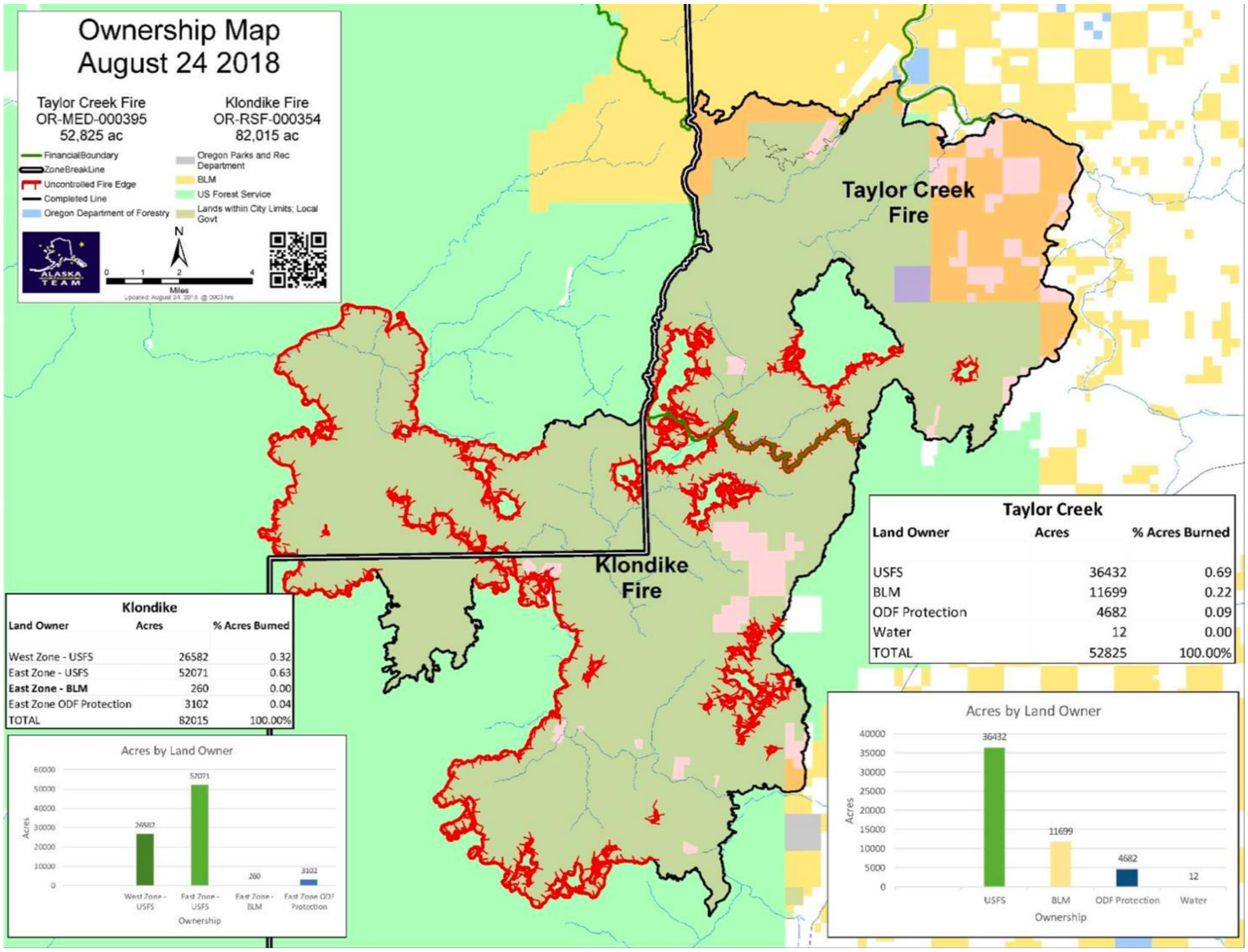

Figure 34. Burn area of Klondike and Tayler Creek Fires (Bureau of Land Management & Alaska Incident Management, 2018).

From July 15th to November 28th, 2018, lightning strikes triggered the Klondike and Taylor Creek wildfires in southwestern Oregon, which burned over 175,000 acres and 53,000 acres, respectively [1]. The Klondike Fire started within areas protected by the Oregon Department of Forestry, whereas the Taylor Creek Fire was triggered in land managed by the BLM [2]. Although both fires originated in separate locations, they grew and connected with one another and as a result, the two fires are typically referenced together.

Organizations involved in the response included the DOI, the US Forest Service, the BLM, the Oregon Department of Forestry, Incident Management teams from various states and regions, and many firefighting agencies [2]. This disaster response demonstrated how different types of UAS could be used in various capacities, as well as how an operational system for UAS could be implemented between private operators and public incident commanders. Throughout the response, Incident Management Teams (IMTs) were cycled every two weeks and strategies were adapted to solve problems, ultimately leading to a successful containment by November [1]. One team, the Alaskan IMT, published a detailed report on their management from August 13^{th} – 25^{th} [2]. On August 18^{th}, the decision was made to split the fires into an east portion and west portion, so the California IMT managed the west portion, and the Alaska IMT managed the east portion [2]. A team of three licensed pilots from Insitu, a Boeing subsidiary, operated the UAS [3]. One pilot was also a Geographical Information Systems (GIS) Specialist [3]. The team operated the UAS, received data, and communicated with firefighters from inside a truck located several miles away from the active burn area [3]. A federal employee served as the mission's UAS Manager, who handled communication between air and ground operations to ensure that FAA guidelines were met, and flights were safe [4]. Lastly, a federal Data Specialist worked with the incident GIS Specialist to produce data products from the flights [4].

Two UAS platforms, the Ignis 2 and ScanEagle, were utilized in the Taylor Creek Fire response, with the former also being employed for the Klondike Fire response [2]. A team from the University of Nebraska, that later became the company Drone Amplified, operated the Ignis 2 (a DJI Matrice 600 variant) [5], [6]. The multirotor platform was equipped with the DOI's UAS Plastic Sphere Dispenser, which contained ignition spheres filled with chemicals that burned when dropped [2], [3], [6]. The UAS operator used Drone Amplified's app, Ignis, to control the flight path and where spheres were deployed [6]. The app allows the operator to view elevation, satellite imagery, and real-time video without needing an online connection, which can be helpful when operating in isolated areas [6]. The company also produces, sells, and instructs people and organizations on how to use the specialized platform [5], [6]. Optional UAS payloads included red-green-blue (RGB) and thermal infrared cameras for monitoring fires and personnel, specifically the DJI X3/Z3 and Z30/XT2 [7], [8]. The Alaskan IMT reported that the UAS Plastic Sphere Dispenser was very useful for starting prescribed fires in rugged terrain and at night [2]. Additionally, the technology offered a safer solution than some traditional methods that would have put firefighters and other personnel at risk [2]. The second platform utilized was the ScanEagle, a 26.5 kg fixed-wing UAS that was deployed from high elevation by a pneumatic launcher and flew over a predefined area [3], [6], [9]. The payload consisted of an actively operated, thermal-infrared camera [7]. In addition to monitoring fires, the UAS served to search for damage and danger to other key landmarks or infrastructure [4]. The ScanEagle was used actively with firefighters on the ground, whereby the pilot would communicate with firefighters about the locations of spot fires that would likely not have been found otherwise [3], [4]. The ScanEagle was primarily flown at night because the thermal camera allowed for easier identification of fires [4]. Additionally, operating a UAS, as opposed to manned aircraft, avoided putting pilots at risk when flying in potentially dangerous conditions and at night [4]. Collecting data at night allowed data to be prepared for IMTs morning briefings, where subsequent decisions on response efforts could be made [4].

Under the management of the Alaska IMT, data management practices could be altered if needed and proved useful for dispersing final products and relevant information to all groups involved. A challenge that arose concerned data management because resource advisors were using two different data platforms (ArcGIS Collector and Avenza) for uploading collected data [2]. The IMT Resource Advisor Coordinator worked with data managers to streamline and coordinate the workflow to address this issue [2]. A report from the Alaska IMT recommends that for future events, further preparation to integrate field data is necessary [2]. Internet access posed another issue for the two remote teams working with data [2]. The teams encountered problems when trying to upload information to and/or view information in their databases [2]. This problem was resolved by working with the internet service provider (ISP) vendor to improve access [2]. The collected UAS data were held in these databases and made accessible to all teams, making access an important component of the workflow [2]. To expand access to data and increase public safety, firefighters and IMTs were encouraged to utilize social media and news sources [2]. The mission's Information Officer had daily Facebook livestreams in the morning to share updates about the fires, including many maps that incorporated UAS data [2]. News and media visits to the fire lines or the IMT and reporting on their findings for the public, which included discussions about the UAS operations, were pre-approved [2]. Geotagged data were utilized to produce perimeter mapping and orthophotos (which were distributed in a variety of formats), as well as an Arc GIS Story Map [10].

Both the UAS Plastic Sphere Dispenser and ScanEagle proved useful in responding to the wildfires and helped to develop better practices for fighting fires. The response benefited from the ability of UAS to fly in conditions that manned aircraft could not, such as smoke, inversion conditions, and at night [4], [9]. With its ability to initiate controlled burning, the Plastic Sphere Dispenser decreased risk to firefighters [8]. UAS proved a worthy investment for the Oregon Department of Forestry, which first integrated UAS into their workflow in 2017 and plans to continue using the technology for similar incidents [8]. The involvement of federal management alongside private UAS operators led to an effective and thorough emergency response to the Taylor Creek and Klondike Fires. These efforts and their results provided key insights and recommendations for future wildfire responses and demonstrated the ability of UAS to augment existing emergency response practices.

1.14.5 Maroon Wildfire –AZ, 2019

Location: Arizona
Year: 2019
FEMA Declared: No
Estimated Cost: N/A

Figure 35. Firefighters prepare UAS for flight (USFS Coconino National Forest, 2019).

On May 16th, 2019, a lightning strike in Arizona's Coconino National Forest generated a wildfire burning 8,605 acres of forest over the course of three weeks [1], [2]. The incident management team that responded to the event deployed UAS to both monitor for spot fires and conduct prescribed ignitions [1]. A survey conducted by the US Army confirmed the existence of unexploded ordnance in the area, which had formerly been an artillery training field in the 1940's and 50's [3]. Given the significant risk that potentially explosive remnants posed to anyone in or around the area, the US Army developed plans to remove these hazards in 2020 [3]. The use of UAS helped ensure firefighting crews on the ground remained safe from any undetonated material and decreased risks to manned aircraft pilots that would have otherwise had to visually survey the wildfire [1].

UAS pilots from the BLM coordinated with the FAA to conduct their operations. The BLM pilots were Part 107 certified and had training in fire-line safety [1]. The operators received a waiver for flight inside the established Temporary Flight Restriction (TRF) and coordinated with local air traffic control towers [1]. Operators noted the need for high amounts of coordination to ensure that the UAS, helicopters, and occupied aircrafts were flying safety at different elevations.

The UAS deployed at the incident was a DJI Matrice 600 multirotor platform. The UAS was equipped with a DJI XT2 thermal infrared sensor used to provide video and imagery of the location and extent of spot fires [4]. Additionally, the UAS carried an Ignis 2 Plastic Sphere Dispenser payload, produced by Drone Amplified [1]. This allowed operators to drop small spheres containing a chemical that would ignite on a delay after being dropped from the UAS, effectively creating a backing fire [4]. The UAS operator used Drone Amplified's app, Ignis, to control the flight path and locations where spheres were to be deployed [2].

Similar to the Klondike and Taylor Creek fires, the usage of UAS for wildland fire response was operationally successful. For manned helicopters to drop fire-starting materials, the pilots must fly slowly and low to the ground. This can be a safety concern when attempting to respond to a fire in areas heavily surrounded by trees, buildings, power lines, or other obstacles. Use of UAS in this response decreased the potential risks for both helicopter pilots and firefighting crews on the ground from the dangers of potential unexploded ordinances. The UAS was important in this role compared to a manned helicopter given the lurking danger from undetonated explosives and high-voltage electrical infrastructure nearby [1].

1.14.6 2020 Wildfires in Oregon

Opportunities and Challenges with UAS Technology in Response to the 2020 Wildfires in Oregon

Introduction

UAS technology can be utilized for several purposes in a variety of disaster situations. In the US, UAS use in disaster response dates back to 2005, when the Texas A&M University CRASAR at the University of South Florida used small fixed-wing and helicopter-style UAS to search for Hurricane Katrina survivors in Mississippi [1]. However, the use of UAS in disaster situations at this time was minimal, given concerns that the UAS could disrupt crewed aircraft flights [2]. Additionally, to operate a UAS in a disaster situation, a COA was required, which could be challenging to obtain and required following strict procedures [3].

Nevertheless, many of these problems were gradually resolved [4] as research progressed on the use of UAS in disaster situations and as research progressed in the fields of lightweight sensing technologies, communication relays, and aerial mapping technologies. In response to these changes, the FAA issued the Small UAS Rule (Part 107) in 2016 as a new regulatory framework for the use of drones for commercial, non-hobby purposes [5]. Part 107 enabled much broader UAS operations for commercial, governmental, and academic purposes. Combined, these technological and policy developments have created an environment where UAS can be more readily utilized in disaster situations.

While UAS have been utilized in many types of disaster response applications, this case study focuses on their usage in preparation for, during, and in response to the 2020 Labor Day fires in Oregon. These fires were one of the most catastrophic on record in the state of Oregon. The fires killed at least 11 people, burned more than 1 million acres of land, and caused more than 40,000 people to flee their homes [24]. The fires caused a $5.9 billion loss for Oregon's forest-dependent industries and businesses [#1]. Recovery costs for the state are estimated at $1.15 billion [#2]. The rapid amplification in scale and intensity of wildfires threatening wildlife, humans, vital infrastructure, and natural resources at unprecedented levels. To help combat these issues, government agencies and firefighters used sophisticated resources and technologies in their attempts to control the unpredictable and rapidly spreading wildfires, including UAS.

Given its flexibility, ease of deployment, efficiency, and ability to offer unique vantage points UAS is showing increased use in wildfire response. UAS can provide data on wildfire impacted areas that are inaccessible to humans, directly or indirectly help rescue lives, and can help to establish a post-disaster damage assessment and recovery plan. Although there have been several studies documenting the use of UAS technology in disaster response, most studies focus on the technological and tactical aspects such as the sensors utilized for a specific application. Relatively few studies have documented how actual disaster-related organizations use UAS and practical challenges they face [1]. Hence, this case study of UAS usage in the 2020 Labor Day fires in (1) captures and qualitatively analyzes information obtained through detailed interviews with respondents (2) identifies current UAS utilization, applications, infrastructure, and standards, (3) documents the technical, political, and social challenges that arise when attempting to use UAS technology to aid in the response, and (4) serves as an important foundational study to create a framework for safe, effective, and systematic UAS utilization for wildfire mitigation, response, and recovery.

Background

This section describes select examples (Table 1) of how UAS technology has been utilized in recent disaster response and potential opportunities based on recent research utilizing UAS. It will focus only on earthquake, tsunamis, wildfires, and hurricanes to provide sufficient information to the reader to have a broad view of how UAS technology is utilized without detailing every possible natural or anthropogenic hazard that has utilized UAS technology. Example use cases are organized by application including search and rescue (SR) operations, general reconnaissance and mapping (RM), detailed damage assessment (DA), and monitoring and detection (MD)

Table 1. UAS use cases by disaster type. SR = Search and Rescue, RM = Reconnaissance and Mapping, DA = Damage Assessment, MD = Monitoring and Detection.

Disaster type	Appli-cation	Example UAS uses
Earth-quake	RM	- Mapping of earthquake-affected and hazardous areas [##2][##3] - Earthquake-induced debris distribution mapping [##4]
	DA	- Initial damage assessment immediately after earthquake [##5][##6] - Structural damage assessment [##7]
	MD	- Providing real- time monitoring data for disaster responder [##8] - Tracking of hazardous areas after earthquake [##] - Earthquake-induced debris slides and rockfalls monitoring, [##10]
	Other	- Disaster management before and after earthquake [9][##11] - The relief distribution system by UAV [##12]
Tsunami	SR	- Evacuation guidance in case of tsunami [10] - Assisting SAR (search and rescue) operation by delivering floatation devices [2015 Johnson County, TX] - Assisting in the establishment of rescue plans by real-time video of disaster areas obtained with UAS [2015 Little Androscoggin River, ME]
	RM	- Tsunami vulnerable area management and disaster response plan establishment [11] - Tsunami hazards modeling [12] - Inundation depth estimation using UAV images and topographic data [Gebrehiwot and Hashemi-Beni 2021]
	DA	- Surveying the degree of inundation of infrastructure [##13] - Damage assessment of urban areas via UAS derived data [Mohammadi and Wood 2018]
	Other	Acquisition of base data for flood prediction modeling [12]

Disaster type	Appli-cation	Example UAS uses
Hurricane	RM	- The employment of UAS in imagery and video data collection in Hurricane-affected areas at the city and region level [The 2016 Hurricane Matthew, Carolinas, USA] [14] - Reconnaissance to develop disaster mitigation plans for hurricane-affected and anticipated areas of risk [##14]
	DA	- Infrastructure damage assessment [Yeom et al. 2019] [Cheng et al. 2021] - Hurricane damage assessment for coastal areas [Rey et al. 2019]
	MD	- Monitoring changes in coastal areas affected by hurricane [Klemas 2015] [Rey et al. 2019] [16] - Collecting post-hurricane imagery of flooded regions [2020 Hurricane Delta, LA]
Wildfire	SR	- Acquiring real-time image and video data for evacuation planning during and after wildfires [19][20] - Helping with rescue operations (finding injured, proving remote assistance, fire alert and relief material distribution) [##15]
	RM	- Mapping of areas affected by wildfire [##16] - Acquisition of image and video data to predict the path of wildfire [##17]
	DA	- Infrastructure damage assessment [2017 Wildfire, Santa Rosa, CA] - Investigation of vegetation distribution in forest areas before and after wildfire [##18]
	MD	- Establishment of an early wildfire detection system [20] [21] [22] - Periodic reconnaissance for real-time wildfire detection [##19] - Tracking vegetation recovery after wildfire [19] - Tracking smoldering from wildfire [##20]
	Other	- Acquisition of base data to analyze the characteristics of wildfires [##21] - Distribution of fire suppression supplies [23]

- **Earthquake**

Following a significant earthquake, UAS are used to collect 2D orthophotos, video logs, or 3D geometric information to document damage patterns throughout an impacted city, capture detailed geometric information on failed infrastructure for forensic information, and map and measure ground movements to evaluate stability and further risk [6]. Although often not available, high quality baseline data from pre-disaster UAS flights can significantly improve quantitative damage analysis after disasters [9]. In many cases lower quality satellite data are used given their wider availability. Not only are the data important to capture the damage from the actual event but repeat flights can be implemented to efficiently monitor changes to the ground surface, slopes, or infrastructure after the earthquake or aftershocks. These applications have been demonstrated in several recent events. For example, following the 2016 Kumamoto, Japan earthquake, data collected by UAS were used to develop three-dimensional models based on the SfM (Structure-from-Motion) reconstruction technique and to identify and quantify damages throughout the affected area [7]. As another example, UAS technology was utilized in reconnaissance to obtain high resolution imagery of the significant damage observed throughout Palu City and the surrounding Central Sulawesi region of Indonesia following the 2016 Palu-Donggala earthquake [8]. In this application, the UAS proved useful to rapidly capture information across a large flowside area efficiently, particularly areas that are difficult, if not impossible, to access by humans in faced with a post-earthquake situation.

- **Tsunami**

UAS have been utilized to collect data on the inundation extents following tsunamis as well as to generate digital elevation model topographic information to simulate the substantial fluctuations in water levels when a tsunami occurred. For planning purposes, high resolution UAS image data can be analyzed in GIS software to estimate areas likely affected by tsunamis based on scenario events to develop disaster response and mitigation plans [11] and develop evacuation plans [10]. Similar to earthquakes, UAS technology is also used for post-disaster damage assessment. For example, a UAS equipped with an infrared camera was used to detect faults in large-scale Photovoltaic (PV) plants in tsunami-affected areas. This utilization is very useful not only in terms of economy, but also in that it can quickly detect secondary damage after a tsunami [12]. In addition to infrastructure evaluation, UAS has the potential to be utilized in direct lifesaving applications such as providing immediate evacuation guidance to persons in tsunami hazard zones [11]. In this application, multiple UASs coordinate and continuously share information with each other such as their location, battery levels, evacuation guidance routes, and the number of people each system has guided [13].

- **Hurricane**

UAS played an important role to support reconnaissance of areas impacted by hurricanes by enabling maps to be generated quickly showing heavily impacted areas. Yuan, and Liu [14] devised a framework that combines UAS with social media to quickly deploy UAS to affected areas of need to obtain timely information to aid responders. Considering areas affected by hurricanes are generally extensive, UAS can play important role in determining the extent of damage and planning the recovery efforts compared with boots on the ground approaches. When compared to reliably baseline data (e.g., orthophotos, LiDAR DEMs), remote sensed data from UAS can serve as a low-cost tool to accurately quantify topographical changes before and after hurricanes As an example, after Hurricane Maria, Schaefer et al. [15] performed rapid change detection for a damaged area by comparing UAS imagery to aerial photographic data collected prior to the storm. Notably, given that the UAS is relatively vulnerable to wind and rain, it has been mainly used for damage assessment after disasters such as hurricanes [16] [17]. Hence, its usage is limited during hurricane events and in the immediate aftermath for search and rescue purposes until environmental conditions have calmed down to the point where the UAS can be safely operated.

- **Wildfire**

UAS are being widely used and studied as a potential tool to detect wildfires. Early wildfire detection is very important in preventing large-scale fires, which can grow rapidly. Current fire detection technologies based on satellite imaging or remote cameras tend to be slow to detect and have less accuracy [18]. Samiappan et al. [19] compared the UAS-based classification produced from the Normalized Difference Vegetation Index (NDVI) and a DSM with the Landsat-based Burned Area Reflectance Classification. The authors noted that a UAS platform with a multispectral sensor could provide more timely data to map the extent of the burned area.

Researchers are currently exploring deep learning methods using UAS imagery to rapidly detect and monitor wildfires to inform respondents. Although, UAS has been proven to be an effective tool to support a variety of monitoring and detection tasks [20] [21], most of this monitoring is done manually by observers watching video feeds from the UAS. In deep learning, a substantial database of images are manually annotated (e.g., fire) to train a neural network that can be used to automatically identify similar features in other images [22]. Hence, deep learning could potentially automate the detection of fires in images and reduce the manual effort required, allowing respondents to more effectively utilize their time in the response in priority locations.

UAS also plays a role as a tool to transport and drop fire suppression materials (e.g., fire retardant, water, or other extinguishing agent) at strategic locations within a wildfire [23]. The UAS enables the fire to be extinguished in a safer way than the conventional manned helicopter method, which puts people directly in harm’s way flying over the flames and smoke from the fire.

Methods

Figure 36 shows the research methodology to implement the questionnaire and synthesize the results. Information on UAS usage by agencies in response to the 2020 Labor Day fires were collected through semi-structured interviews. A questionnaire was drafted to guide the conversation with questions organized into topical areas (Figure 1) to address the four objectives of this research. The questionnaire consisted of open-ended questions with prompts for responses, when needed. Questions were drafted based on information gleaned from the literature as well as discussions with other researchers specializing in UAS utilization in disaster response. Given the limited usage of UAS technology and potential number of respondents, a snowball approach was utilized for participant recruitment. In addition, after each interview, the questionnaire was revised to tailor questions better to the target audience based on input received from the prior interviewee. The questionnaire and associated interview methodology was submitted and approved by Oregon State University’s Institutional Review Board.

Several methods were employed to identify potential interviewees consisting of government officials and UAS experts involved in the response to the wildfires. First, several potential interviews were identified through collaboration networks of the authors and their colleagues. Next, the research team conducted an extensive search through media articles to identify key personnel at agencies involved in the response. Additional potential respondents were subsequently identified by searching through public agencies websites. If a clear candidate could not be identified from the webpage, the head of relevant divisions were contacted who then identified suitable personnel to participate in the interviews. Lastly, interviewees were asked to provide names of other potential respondents.

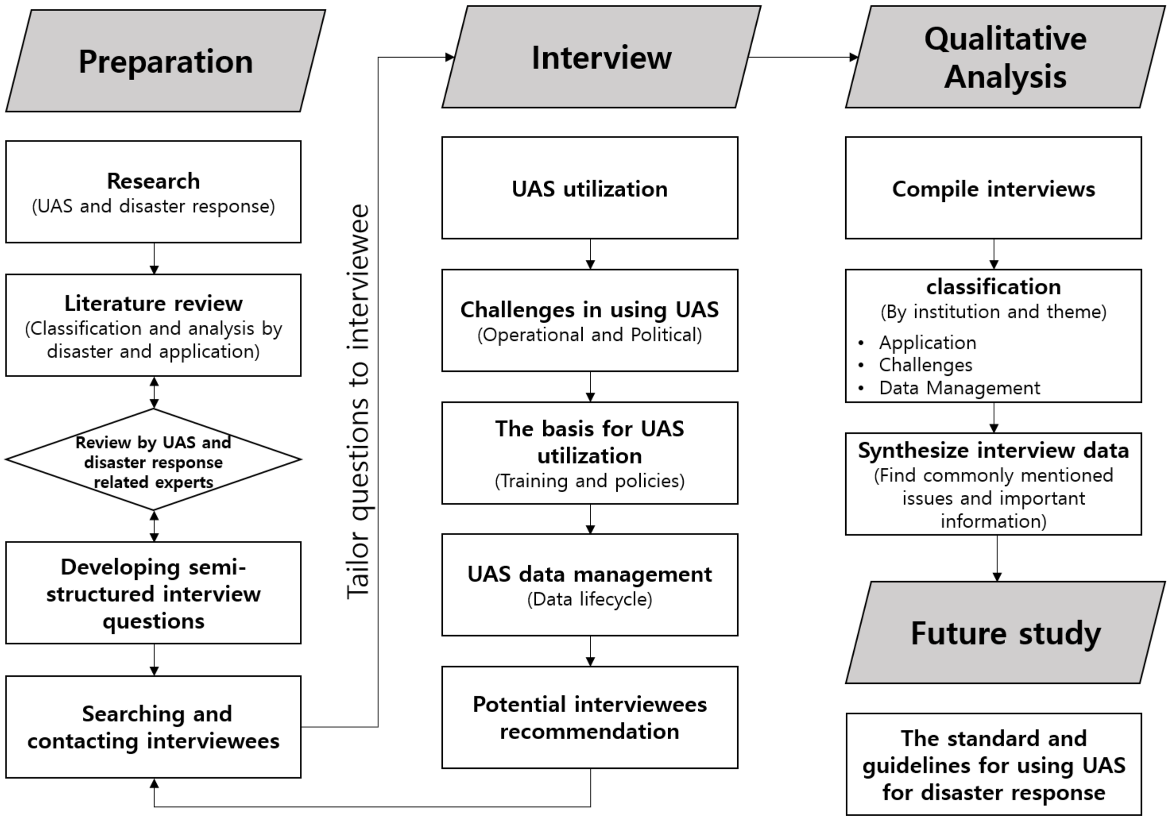

Figure 36. The overview of the research methodology for the application of UAS for disaster response

Each interview was conducted as a web videoconference and lasted between 40-60 minutes. The interview questions generally followed the order shown in Figure 1. First, questions were asked about the use of UAS in general and their use in wildfire situations. Through this question, the authors tried to obtain information about how each institution currently utilizes UAS. Then, the authors asked if there are any problems or points to be improved in the process of using UAS to identify reasons limiting the usage of UAS. Lastly, questions were asked about UAS-related policies, training resources, and UAS data management and sharing. Some respondents then provided follow up materials such as presentations and documents that could be reviewed by the research team. Following the interviews, key information was transcribed from notes and review of recordings to ensure all important information was document.

Given the semi-structured format, the authors implemented a qualitative analysis methodology to explore how UAS was used before and after wildfire disasters, what were the major barriers, and how the collected UAS data was managed. The obtained interview data provided by each respondent were first integrated for each question. The integrated data was reclassified according to the three pre-determined themes (application, challenges, and data management) and its sub-themes (timeline, operational and political, and data lifecycle). Through this process, the authors could both identify information commonly mentioned by several agencies as well as information that was unique to a particular respondent.

Results & Discussion

Seven people were interviewed to determine how UAS were utilized in the response to the wildfire within their agency. These interviews were timed in the "off season" to improve the availability of the respondents; however, although the major wildfire surges had resided in October 2020, potential respondents remained busy throughout the year juggling continued response work or preparation for another substantial wildfire season anticipated in 2021. The data obtained through these interviews were classified into three general categories for the qualitative analysis: UAS application, challenges, and data management practices.

UAS Applications

The respondents highlighted applications where UAS were utilized before, during, and after the disaster situation. Table 13 documents the utilization of UAS in wildfires by each agency organized by within the context of the event timeline.

Table 2. Summary of UAS use cases in wildfire response organized by timeline.

Timeline	Uses	Agencies	Explanation
Before	Overview of vulnerable areas	USFS (Forest Products Laboratory)	UAS flights immediately prior to a fire – establish baseline for monitoring/rapid damage assessment of a community
During	Reconnaissance of large wildfire areas	USFS (Aviation Management)	Replacement of reconnaissance missions performed by conventional helicopters
		USFS (Forest Products Laboratory)	
	Nighttime fire assessment	USFS (Aviation Management)	IR capabilities enable detection of fire and smoke
		USFS (Forest Products Laboratory)	
		USFS (Assistant Director Aviation)	

Timeline	Uses	Agencies	Explanation
	Aerial ignition	USFS (Assistant Director Aviation)	A replacement for aerial ignition previously performed with a helicopter
	Assist the incident management team	USFS (Aviation Management)	Using UAS provide products the incident management team wants (real time video, IR mapping, etc.)
		USFS (Assistant Director Aviation)	
During / After	Cargo distribution	USFS (Assistant Director Aviation)	Medical supplies, Fire suppression equipment, etc.
	Monitor emissions	USFS (Forest Products Laboratory)	Track smoldering
After	Damaged area mapping	USFS (Forest Products Laboratory)	After a fire, a map is created based on the damage area information using the UAS to prevent people from going to the poisonous area.
	Damage assessment	Professional emergency manager	Comparison of images before and after the fire to determine the degree of damage caused by the fire and identify areas likely to be affected requiring evacuation
	Manage hazard trees	ODOT	- Using spectral imagery to determine the health of the trees that present falling hazards. - Estimate the height and diameter of a tree as well as acquire a photograph to assess the likelihood of the tree falling into the highway.

Timeline	Uses	Agencies	Explanation
			- Investigate trees in sloped areas that are difficult for people to access.
	Rescue birds	ODOT	Using captured imagery by UAS to monitor the health of and potentially rescue birds nested on a damaged tree

The US Forest Service (USFS) uses UAS before wildfires to identify vulnerable areas and gather data on these areas. This baseline data can then be used in preparation for wildfires through strategic mitigation practices. The use of UAS during wildfires was more diverse. However, many agencies mentioned that conventional helicopter operations can be replaced with UAS as UAS can perform missions more safely and efficiently than a helicopter. The USFS used UAS for aerial ignition purposes as well when firefighter safety on the ground was compromised, or large areas of land required ignition to slow and help contain the wildfire. Aerial ignition requires flying low to the ground and at a slow speed while igniting fire. This type of flying methodology can cause accidents using a helicopter and the accidents can be reduced using UAS. UAS can also be paired with infrared cameras for photos during the wildfire. Due to required heights, most aircrafts will fly too high and only obtain photos with smoke; however, UAS can fly at significantly lower heights and obtain the necessary photos to understand where burning and combustion is occurring during the fire. Lastly, USFS incident command teams have UAS for management through real-time videos and mapping.

After the fires, there was considerable UAS use across the different agencies. First, all agencies use UAS to collect damage imagery after wildfires. This imagery is then used to evaluate the extent and type of damage that land and communities were exposed to during the wildfires. For vulnerable regions, the pre-fire imagery is used for comparison purposes. The USFS uses UAS further to monitor emissions and community activity following the wildfires. This data is used to determine which regions are safe for on-the-ground crews to start forest restoration processes. Oregon Department of Transportation (ODOT) uses UAS after a fire to determine where trees threaten right of way on roadways. UAS imagery can show where trees are significantly compromised and which trees need to be removed such that transportation through and to wildfire-impacted regions is not compromised. ODOT is also performing an ongoing study to use spectral imagery obtained by UAS to categorize the condition of trees. Currently, this data is performed using ground LiDAR, but the use of UAS with mobile LiDAR is expected to make the current work more efficient and safer. After the 2020 Labor Day fires, ODOT used UAS to monitor and rescue Osprey baby birds. A nest was constructed on top of a tree located next to a highway that was burned and needed to be removed. UAS was used to obtain images of the nest, how many Osprey were in the nest, and then remove the nest safety from the damaged tree so that the tree could be removed and prevent a life safety hazard on the highway.

Challenges in using UAS

As mentioned in the UAS utilization section, most organizations have noted that there are many positive roles for the use of UAS in wildfire situations. However, there were also challenges that each agency faced in using UAS during and after the 2020 Labor Day fires. These challenges can be broadly classified into two categories: operational and political.

- **Operational Challenges**

Table 3 shows the summary of the operational challenges in using UAS, organized by the primary problems encountered. As observed in the table, many challenges were common to several organizations.

Table 3. Operational challenges in using UAS.

Operational Challenges	Agencies	Explanation
Strong wind (stability of UAS)	ODOT USFS Professional emergency manager	When it comes to the stability of UAS technology for safe operation, moderate to strong wind is often an issue.
Flight height restrictions (< 400 ft) and the line of sight	ODOT USFS	- Staying < 400 ft above the surface of the earth is incredibly difficult and limiting when there is a steep slope - Not being able to fly outside of the line of sight is difficult to get an overall photo of the situation
Outdated software(platform) problem	USFS (Assistant Director Aviation)	Problems with the correctness of the platform currently in use
Lack of data processing experts and UAS **LiDAR** sensor	ODOT	Had sufficient staff and capacity to operate the UAS and perform data acquisition but did not have enough staff to process the data
Communication standards	USFS (Assistant Director Aviation)	Difficulties in communication between UAS and manned aircraft
Introduction of new technologies and issues of efficiency	USFS (Forest Products Laboratory)	Introduced and preliminary implementation of new technology, but the result is not efficient

Operational challenges that agencies mentioned during the interviews were in flying conditions, data processing, and communication. Instability from strong wind was a challenge that all agencies mentioned. Wildfire situations are often more extreme than normal operating conditions of UAS. High temperatures and strong winds can challenge UAS that need to fly at a constant altitude for data collection. The USFS mentioned an additional operational challenge is software. The UAS-related software they are used in the response was outdated, so there is room for error in the data processing. Relatedly, ODOT has enough personnel to gather the data in the field; however, not enough personnel for data processing. At the time of the interview, ODOT did not have personnel to processing UAS LiDAR sensor data; however, they had recently purchased this equipment to aid in future response efforts.

Operating under Part 107, ODOT is required to have a line of sight of the UAS at all times throughout the flights. This challenge is also related to the political challenge that will be discussed in the next section. According to FAA Part 107, the maximum allowable altitude is 400 feet above the ground. This limited height can be a hinderance to obtain imagery that shows the overall damage of an area, particularly when there are significant slopes and terrain variations. The USFS also has field operation challenges through communication. Communication issues can arise when both UAS and manned aircraft are flying in the same space at the same time. UAS and manned aircraft have two different communication standards and extensive standards on how to communicate individually; however, there is a lack of standards or protocols on how to communicate between these two different aircrafts. This challenge not only impedes effective response in wildfire situations but can also create safety concerns.

- **Political (and Social) Challenges**

In addition to operational challenges, political challenges were also mentioned many times by each agency. These issues are summarized in Table 15.

Experts from ODOT and USFS mentioned that the UAS procedures can be a hinderance to using UAS during or after a disaster, particularly a wildfire due to the complexity and restrictions imposed by these procedures. All agencies acknowledged the appropriateness of these restrictions around airports. For example, ODOT mentioned that altitude restrictions hinder the process of collecting data in areas with large elevation changes in the terrain. In special circumstances, the FAA may temporarily restrict access to certain designated areas of our airspace. These airspace restrictions are called TFR. This can be a problem if agencies need to use a type 1 or 2 UAS (UAS over 25 pounds). Most type 1 and 2 UAS are not owned by USFS and are used through contracts with general agencies. Therefore, rapid response will require TFR permissions, and the FAA can take considerable amount of time to issue these permissions. The second theme of political and social challenges is the use of contracts. Agencies, such as the USFS, do not have fleets of UAS. Therefore, after a wildfire, they will develop a contract with a private company for an exclusive use contract. However, because agencies such as USFS are not working with these companies on a consistent basis, scope of work must be discussed every time. This delays the deployment of UAS and collection of data. To remedy this issue, the USFS is considering conducting mission review and training together with the private contractors in advance of the wildfire season by contacting companies in advance.

Table 4. Political (and Social) Challenges in using UAS.

Political Challenges	Agency	Explanation
Flight height restrictions (< 400 ft)	ODOT USFS	FAA Part 107 (Operating Requirements)
*Temporary flight restriction (TFRs)	USFS (Aviation Management)	Type 1 and 2 (UAS over 25 pounds) UAS utilization and Special Governmental Interest (SGI) process issues.
Exclusive use contracts & Pre training and practice	USFS (Assistant Director Aviation)	Mission review, sand table exercise, training, etc.
Technological progress outweighed political progress	ODOT USFS	Policy support is needed to keep up with the pace of development of UAS technology.
Temporal cessation of UAS related training	USFS (Assistant Director Aviation)	Because of the COVID, training has been shut down for 1 - 1.5 years. On the other hand, UAS-related technologies are advancing.
Privacy issues Security issues for critical areas	USFS (Forest Products Laboratory) Professional emergency manager	- Possibility of invasion of personal privacy during UAS flight and filming. - Exposure to major national facilities.

The last theme of political and social challenges is that technological progress is outweighing political progress. For example, in a mission to classify and remove hazardous trees after the 2020 Labor Day fires, ODOT knew the effectiveness of the method using UAS (LiDAR sensor) technology, but they could not utilize it because there was no official approval from higher authorities. A careful review and verification process is essential when introducing a new technology. However, if this process and technological progress are not balanced, it will become a hindrance to the use of UAS technology in case of wildfires. On the other hand, these agencies have a rigorous certification process for the aerial fire community, which can certify the reliability of new technology. The COVID-19 pandemic presented many challenges to these agencies; however, the biggest barrier was the suspension of training. This suspension caused issued when trying to use UAS during and after the 2020 Labor Day fires because not as many agency individuals were trained compared with normal operating times.

UAS data management

A variety of data types are produced when utilizing UAS technology for many applications in wildfire response, resulting in substantial data volumes. Data types range from simple images to videos and purpose-built maps. Interviewees discussed how these data are managed by each agency, particularly from the point of view of data sharing. Notably, most agencies faced similar concerns about data management and sharing- including the difficulty of sharing across agency boundaries and refreshing data with the most up to date information. These concerns have been summarized within the perspective of the data lifecycle (Figure 2), which refers to the sequence of processes from creation, storage, use, sharing, archiving, and destruction of data.

Figure 37. Stages of the UAS Data lifecycle.

Most of interviewees mentioned the critical need for standards and specific criteria throughout the data life cycle. For example, the USFS noted that the need for protocols to distinguish which data are considered federal data and which are public data, which can be ambiguous. They also noted challenges in determining which data should be archived to serve as a formal record and which data should be disposed of as its main purpose was to inform the immediate situation and was soon outdated. Attempting to archive all data is not only a significant burden in personnel to provide all of the necessary metadata to comply with federal data sharing standards, but it also creates bottlenecks and confusion in reuse of the data in the future given the large data volume users must sift through to find the data of interest, ultimately causing the most important information to be lost.

In order to effectively (and in some cases legally) share data, a consistent data storage format (metadata) is required but there some agencies such as the USFS' Forest Products Laboratory do not have standards in place. The interviewee also noted that this lack of standards poses difficulty in sharing data within the USFS. The Aviation Management officials at the USFS said that they are working on building a better data storage system to address these issues.

Conclusion

The 2020 Wildfire season significantly impacted the state of Oregon. While UAS usage was not widespread, several agencies effectively utilized the UAS technology to support their response in many ways including mapping the burn area, monitoring the wildfires, assessing the damage, and evaluating long term impacts such as impacts on wildlife and falling tree hazards. Several challenges with current FAA Part 107 requirements were noted when operating UAS in emergency situations in steep, narrow canyons with substantial amounts of vegetation. Interviewees were optimistic that UAS technology would become increasingly used and serve as an efficient tool to aid wildfire response as some technological, political, and logistical barriers are addressed.

1.15 Industrial-Urban Fires

1.15.1 Crotona Park North Fire –NY, 2017

Location: Crotona Park North, NY
Year: 2017
FEMA Declared: No
Estimated Cost: N/A

Figure 38. Hoverfly UAS deployed by FDNY (FDNY, 2017).

On March 6th, 2017, the Fire Department of New York (FDNY) responded to a four-alarm fire at a 6-story residential building at Crotona Park North in the Bronx. At the scene, the Incident Commander and the FDNY Operations Center utilized information from a UAS to provide situational awareness and to inform decision making during the response. This was the first instance of the FDNY applying UAS technology to an incident in the field [1].

Responders from the local FDNY firehouses arrived at the residential fire along with personnel from the Command Tactical Unit (CTU) who own and operate a Hoverfly multirotor UAS [1]. At the scene, the UAS was launched adjacent to the building [1]. The UAS was put into a hover at an altitude greater than the roof of the building so that it had clear sight of both the fire and all nearby personnel. The UAS carried high-resolution color and infrared cameras that streamed real-time video to both the Incident Commander on the ground and the FDNY Operations Center [1]. This data stream was accomplished via a tether that attached it to the operator, allowing for continuous streams of data to be relayed to the computer or tablet below [3]. Following the incident, the FDNY released the video captured from the UAS through YouTube [1].

The UAS was operated by at least one person from the CTU, who was directed where to look and which camera to use by the Incident Commander and the Operations Center [1]. The CTU requires that all their UAS pilots have FAA Part 107 Certification as well as previous experience with flying their UAS and operating accessory equipment like tablets, computers, and the necessary software [3]. CTU UAS personnel also have a variety of experiences or specializations related to operations such as with Geographic Information Systems and HazMat training. [2]. As of September 2019, the CTU had 10 certified pilots [2]. The CTU UAS teams reported success in coordination and contact with the FAA when requiring permissions for flights during night or in Class B airspace. Approvals, likely via the SGI waiver process, often take less than 10 minutes allowing for the UAS operators to rapidly deploy to fires [1]. FDNY also ensure a legal advisor is either at the incident or available for consultation in case of concerns [2].

The Hoverfly UAS is the primary system that the FDNY utilized for this fire response. This is a multirotor tethered UAS, which decreases several risks associated with operations. The tether delivers continuous power to the UAS, allowing for longer operational flight times than a comparable battery powered UAS [1]. Tethering also allows for a continuous transfer of data to the ground, providing the Incident Commander with real-time information [1]. Lastly, tethering removes the probability of interference from a variety of other signal types present in urban environments [1]. At the time of the incident, FDNY owned only a single Hoverfly, but have since expanded their UAS fleet by acquiring two more Hoverfly units and a DJI Phantom 3 UAS by October 2018. The Phantom 3 is an untethered multirotor platform that may provide additional capabilities in search and rescue missions or when dealing with hazardous materials [3].

Though this was the first instance of UAS usage by FDNY for an urban fire, the department believed it was a positive showcase of the potential of such technologies both within their organization and to other fire departments [2]. Fire Commissioner Daniel Nigro noted that, as shown in this response, UAS can be a critical tool for improving the safety of firefighters and the public [1]. Following this fire, the FDNY indicated a strong interest in continued and increasing use of UAS for urban fires, potentially even introducing UAS at the battalion level [2].

1.15.2 Oil Well Fire –CO, 2020

Location: Colorado

Year: 2020

FEMA Declared: No

Estimated Cost: N/A

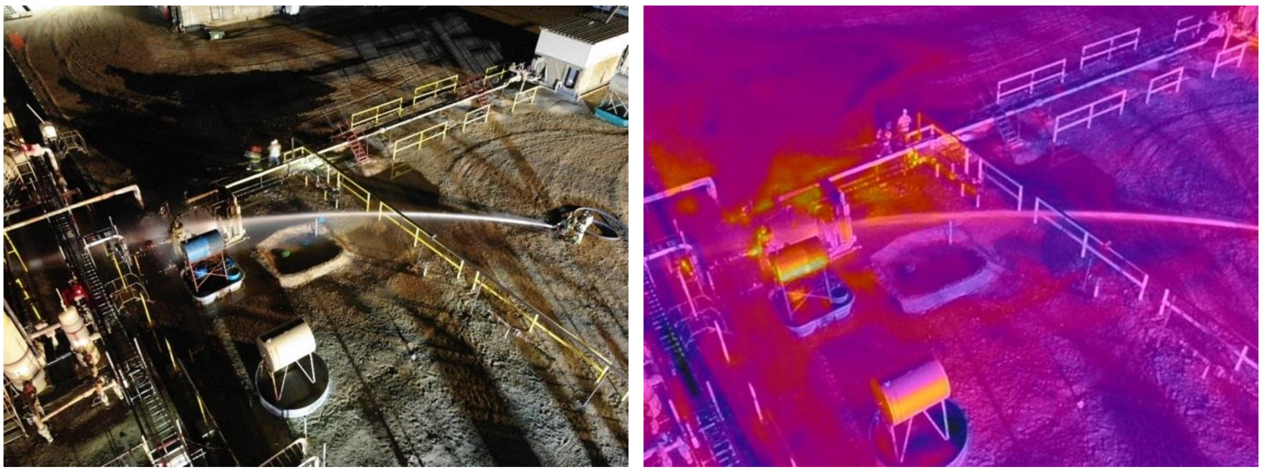

Figure 39. True-color and thermal UAS images of active firefighting (Smith, 2020).

An oil well at a facility three miles east of Windsor, Colorado caught fire during the night on October 8th, 2020. Windsor-Severance Fire Rescue (WSFR) responded to the incident, where UAS were used to provide situational awareness and updates for the for the incident commander [1]. This was the inaugural deployment of a UAS by WSFR and the operation was deemed a success [1].

The UAS was operated by a member of WSFR, who was recently trained on the technical and legal aspects of UAS operation at Colorado State University [2]. The UAS and training for the pilot was paid for by the local oil and gas industry, likely in anticipation of an event like this. [1]. According to FAA records, WSFR was granted a waiver from 14 CFR § 107.29—Daylight operations in December 2020 [3]. This response occurred months prior to the issue of this waiver, and it is unclear if this operation was conducted via the SGI waiver process to allow operations at night.

The platform utilized was a DJI Mavic 2 Enterprise, a multirotor UAS equipped with a high-definition camera and thermal sensor. At the scene, both the thermal and the true color cameras were used onboard the UAS to show the position of firefighters on the ground as well as the fire itself [1]. Video was live streamed for the incident commander to monitor. This live-stream video used to determine when it was safe for firefighters to approach the fire and if their fire suppression was effective [1].

1.16 Case Study Summarization Table

Table 5. Case Study Summarization.

Type	Case study	UAS Applications Identified in Response	Key Lessons Learned
Fire			
Wildland	2017 Wildfire, Parker 2, CA	UAS were used for mapping fires within a 500-acre area. Data products were used to determine and analyze characteristics of the fire.	UAS operated under a COA to conduct flights within the TFR. This marked the first time that a COA allowed for BVLOS operation, facilitating faster and more efficient data collection. A 3D infrared map was used to evaluate and quantify the amount of land burned from the fire. The use of UAS increased response efficiency and was far safer for emergency responders than traditional response tactics.
	2017 Wildfire, Santa Rosa, CA	UAS imagery was collected for infrastructure and other damage assessments following the fire. Data products including 3D models and orthomosaic.	UAS enabled faster and safer damage assessments by reducing the need for estimators to navigate debris, unstable structures, and other hazards. Challenges included highly trafficked airspace due to recreational UAS operating in restricted airspace, which limited emergency UAS operations. These incursions also prevented emergency responders from mitigating and managing the spread of fires. Following the response, the need to increase education for recreational UAS operators was identified.

Type	Case study	UAS Applications Identified in Response	Key Lessons Learned
	2018 Wildfire, Klondike Taylor Creek, OR	UAS were used to remotely drop incendiary spheres to start fires. Thermal and true-color imagery were collected for monitoring purposes.	UAS decreased risk by eliminating the need for someone to start the fires in-person. Thermal imaging operations took place at night. A major benefit of UAS is that they were able to fly where occupied aircraft could not. A federal employee served as the UAS Manager and managed communication between ground and air operations. This response showed how an operational system for UAS could be implemented between private operators and public incident commanders.
	2018 Wildfire, Weaver Dunes, MN	UAS mapped a 320-hectare area prior to prescribed burning. UAS data were collected following the burns for change-detection analysis.	UAS data was analyzed to determine characteristics of the fire and landscape. UAS was quick, cost efficient and provided high quality data compared to other imagery collection methods. Challenges included battery size and operating time limits of the UAS as well as image resolution and clarity issues, including inconsistent resolution and camera movement.
	2019 Wildfire, Maroon, AZ	UAS monitored spot fires using thermal infrared imagery and video. UAS also conducted prescribed ignitions by dropping incendiary spheres.	UAS reduced risk to ground crews and occupied aviation in an area with unpredictable hazards. UAS operators from the Bureau of Land Management led the successful UAS response. High amounts of communication were required to safely operate in a TFR.

Type	Case study	UAS Applications Identified in Response	Key Lessons Learned
Geohazards			
Volcano	2018 Volcanic Eruption, Kilauea, HI	UAS provided real-time monitoring data for scientists and emergency managers. UAS also provided situational awareness and supported emergency response efforts, like hazard tracking, evacuation, and SAR. Visible and thermal imagery, video, and gas emissions measurements were collected with UAS.	This case marked the first known use of UAS for volcanic eruption disaster response in the US The operations demonstrated successful coordination and collaboration from many local, state, and federal organizations. UAS response time, data collection, and processing abilities were quick and low cost. Waivers were obtained to operate at night and above 400ft AGL.
Seismic	2020 Earthquake, Puerto Rico	UAS imagery and video informed response efforts and resource allocation. The data were used to document damage, assess impacts on the community, and to identify locations for emergency infrastructure. UAS collected data at low altitudes when weather conditions prevented occupied aviation from flying.	UAS were utilized for longer-term, post-disaster response and support, which occurred over the span of 3 months. More than 13,000 photos and videos were collected. CAP assumed the role of managing coordination with other involved parties and occupied aviation. The ability to quickly process and share UAS data enabled rapid documentation.

Type	Case study	UAS Applications Identified in Response	Key Lessons Learned
Landslide	2013 SR530 Mudslide, WA	UAS were used to assess further landslide/flooding risk, collect hydrological and geological data, and provide access to inaccessible/dangerous areas. UAS real-time video and imagery informed flood mitigation and hazard risks.	UAS allowed first responders to limit the need to direct access dangerous areas. Challenges included lack of launching/landing space for the UAS, coordination issues, potential interference with other aircraft, inability to get a COA for one UAS, and privacy concerns. LiDAR and thermal sensor payloads could improve data collection in future responses.
	2014 Landslide, West Salt Creek, CO	UAS data were used to map, model, and monitor the landslide. UAS informed decisions about which areas were safe for ground crew entry and their thermal capabilities were used for SAR and mapping.	UAS increased emergency response efficiency and was cost-effective compared to other methods of surveying, performing SAR, and gathering data. UAS use increased first responders' safety and provided remote access to dangerous areas. UAS data products furthered scientific understanding of the landslide and informed future monitoring.
	2016 Landslide Assessment, AK	UAS data products were used to evaluate rock-slope stability and to monitor transportation risks near highly trafficked roads.	UAS were able to capture more data compared to terrestrial LiDAR. In addition, the remote launch/land abilities of UAS made them a safer option than terrestrial LiDAR. UAS data products were deemed capable for use in landslide assessments.

Type	Case study	UAS Applications Identified in Response	Key Lessons Learned
Subsi-dence	2017 Sinkhole, FL	UAS data were used to monitor surface terrain changes and to inform stabilization/recovery efforts.	UAS were able to rapidly deploy and gather accurate data to increase response efficiency. UAS data were easy to integrate with other data sources and facilitated analysis of the causes behind the sinkhole.
Avalanche	2007 Avalanche Monitoring, WA	Avalanche control/monitoring and traffic monitoring in areas with higher avalanche risk.	UAS captured useful aerial imagery for traffic monitoring. UAS technology had potential to constructively supplement WSDOT's existing avalanche control practices. Additional research needed for effective application of UAS for avalanche monitoring and control.
	2020 Avalanche SAR, CO	UAS were used in conjunction with ground search crews for a SAR mission in response to an avalanche. The search was conducted after sunset.	UAS increased situational awareness and provided a useful aerial perspective for responders on the ground.
Wind & Storm			
Hurricane	2017 Hurricane Harvey, LA-TX	UAS enabled faster, safer SAR and provided mapping and imagery data used for damage, flood, and infrastructure assessments.	This UAS response marked the largest known organized response of UAS by public officials for a federally declared disaster in the US. The response involved many collaborating organizations and operators piloting a variety of UAS systems. Multirotor UAS were used were used more before the hurricane, during the event, and in the response phase, while fixed-wings

Type	Case study	UAS Applications Identified in Response	Key Lessons Learned
			were used most in the disaster recovery phase. Challenges included crowded airspace and a lack of strict airspace regulation from the FAA. Pre-existing relationships between local actors and UAS response organizations greatly benefitted the response.
	2017 Hurricane Irma, FL	UAS were deployed for SAR operations and enhanced situational awareness for responders. UAS also collected mapping data and imagery for infrastructure damage assessments.	UAS involvement in SAR and situational awareness enhanced the efficiency of SAR operations. The UAS data from damage assessments was highly detailed. This response demonstrated effective coordination between many organizations to collect, process, analyze, and share UAS data. Challenges included loss of cellular networks following the hurricane, which complicated communication and data sharing.

Type	Case study	UAS Applications Identified in Response	Key Lessons Learned
	2018 Hurricane Florence, NC	Pre-storm flights were used to collect baseline data for post-storm comparisons. UAS imagery and video were collected in the wake of the hurricane and used to assess traffic conditions, road closures, and flood extent. UAS data were also used to authenticate reports of hazards and informed resource allocation.	UAS operations were managed by a single organization, overseeing successful deployment of 15 UAS teams. This response was planned over a week before Hurricane Florence hit. One team operated BVLOS under a COA. There was regular daily communication between UAS teams and managing group about TFRs and daily tasks. All UAS ops were coordinated with FAA and other major federal/state agencies involved to prevent interference with occupied aviation.
	2020 Hurricane Delta, LA	UAS collected post-storm imagery of flooded regions along the Mississippi River.	Using UAS in this response enabled cost-efficient, rapid data sharing that in turn, informed decision making and improved forecasting accuracy.
	2021 Hurricane Ida, LA	UAS provided cellular data coverage following the storm, aided in SAR operations, conduct damage and insurance assessments, collected imagery of damage, and supported first responders and law enforcement.	UAS were successfully used to provide cellular data in areas where cell signal was lost due to damage. Having cellular coverage enabled other emergency response operations (UAS and non-UAS) and increased communication and accessibility to local communities.
Tornado	2018 Amherst, VA	UAS imagery and video informed damage assessments, documented recovery efforts, and provided	UAS data informed and documented disaster response and recovery efforts. UAS operations were led by a high school technology club and their advisor. They worked with emergency management service and local Sheriff's offices

Type	Case study	UAS Applications Identified in Response	Key Lessons Learned
		situational awareness to emergency responders.	throughout the response. This response demonstrated that even a small and localized UAS operation can be effective in the wake of a disaster.
	2018 Tescot, TX	UAS conducted damage assessments and site investigations following the incident.	UAS, flown VLOS, were able to collect data in remote/inaccessible locations and were a cost-effective option.
	2019 Lee County, AL	UAS provided support during SAR operations and helped increase situational awareness.	The UAS response was cost-effective and more efficient than dispatching occupied aircraft. When combined with infrared sensors, UAS also provided increased search capabilities for SAR teams. Regular, daily communication occurred between UAS operators and local officials.
	2021 Tornadoes, KY	UAS imagery, video, and mapping products were used to document and communicate the extent of damage following the storm.	The rapid speed at which UAS data was shared benefitted the emergency response and public awareness. UAS imagery and video coverage utilized by news outlets provided a broader perspective of storm damage and more accurately communicated the urgency and scale of the catastrophe.
Wind	2017 Microburst, VT	UAS provided up-to-date mapping products and imagery of property damage following the microburst.	UAS data informed damage assessments and was made publicly available and accessible. The

Type	Case study	UAS Applications Identified in Response	Key Lessons Learned
			UAS data provided much more up-to-date imagery than satellite imagery could provide.
	2020 Derecho, IA	UAS were used to increase efficiency of post-storm damage assessments, especially in otherwise inaccessible locations.	Due to the increased accessibility and aerial perspective they provided, UAS made damage assessments more efficient than traditional ground-based methods.
Flood	2015 Blanco River, TX	UAS were utilized for SAR operations and collected imagery used for mapping and damage assessment. These data helped to identify priority areas requiring response and to inform future disaster preparedness planning.	Challenges included delayed flying due to crowded airspace, delays in receiving an emergency COA, and issues with power outages and cellular connectivity. UAS operators communicated with ATC to request and adjust an emergency COA because requesting a COA through the FAA was too slow. Later in the response, the FAA established a TFR covering 13 miles along the Blanco River, in which, BVLOS UAS ops were permitted. Both multirotor and fixed-wing UAS of varying sizes were used in the response and provided different functions.
	2015 Johnson County, TX	UAS assisted in SAR operations by helping emergency responders to rapidly locate stranded people and delivering floatation devices.	UAS were helpful in rapid SAR operations, especially when major flood conditions made areas completely inaccessible. UAS can be extremely helpful due to their versatility beyond providing live video streams, including the

Type	Case study	UAS Applications Identified in Response	Key Lessons Learned
			ability to transport floatation devices to stranded people.
	2015 Little Androscoggin River, ME	UAS were used to transport a flotation device to someone stranded in a river and live video was used to survey downstream river conditions to plan rescue efforts.	Quick deployment of UAS, the ability of UAS to carry flotation devices, and live video feed capabilities to inform rescue efforts were the key components of this case. UAS also provided useful documentation of the rescue.
Technological			
Pandemic	2020 COVID-19 Social Distance Monitoring, VT	UAS collected video that was used for social distance monitoring to inform park management procedures.	Simple video products provided useful data that informed park management decisions in a COVID-safe way. The ability of LAANC to provide real-time airspace authorizations was valuable for this response.
	2020 Medical Delivery UPS and CVS, FL	UAS delivered essential medications from a local pharmacy to a nearby retirement community in a COVID-safe and efficient way.	This pilot effort demonstrated coordination, collaboration, and problem solving between multiple companies, like CVS, UPS, Matternet, and a retirement community to find a creative solution to a wide-reaching problem.

Type	Case study	UAS Applications Identified in Response	Key Lessons Learned
Oil Spill	2015 Refugio Oil Spill, CA	UAS utilized to map a beach and the ocean after an oil spill for damage assessment and response purposes.	Collecting data with UAS provided insight to the involved agencies around what technology and practices can be improved moving forward. The response and NOAA's involvement resulting in increased interest in UAS tech and lead to a workshop focused on UAS for oil spill responses. The UAS response demonstrated rapid response, planning, data collection, and processing. This response also demonstrated the need for further development of how the technology can be used for oil spill responses and generated interest and concepts for further oil spill response training.
Terrorism	2020 Nashville Bombing, TN	UAS captured images and video to document damage from the blast and impact on surrounding infrastructure. UAS data also served to communicate both the detailed and broader scale of the damage.	UAS video and imagery were used by emergency response organizations and media to gain further insight into impacts from the disaster and to increase public understanding and scale of the event.
Vehicular	2015 Train Derailment, VT	UAS helped document the incident by collecting imagery and mapping the train derailment. UAS data and products were used to inform subsequent investigations into the event.	UAS response, data collection, processing, and sharing were rapid and greatly enhanced recovery and future mitigation efforts.

Type	Case study	UAS Applications Identified in Response	Key Lessons Learned
	2017 Train Derailment, WA	UAS captured aerial photos and videos to document the incident. UAS data were used to map and reconstruct the crash scene.	The crash scene recreation informed decision making and future mitigation efforts and showed effective integration of UAS data with other data. Challenges included disorganized and uncoordinated communication, which improved after the initial stages of the response.
	2020 Helicopter Crash, NV	UAS helped authorities determine the extent of the crash and locate parts in the debris. UAS increased investigator's safety and increased efficiency in searching the difficult terrain.	Two UAS were flown at the same time, but at slightly different altitudes to increase efficiency. Pre-planning was very important for coordination and to avoid collision and ensure consistent data. UAS data products, including 3D point clouds and high-resolution imagery, were used to inform the investigation following the crash.
Biohazard	2018 Methane Leaks, TX & NM	UAS used for pipeline inspections to detect methane leaks.	BVLOS flight permitted by the FAA, though BVLOS was not used. UAS were used in combination with AI to conduct autonomous flight.

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