

Optimising disaster response: opportunities and challenges with Uncrewed Aircraft System (UAS) technology in response to the 2020 Labour Day wildfires in Oregon, USA

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ABSTRACT

Background. The expanding use of Uncrewed Aircraft System (UAS) technology in disaster response shows its immense potential to enhance emergency management. However, there is limited documentation on the challenges and data management procedures related to UAS operation. **Aims.** This manuscript documents and analyses the operational, technical, political, and social challenges encountered during the deployment of UAS, providing insights into the complexities of using these technologies in disaster situations. **Methods.** This manuscript documents and analyses the operational, technical, political, and social challenges encountered during the deployment of UAS, providing insights into the complexities of using these technologies in disaster situations. **Key results.** UAS technology plays a significant role in search and rescue, reconnaissance, mapping, and damage assessment, alongside notable challenges such as extreme flying conditions, data processing difficulties, and airspace authorisation complexities. **Conclusions.** The study concludes with the need for updated infrastructure standards, streamlined policies, and better coordination between technological advancements and political processes, emphasising the necessity for reform to enhance disaster response capabilities. **Implications.** The findings of this study inform future guidelines for the effective and safe use of UAS in disaster situations, advocating for a bridge between state-of-the-art UAS research and its practical application in emergency response.

Keywords: disaster response, drone, hazards, Labour Day fire, Oregon, UAS, UAV, Uncrewed Aircraft System, wildfire.

Introduction

Uncrewed Aircraft System (UAS) technology can be used for several purposes before, during, and after a wide range of disaster situations. In the United States, for example, UAS use in disaster response dates back to 2005, when the University of South Florida Centre for Robot-Assisted Search and Rescue (CRASAR) used small fixed-wing and helicopter-style UAS to search for Hurricane Katrina survivors in Mississippi (Greenwood *et al.* 2020). At that time, the use of UAS in disaster response was very limited, given concerns that the UAS could disrupt occupied aircraft flights necessary for the response (Murphy 2015). Additionally, a certificate of authorisation (COA) was required to operate a UAS in a disaster situation. A COA was difficult to obtain and required the team operating the UAS to follow strict protocols (Cross 2015).

Many of these barriers have been resolved over the past 15 years (Gupta *et al.* 2013) as research on the use of UAS in disaster situations progressed and as lightweight sensing technologies, communication relays, and aerial mapping technologies have been developed. The Federal Aviation Administration (FAA) in 2006, in response to these changes, issued the Small UAS Rule (Part 107) as a new regulatory framework for the use of UAS or commercial, non-hobby purposes (Ancel *et al.* 2017). Part 107 enabled much broader UAS operations for commercial, governmental, and academic purposes. These technological

and policy developments created an environment where UAS can be more readily used in disaster situations.

Building on the advancements in UAS technology and policy that have significantly improved their application in disaster scenarios, UAS play a crucial role in addressing the challenges posed by wildfires. Worldwide, wildfires are rapidly amplifying in scale and intensity threatening wildlife, humans, vital infrastructure, and natural resources (Mueller *et al.* 2020). To help combat these issues, government institutions and firefighters used sophisticated resources and technologies in their attempts to control the unpredictable and rapidly spreading wildfires. Specifically, the use of UAS technology in wildfire response is increasing due to its flexibility, ease of deployment, efficiency, and ability to offer unique vantage points (Gonzalez *et al.* 2016). 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 several studies document the use of UAS technology in disaster response, most studies focus on the technological and tactical aspects, such as the sensors for a specific application. Relatively few studies document how actual disaster-related organisations use UAS and the practical challenges they face during operation (Erdelj *et al.* 2017; Rosser Jr *et al.* 2018; Jones and Despotou 2019; Cho *et al.* 2020; Greenwood *et al.* 2020; Sivasuriyan 2021; Daud *et al.* 2022; Ojetunde *et al.* 2022). Thus, the objectives of this study are to: (1) identify current UAS utilisation, applications, infrastructure, and standards; (2) capture and qualitatively analyse information obtained through detailed interviews; (3) document the technical, political, and social challenges that arise when attempting to use UAS technology to aid in wildfire response; and (4) serve as an essential foundational study to create a framework for safe, effective, and systematic UAS utilisation for wildfire mitigation, response, and recovery. These objectives will be met by exploring UAS usage in the 2020 Labour Day fires in Oregon.

Background

Exploring the use of UAS in different disaster scenarios provides a comprehensive perspective to provide context to this study focused on wildfire. Hence, this section presents trends in current UAS use in disaster situations in the broad sense. The advantages UAS offer over traditional remote sensing technologies, such as occupied aircraft and satellite platforms, led to their rapid adoption and implementation for disaster response and recovery (Wartman *et al.* 2020). This section describes select examples of how UAS technology has been deployed in recent responses to disasters, along with the potential opportunities (Table 1). Amongst all possible disaster events, the intent was to focus

on select disasters (e.g. earthquakes, tsunamis, wildfires, and hurricanes) to provide sufficient information presenting a broad view of how UAS technology is used. Detailing all possible natural or anthropogenic hazard that has used UAS technology is beyond the scope of this manuscript.

Earthquake

Following significant earthquake events, Rathje and Franke (2016) used UAS to collect 2D orthophotos, video logs, or 3D geometric information to document and quantify 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. Although often not available, high-quality baseline data from pre-disaster UAS flights can significantly improve quantitative damage analysis after disasters (Restas 2015). In many cases, researchers and disaster responders used lower-spatial resolution satellite data for baseline reference, given its wider availability. These data are essential to capture the initial damage from the actual event, while repeat flights can efficiently monitor changes to the ground surface, slopes, or infrastructure after the earthquake or associated aftershocks. Several recent events demonstrated these applications. For example, following the 2016 Kumamoto, Japan earthquake, Yamazaki *et al.* (2017) used UAS data to develop 3D models based on the Structure-from-Motion (SfM) reconstruction technique to support identification and quantification of damage throughout the affected area. Montgomery *et al.* (2021) also used UAS technology for reconnaissance to obtain high resolution imagery of the significant damage observed throughout Palu City and the surrounding Central Sulawesi region of Indonesia following the 2018 Palu-Donggala earthquake. The use of UAS for this application enabled rapid capture of information across a large flowside area efficiently, particularly for areas that are difficult, if not impossible, to access directly by humans to perform conventional surveying and mapping.

Tsunami

UAS have been used to collect data on the inundation extents following tsunamis as well as to generate detailed digital elevation model topographic information to simulate the substantial fluctuations in water levels when a tsunami occurs. For planning purposes, Marfai *et al.* (2019) used high-resolution UAS imagery and GIS software for developing disaster response and mitigation plans as well as evacuation plans by estimating areas likely to be affected by tsunamis based on scenario events. Similar to earthquakes, UAS technology is also used for damage assessment following a tsunami. For example, De Oliveira *et al.* (2018) used a UAS equipped with an infrared camera to detect faults in large-scale Photovoltaic plants in tsunami-affected areas. The UAS was very beneficial in terms of cost-efficiency

Table 1. UAS use cases organised by disaster type and general application categories. SAR, Search and Rescue; RM, Reconnaissance and Mapping; DA, Damage Assessment; MD, Monitoring and Detection.

Disaster type	Application	Example UAS uses
Earthquake	RM	<ul style="list-style-type: none"> • Mapping of earthquake-affected and hazardous areas (Rathje and Franke 2016; Wood <i>et al.</i> 2017; Montgomery <i>et al.</i> 2021). • Earthquake-induced debris distribution mapping (Valkaniotis <i>et al.</i> 2018; Koukouvelas <i>et al.</i> 2020).
	DA	<ul style="list-style-type: none"> • Initial damage assessment immediately after earthquake (Baiocchi <i>et al.</i> 2013). • Structural damage assessment (Yamazaki <i>et al.</i> 2017; Freeman <i>et al.</i> 2019; Mavroulis <i>et al.</i> 2019).
	MD	<ul style="list-style-type: none"> • Providing real-time monitoring data for disaster responders (Aljehani and Inoue 2016). • Tracking of hazardous areas after earthquake (Aljehani and Inoue 2016). • Earthquake-induced landslide, debris flow, and rockfall (Valkaniotis <i>et al.</i> 2018; Koukouvelas <i>et al.</i> 2020).
	Other	<ul style="list-style-type: none"> • Disaster management before and after earthquake (Restas 2015). • Distribution of relief supplies and resources by UAS (Nedjati <i>et al.</i> 2016).
Tsunami	SAR	<ul style="list-style-type: none"> • Evacuation guidance in case of tsunami (Katayama <i>et al.</i> 2018). • Assisting SAR (search and rescue) operation by delivering floatation devices (Silvagni <i>et al.</i> 2017; Dol 2020). • Assisting in the establishment of rescue plans by real-time video of disaster areas obtained with UAS (Sun <i>et al.</i> 2016; Silvagni <i>et al.</i> 2017).
	RM	<ul style="list-style-type: none"> • Tsunami vulnerable area management and disaster response plan establishment (Nurulloh <i>et al.</i> 2020). • Tsunami hazards modelling (De Oliveira <i>et al.</i> 2018; Rezaldi <i>et al.</i> 2021). • Inundation depth estimation from images and topographic data (Alvarez <i>et al.</i> 2018).
	DA	<ul style="list-style-type: none"> • Surveying the degree of inundation of infrastructure (De Oliveira <i>et al.</i> 2018).
	Other	<ul style="list-style-type: none"> • Acquisition of base data for flood prediction modelling (Rezaldi <i>et al.</i> 2021).
Hurricane	RM	<ul style="list-style-type: none"> • Utilisation of UAS in imagery and video data collection in hurricane-affected areas at the city and region level (Yuan and Liu 2018). • Reconnaissance to develop disaster mitigation plans for hurricane-affected or anticipated areas of risk (Derricott <i>et al.</i> 2019; Wickliffe <i>et al.</i> 2019).
	DA	<ul style="list-style-type: none"> • Infrastructure damage assessment (Adams <i>et al.</i> 2010; Mohammadi and Wood 2018; Yeom <i>et al.</i> 2019). • Hurricane damage assessment for coastal areas (Nikolakopoulos and Koukouvelas 2018).
	MD	<ul style="list-style-type: none"> • Monitoring changes in coastal areas affected by hurricane (Schaefer <i>et al.</i> 2020). • Collecting post-hurricane imagery of flooded regions (Adams and Friedland 2011).
Wildfire	SAR	<ul style="list-style-type: none"> • Acquiring real-time image and video data for evacuation planning during and after wildfires (Samiappan <i>et al.</i> 2019). • Helping with rescue operations (finding injured people, providing remote assistance, fire alert and relief material distribution) (Karma <i>et al.</i> 2015).
	RM	<ul style="list-style-type: none"> • Mapping of areas affected by wildfire (Samiappan <i>et al.</i> 2019). • Acquisition of image and video data to predict the path of wildfire (Tang <i>et al.</i> 2020).
	DA	<ul style="list-style-type: none"> • Infrastructure damage assessment (Samiappan <i>et al.</i> 2019). • Assessment of residential structures (Kang <i>et al.</i> 2023). • Investigation of vegetation distribution in forest areas before and after wildfire (Shin <i>et al.</i> 2019).
	MD	<ul style="list-style-type: none"> • Establishment of an early wildfire detection system (Krüll <i>et al.</i> 2012; Zhao <i>et al.</i> 2018; Kanand <i>et al.</i> 2020). • Periodic reconnaissance for real-time wildfire detection (Allison <i>et al.</i> 2016). • Tracking vegetation recovery after wildfire (Samiappan <i>et al.</i> 2019). • Tracking smouldering from wildfire (Krüll <i>et al.</i> 2012).
	Other	<ul style="list-style-type: none"> • Acquisition of base data to analyse the characteristics of wildfires (Lazzeri <i>et al.</i> 2021; Sharma and Singh 2021). • Distribution of fire suppression supplies (Saikin <i>et al.</i> 2020).

and its ability to detect post-tsunami damage rapidly. UAS also has the potential to be used in direct lifesaving applications. Katayama *et al.* (2018) explored the usage of UAS technology to provide immediate evacuation guidance to persons in tsunami hazard zones. In this application, multiple UAS coordinate and continuously share information such as their location, evacuation guidance routes, and the number of people each system has guided.

Hurricane

UAS played an important role in supporting reconnaissance of hurricane-impacted areas by enabling quick map generation of heavily impacted areas. Yuan and Liu (2018) devised a framework that combines UAS with social media to quickly deploy UAS to affected areas in order to obtain timely information for response planning. Hurricane affected areas are generally extensive; hence, UAS can prove valuable

to determine the extent of damage and plan the recovery efforts compared with deploying humans to the impacted sites. When compared to reliable baseline data (e.g. ortho-photos; lidar digital elevation models, DEMs), remotely sensed data from UAS can serve as a low-cost tool to accurately quantify topographical changes resulting from hurricanes. For example, after Hurricane Maria, [Schaefer *et al.* \(2020\)](#) investigated changes within a damaged area by comparing UAS imagery to aerial photographic data collected before the storm. Notably, given that the UAS is relatively vulnerable to wind and rain, it has primarily been used for post-disaster damage assessment rather than directly during the event ([Yeom *et al.* 2019](#)). UAS usage is limited during hurricane events and in the immediate aftermath for SAR purposes until environmental conditions permit safe UAS operation.

Wildfire

UAS are being widely used and studied as a potential tool to detect wildfires. Early wildfire detection is very important to help prevent large-scale fires, which can grow rapidly. Current fire detection technologies based on satellite imaging or remote cameras tend to be slow to detect fires and have lower accuracy ([Bushnaq *et al.* 2021](#)). [Kanand *et al.* \(2020\)](#) used UAS equipped with high-resolution RGB and thermal cameras and a modern 5G mobile network infrastructure. They strategically deployed this for early detection of wildfires, enhancing both the speed and accuracy of detection. UAS have demonstrated remarkable capabilities, extending beyond the early detection of wildfires to include identifying and mapping burned areas. [Samiappan *et al.* \(2019\)](#) compared the UAS-based classification produced from the normalised difference vegetation index (NDVI) and a digital surface model (DSM) with the Landsat-based Burned Area Reflectance Classification (BARC). The authors noted that a UAS platform with a multispectral sensor could provide more timely data for mapping the extent of the burned area than an RGB photogrammetric camera alone.

UAS technology proves effective for supporting a variety of monitoring and detection tasks, most of which are performed manually by human observers watching video feeds from the UAS ([Kanand *et al.* 2020](#); [Tang *et al.* 2020](#)). Researchers are currently exploring deep learning methods using UAS imagery to rapidly detect and monitor wildfires ([Tang *et al.* 2020](#), [Kang *et al.* 2023](#)). Although capable of very efficient and promising data analysis, machine learning, more specifically deep learning, require extensive image data sets that are manually annotated (e.g. fire) in order to train a model to identify similar features in other images ([Zhao *et al.* 2018](#)). Hence, a hindrance to this approach will be the robust collection and systematic annotation of the very large dataset necessary to detect wildfires accurately. However, once sufficient datasets are available,

deep learning models can automate the detection of fires in imagery, enabling responders to use their time more effectively in responding to priority locations.

During the event, UAS also transport and drop fire suppression materials (e.g. fire retardant, water, or other extinguishing agents) at strategic locations ([Saikin *et al.* 2020](#)). The UAS enables the fire to be extinguished in a safer method than the conventional crewed helicopter method, which puts people directly in harm's way by flying over the flames and smoke from the fire. By incorporating infrared camera technology on UAS, wildfire management teams can detect thermal energy and produce images highlighting heat signatures. This capability is critical for identifying hotspots along the perimeter of a fire zone, enhancing the safety and strategic deployment of firefighting crews ([Fagen *et al.* 2021](#)).

Materials and methods

Study area

This study explores UAS usage in preparation for, during, and in response to the 2020 Labour Day Fires in Oregon, USA ([Fig. 1](#)), which initiated on 7 September 2020. These fires were some of the most catastrophic on record in the State of Oregon, killing at least 11 people, burning more than 1 million acres of land, and causing more than 40,000 people to flee their homes ([Oregon Office of Emergency Management 2020](#)). Additionally, the fires had significant economic impacts, including a USD5.9 billion loss for Oregon's forest-dependent industries and businesses as well as recovery costs estimated at USD1.15 billion for the state ([Oregon Office of Emergency Management 2021](#); [Tillamook Headlight Herald 2021](#)).

Interview research methodology

[Fig. 2](#) shows an overview of the interview research methodology and how we synthesised the results. We used semi-structured interviews to collect information on UAS usage by institutions in response to the 2020 Labour Day fires. The general goal of a semi-structured interview is to gather systematic information about a set of central topics while also allowing flexibility for exploration when new issues or topics emerge ([Longhurst 2009](#); [Wilson 2014](#)). Considering that the purpose of the interviews in this study is to collect information on the use of UAS in wildfire response and associated challenges derived from the situations and experiences of each organisation and expert, the flexibility of the semi-structured interview approach is well-suited for this study given the limited amount of information currently available.

We generated a questionnaire to guide the conversation and address the four aforementioned research objectives. The questionnaire consisted of open-ended questions with

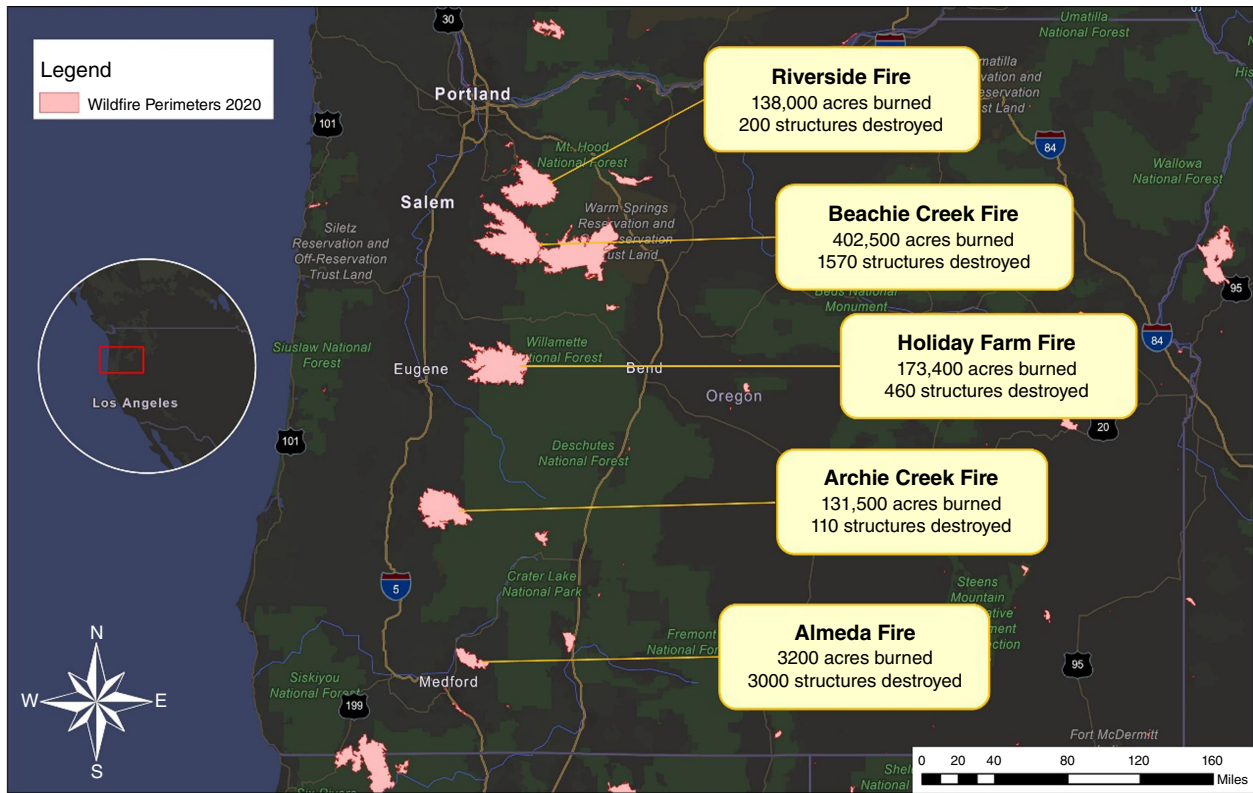


Fig. 1. Map of the extent of major fires occurring during the 2020 Labour Day Fires in Oregon, USA along with approximate numbers of damaged structures and acreage. (Data sources: NWS Billings, National Institution Fire Centre (NIFC) geodata, and Incident Information system’s (Inciweb) daily fire reports.)

prompts for responses when needed. The literature review explored UAS utilisation in disaster questions (Table 1), which enabled the creation of categories for common UAS use methods (Search and Rescue, SAR; Reconnaissance and Mapping, RM; Damage Assessment, DA; Monitoring and Detection, MD). These categories then informed the questionnaire process, enabling the development of more specific questions tailored to the situations in which UAS was used. Synthesising the limitations and further research mentioned in studies, we formulated specific questions to identify the challenges of using UAS in disaster situations, which led to in-depth discussions with respondents. Another important outcome of the literature review was the identification of possible gaps between research and real-world challenges regarding using UAS in disaster situations. Through these discussions with experts, we generated questions about operational and political challenges as well as data management that were not addressed in much of the literature. Given the limited potential number of respondents with UAS experience, we used snowball sampling for participant recruitment (Goodman 1961). After each interview, we revised the questionnaire to tailor questions to the target audience based on input received from the prior interviewee(s). Oregon State University’s Institutional Review Board (IRB) reviewed the questionnaire and associated interview methodology and

rendered an exempt decision based on the determination that it was not classified as human subject research.

We employed several methods to identify potential interviewees consisting of government officials and UAS experts involved in wildfire response. First, we identified potential interviewees through the collaboration networks of the authors and their colleagues. The research team then extensively searched media articles to identify key personnel at agencies involved in the response. Second, we explored public agency websites to identify additional potential respondents. If no clear candidate was identified on the webpage, we contacted the heads of relevant divisions to identify suitable personnel to participate in the interviews. Lastly, we asked interviewees to provide the names of other potential respondents.

We conducted each interview as a web-based video conference lasting between 40 and 60 min. The interview questions generally followed the order are in Fig. 2, but were adapted based on the conversation’s flow. We first asked questions about the use of UAS, in general, within the respondent’s institution and their use in wildfire situations. Through this question, the authors tried to understand each institution’s current UAS uses and applications. The authors then asked if there were any problems or challenges that could be improved in the processes for using UAS. This question aimed to identify reasons limiting

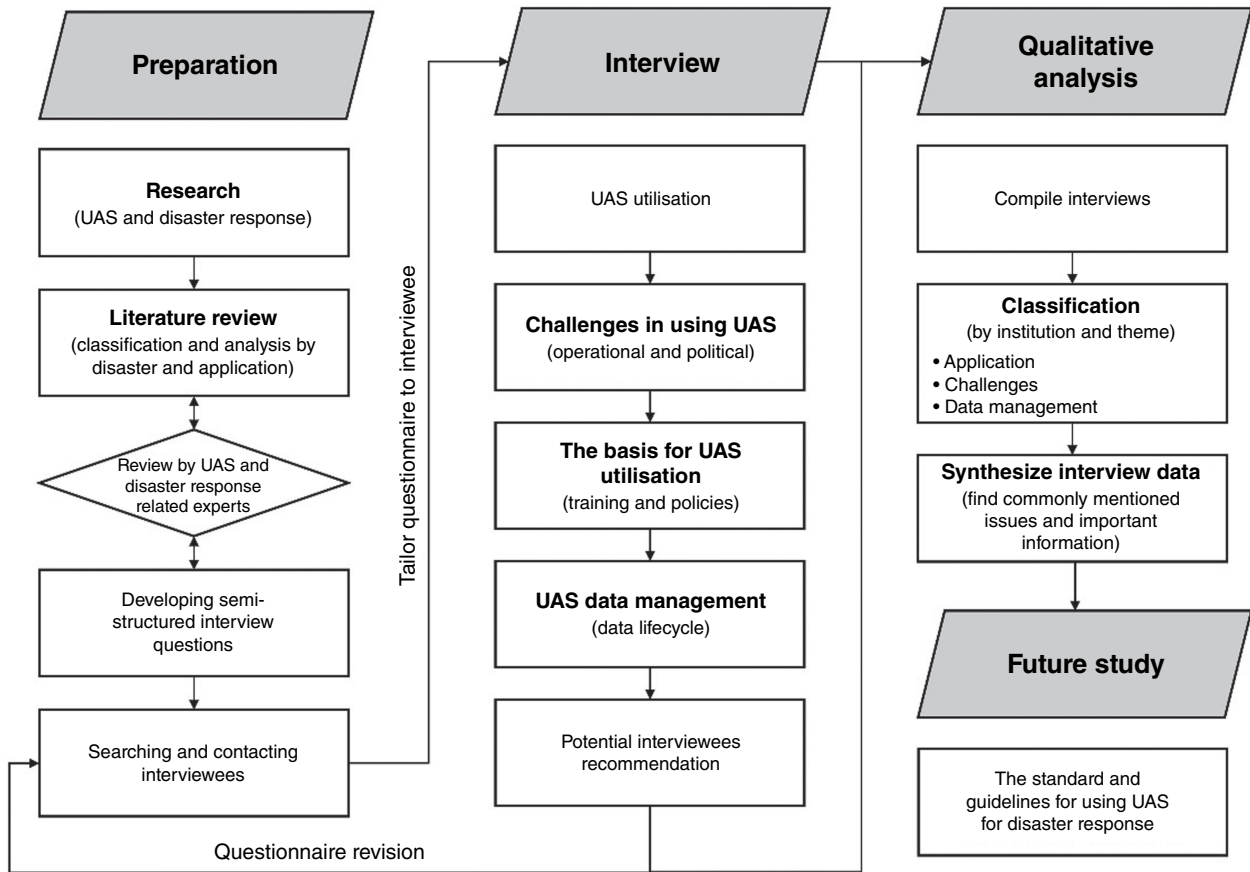


Fig. 2. Overview of the research methodology for the application of UAS for disaster response. The topics in the centre column were used to guide the semi- structured interviews.

UAS usage. Finally, we discussed UAS-related policies, training resources, as well as UAS data management and sharing. Some respondents provided follow-up materials, such as presentations and documents, to be reviewed by the research team. Following the interviews, we transcribed key information based on interview notes and recordings. At least two research team members participated in the interviews to reduce potential bias in transcription and interpretation. We also employed a process where multiple team members carefully reviewed the transcriptions to ensure consistency and objectivity in reporting key information.

We applied qualitative analysis methodology to the semi-structured interview results in order to explore how they used UAS before and after wildfire disasters, what were the major barriers to their use, and how they managed the collected UAS data. We integrated each respondent’s response to each question. Lastly, we reclassified the integrated data according to the three pre-determined themes: (1) application; (2) challenges; (3) and data management), with three sub-themes: (1) timeline; (2) operational and political; (3) and data lifecycle. This process identifies common information mentioned by several institutions and information unique to a particular respondent.

Results and discussion

We contacted a total of 25 institutions and 32 people. We were able to interview eight of them from five institutions to determine how they used UAS in response to the wildfire. Most of the institutions declined because they were not aware of any UAS usage for the 2020 Labour Day wildfire by their institution. As much as possible, we conducted the interviews during the ‘off-season’ to improve responder availability. Although the Oregon 2020 Labour Day wildfire danger had receded in October 2020, the potential respondents remained busy throughout the year with continued wildfire response work or preparation for an anticipated substantial 2021 wildfire season. We classified the data obtained through these interviews into three general categories for the qualitative analysis: (1) UAS application; (2) challenges; and (3) data management practices.

UAS applications

Respondents highlighted UAS deployments that occurred before, during, and after the disaster situation. Table 2 shows the utilisation of UAS in wildfires by each institution organised within the context of the event timeline. Agency A

Table 2. Summary of UAS use cases in the 2020 Labour Day wildfire response organised by timeline.

Timeline	Uses	Institution	Explanation
Pre	Overview of vulnerable areas	Agency A	<ul style="list-style-type: none"> UAS flights immediately prior to a fire – establish baseline for monitoring/rapid damage assessment of a community.
During	Reconnaissance of large wildfire areas	Agency A, B, E	<ul style="list-style-type: none"> Replacement of reconnaissance missions performed by conventional helicopters.
	Night time fire assessment	Agency A, B, C	<ul style="list-style-type: none"> IR capabilities enable detection of fire and smoke.
	Aerial ignition	Agency C	<ul style="list-style-type: none"> A replacement for aerial ignition previously performed with a helicopter.
	Assist the incident management team	Agency B, C	<ul style="list-style-type: none"> Using UAS provide products the incident management team wants (e.g. real-time video, IR mapping).
During/Post	Cargo distribution	Agency C	<ul style="list-style-type: none"> Medical supplies, Fire suppression equipment, etc.
	Monitor emissions	Agency A	<ul style="list-style-type: none"> Track smouldering.
Post	Damaged area mapping	Agency A, E	<ul style="list-style-type: none"> 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	Agency E, F	<ul style="list-style-type: none"> 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 and requiring evacuation. The geotechnical assessment of fire-affected structures and landscapes.
	Manage hazard trees	Agency D	<ul style="list-style-type: none"> Use of 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. Investigate trees in sloped areas that are difficult for people to access.
	Monitor wildlife	Agency D	<ul style="list-style-type: none"> Using captured imagery by UAS to monitor the health of and potentially rescue birds nested on a damaged tree.

was the only institution that indicated the use of UAS before wildfires to identify vulnerable areas and gather image data on these areas. They used these baseline data to prepare for wildfires through strategic mitigation practices.

During wildfire response, the usage of UAS was diverse. Many institutions mentioned that UAS may replace conventional helicopter operations as UAS can perform missions more safely and efficiently. Agency C used UAS for aerial ignition purposes when firefighter safety on the ground was compromised or when large land areas required ignition to slow and help contain the wildfire. Aerial ignition requires flying low to the ground and at a slow speed while igniting the fire. This method of flying is risky and can cause accidents using a helicopter. UAS can substantially reduce the risk. UAS paired with infrared cameras can capture high-resolution photographs during a wildfire. Due to safe flying altitudes, most crewed aircraft will obtain photos with smoke; however, a UAS can fly at significantly lower altitudes above ground and obtain the necessary photos to understand where burning and combustion are occurring. Agencies B and C used UAS for response management through real-time videos and mapping.

After the fires were contained, there was considerable UAS use across the different institutions. All institutions used UAS to collect imagery to evaluate the extent and type of damage resulting from the wildfires. They used vulnerable regions (communities and forested land), the pre-fire imagery for comparison purposes. Agency A used UAS post-wildfire to

monitor emissions and community activity to determine which regions are safe for on-the-ground crews to commence the forest restoration processes. Agency D used UAS after a fire to determine where trees threaten the right of way on roadways. UAS imagery showed where trees were significantly compromised and which trees needed to be removed, such that transportation through wildfire-impacted regions is not compromised. Agency E was also conducting an ongoing study using multispectral imagery obtained by UAS to categorise the conditions of trees. Currently, these data are acquired using ground-based lidar; however, a UAS with kinematic lidar is expected to expedite this work and protect crew members. During this evaluation of trees for removal, Agency D also used UAS to monitor and rescue osprey baby birds living in the burn zone. A nest had been constructed on top of a burned, which needed to be removed for safety reasons given its proximity to the highway. The UAS minimised disturbing the osprey by obtaining nest imagery, counting how many baby ospreys were in the nest, and safely removing the nest from the unstable tree.

In addition to government institutions, Agency E, whose primary role is to assist the natural hazards and disaster research communities in collecting perishable data in post-natural disaster reconnaissance. Agency E used UAS to quickly investigate the extent of the wildfire impacted area and produce detailed orthomosaic maps for future disaster monitoring, change detection, debris removal work, and geotechnical assessment of fire-affected structures and

landscapes. Note that Agency E is not a first responder performing direct lifesaving or fire suppression tasks. Instead, they used the UAS to obtain research-related data for post-fire damage assessment and disaster recovery.

Challenges in using UAS

As mentioned in the UAS utilisation section, most institutions noted many positive roles for UAS in wildfire situations. However, there were also challenges cited by each institution when using UAS during and after the 2020 Labour Day fires. We classified these challenges into two categories: operational and political.

Operational challenges

Table 3 shows the operational challenges in using UAS. Many of the operational challenges are common across institutions. The operational challenges mentioned during the interviews occurred from flying conditions, data processing, and communication. Instability from strong winds was a challenge mentioned by all institutions. In wildfire situations, high temperatures and strong winds pose challenges to a UAS attempting to fly at a constant altitude for data collection. Agency C mentioned maintaining up-to-date software as a particular challenge as outdated UAS-specific software can lead to data acquisition and/or processing errors. On a related note, Agency D had enough personnel to gather the data in the field; however, they had insufficient personnel to support the associated data processing needs. Additionally, Agency D had recently purchased a UAS lidar system, but at the time of the interview, they did not have personnel trained to process the UAS lidar sensor data.

Operating under Part 107, Agency D requires the pilot in control to maintain a line of sight with the UAS at all times during a flight, which is also related to a political challenge discussed in the next section. According to FAA Part 107, the maximum allowable altitude is 122 m (400 feet) above the

ground, which can significantly hinder obtaining imagery capturing the overall damage experienced within an area, particularly in locales with steep slopes and substantial terrain variation. Such rugged terrain is common in wildfire prone areas in the western US. Regarding this issue, Agency E suggested possible refinement of the definition of 122 m (400 feet) restricted area based on the general terrain height as a potential solution. Currently, flight restrictions are also applied in a circular fashion surrounding an airport area, even if UAS are not within common paths of the crewed aircraft at the airport. Agency E provided suggestions to improve operability near low-volume airports. For example, a more detailed no-fly, or restricted flight zone based on the crewed aircraft's routes can allow responders to safely work in areas that do not conflict with the crewed aircraft's flight paths.

Agency C also discussed field operation communication challenges. Communication issues can arise when both UAS and crewed aircraft are flying in the same space at the same time. UAS and crewed 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 aircraft. This challenge impedes effective response in wildfire situations and can result in additional safety concerns.

Political (and social) challenges

Table 4 shows political challenges mentioned many times by each institution. Experts from Agencies A, B, C, D, and E mentioned that UAS procedures may be a hindrance to using UAS during or after a disaster, particularly during a rapidly changing event such as wildfire, due to the complexity and restrictions imposed by these procedures. All institutions acknowledged the appropriateness of these restrictions around airports. Nevertheless, Agency D mentioned that altitude restrictions hinder data collection in areas with large terrain elevation changes. In special circumstances, the FAA may temporarily restrict access to certain designated airspace

Table 3. Operational challenges in using UAS.

Operational Challenges	Institution	Explanation
Strong wind (stability of UAS)	Agency A, B C, D, F	<ul style="list-style-type: none"> When it comes to stable, safe control of UAS, moderate to strong wind is often an issue.
Flight height restrictions (<122 m) and the line of sight	Agency A, B C, D, E	<ul style="list-style-type: none"> Staying <400 ft above ground is incredibly difficult and limiting in areas with steep slopes or rapidly changing topography. Not being able to fly beyond visual line of sight poses difficulty in obtaining overall imagery of the situation, particularly in areas with rugged topography.
Outdated software (platform) problem	Agency C	<ul style="list-style-type: none"> Experienced problems with software updates on the platform currently in use.
Lack of data processing experts and UAS lidar sensor	Agency D	<ul style="list-style-type: none"> Had sufficient staff and capacity to operate the UAS and perform data acquisition but did not have enough staff to process the data in a timely manner.
Communication standards	Agency C	<ul style="list-style-type: none"> Difficulties arose in communication between UAS and crewed aircraft.
Introduction of new technologies and issues of efficiency	Agency A	<ul style="list-style-type: none"> Performed some preliminary implementations of new technology; however, they introduced efficiency challenges.

Table 4. Political (and social) challenges identified by the respondents using UAS.

Political challenges	Institution	Explanation
Flight height restrictions (<122 m)	Agency A, B C, D, E	• FAA Part 107 (Operating Requirements).
Receiving airspace authorisation	Agency A, B C, E	• The process of obtaining airspace authorisation is lengthy and sometimes confusing.
Temporary flight restriction (TFRs)	Agency B	• Type 1 and 2 (UAS over 25 pounds) UAS utilisation and Special Governmental Interest (SGI) process issues.
Exclusive use contracts & Pre training and practice	Agency C	• Mission review, sand table exercise, training, etc.
Technological progress outweighed political progress	Agency A, B C, D	• Policy support is needed to keep up with the pace of development of UAS technology.
Temporal cessation of UAS-related training	Agency C	• 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	Agency A, F	• Possibility of invasion of personal privacy during UAS flight and filming. • Exposure to major national facilities.

for the response, called Temporary Flight Restrictions (TFR). This can be a problem if institutions need to use a type 1 or 2 UAS (UAS over 11.3 kg (25 lbs)). Most type 1 and 2 UAS are not owned by Agency B and are used via contracts with general institutions. Thus, a rapid response will require TFR permissions, and the FAA can require a considerable time to issue these permissions. Many institutions have also mentioned airspace authorisation as a related challenge. Prior to flight, institutions must send a request to obtain airspace authorisation, and most are automatically accepted. However, requests for additional coordination are sometimes rejected or receive no response without further explanation. Considering the nature of disaster response, these delays can increase the likelihood that critical information will not be obtained in time, which can hinder the response.

The second political and social challenge theme is the use of contracts. Institutions, such as Agency C, do not own UAS fleets. Thus, after a wildfire, Agency C will develop an exclusive use contract with a private company. However, because institutions such as Agency C do not consistently work with these companies, they must discuss the scope of work and details each time, ultimately delaying the deployment of UAS and data collection. Agency C is considering remedying this issue by conducting mission reviews and training together with the private contractors in advance of the wildfire season via advance contracting.

The last political and social challenge theme is that technological progress is outpacing political progress. For example, in a mission to classify and remove hazardous trees after the 2020 Labour Day fires, Agency D knew the effectiveness and benefits of data capture using a UAS with lidar sensor payload, but they were unable to use it because there was no official approval from higher authorities. A careful review and verification process is essential when introducing new technology to ensure effective use. However, if this process and technological progress are not balanced, it becomes a hindrance to the use of UAS technology, particularly in the case of wildfires where the response situation changes rapidly.

However, these institutions 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; however, the biggest barrier was the suspension of training. This reduced training was evident when trying to use UAS during and after the 2020 Labour Day fires because, compared to normal operational times, they did not have sufficient institution personnel training.

UAS data management

UAS technology can produce various data types for applications in wildfire response, from basic images to videos to purpose-built maps. The efficiency of a UAS also tends to result in substantial data volumes. Interviewees discussed how they handle UAS data in each institution, particularly from a data-sharing perspective. Notably, most institutions faced similar concerns about data management and sharing, including the difficulty of sharing across institution boundaries and refreshing data with the most up-to-date information. These concerns are summarised in the data lifecycle (Fig. 3), which refers to the sequence of processes from data creation, storage, use, sharing, archival, and destruction.

Most interviewees mentioned the critical need for standards and specific criteria throughout the data life cycle. For example, Agency C noted the need for protocols to distinguish which data are classified as federal data and which are public data. This determination can be ambiguous. Agency C also noted challenges in determining which data to archive as a formal record and which data to dispose of whose purpose was to inform the immediate situation and was soon outdated. Attempting to archive all data are a substantial burden on personnel to provide all necessary metadata to comply with federal data sharing standards. It also creates bottlenecks and confusion in the reuse of the data in the future, given the large data volume users must sift through to locate the data of interest, ultimately causing the most important information to be lost in the vast data repositories.

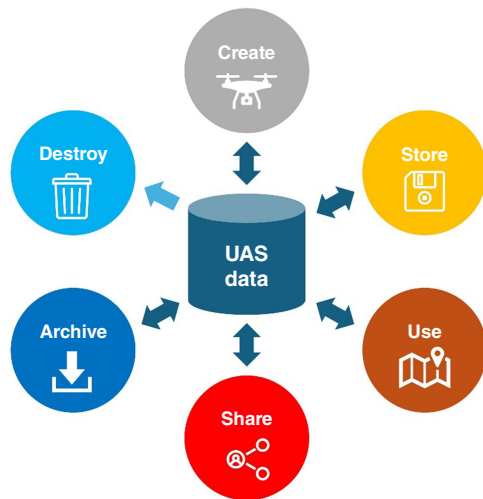


Fig. 3. Stages of the UAS Data lifecycle. Adapted from Rahul and Banyal (2020).

A consistent data storage format is necessary for effective (and, in some cases, legal) data sharing. However, some institutions, such as Agencies A and C, do not have standards in place. One interviewee noted that this lack of standardisation poses difficulty in sharing data within Agency C. Agency B said that they are working on building an improved data storage system to address these issues.

Conclusion

We applied an exploratory case study methodology to investigate the uses of UAS during the 2020 Labour Day wildfires in Oregon. The primary conclusion is that while the use of UAS in disaster situations continues to increase, research on the infrastructure, standards, as well as technical and political challenges related to UAS use remains insufficient. In this study, we conducted a comprehensive investigation into the current use of UAS through a literature review and interviews with experts (Objective 1). The research commenced with a detailed literature review exploring applications of UAS in disaster response with a focus on wildfire. Building upon those insights and common threads found in the literature review, we carefully crafted a questionnaire centred around the knowledge gaps identified. We then conducted semi-structured interviews with organisations involved in managing wildfires and deploying UAS technology in the vast data repositories. The interview process was refined with each interview and feedback from the experts. These discussions explored the practical use of UAS in wildfire scenarios, seeking to identify and bridge gaps between academic research on UAS applications in disasters and the actual challenges faced in real-world situations. Through a synthesis of the interview results and literature review, we documented and organised important findings into four

subject areas: (1) current UAS utilisation; (2) operational challenges; (3) political challenges; and (4) UAS-related data management (Objective 3). Several institutions effectively used the UAS technology to support their response to the Oregon 2020 Labour Day wildfires, including mapping the burn area, monitoring the wildfires, assessing the damage, and evaluating long-term impacts, such as those on wildlife and falling tree hazards. However, we identified several challenges with current FAA Part 107 requirements when operating UAS in steep, narrow canyons with substantial amounts of vegetation. We also found the absence of special disaster-related regulations or procedures. Institutions also acknowledged difficulties in managing and sharing data due to the lack of standards and specific criteria.

Overall, many wildfire responding entities have already used UAS effectively in wildfire response. Nevertheless, improvements are still needed for the application of more efficient UAS. Many institutions mentioned a variety of political restrictions on using UAS. Policy changes through coordination and communication between higher-level organisations and UAS operators based on the understanding of UAS utilisation in wildfires, rather than simple relaxation of restrictions, are needed. It will also be necessary to establish a mutually agreed-upon framework for the operation of UAS in wildfire response. Without such a framework, each institution will devise its unique methods for UAS operation, data collection, management, and sharing. This lack of a framework can reduce the efficiency of collaboration and information sharing between organisations operating UAS during a wildfire. Further studies are needed regarding regulations and organisational structures to provide a framework for safe, effective, and systematic UAS utilisation in broader disaster response situations. Despite these challenges and setbacks, the interviewees all found substantial benefits and great promise from the use of UAS based on their use when responding to the 2020 Labour Day wildfires in Oregon.

This study lays the groundwork for a comprehensive UAS framework by systematically analysing current applications, restrictions, and challenges in wildfire scenarios (Objective 4). It highlights the necessity for enhanced communication and policy reform to facilitate UAS integration into wildfire management. By identifying and documenting these subject areas, this study provides a strategic blueprint for developing a framework that ensures UAS operations are safe, effective, and synergised across different agencies for wildfire mitigation, response, and recovery.

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