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USE OF UNMANNED AERIAL SYSTEMS IN OUTDOOR FIREFIGHTING

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ABSTRACT

The use of unmanned aerial systems (UAS) by the fire service is becoming more common, especially for large outdoor fires where it is difficult to understand the state of the fire conditions or efficiently suppress the fire. The focus of this paper is to discuss the challenges that are currently faced in using UAS, which are limiting the broader application of these systems for use in large outdoor fire events. The paper provides an overview of UAS currently used today as well as some guides and standards that have been developed to support the use of UAS. Challenges for use of these systems are discussed based on technical hardware/software as well as operational details related to policy and training. These challenges highlight hurdles that need to be overcome by the community to support broader, more frequent use of UAS in the field.

KEYWORDS

Unmanned aerial vehicle (UAV); wildland fire; fire management policy; wildland-urban interface (WUI); training and operation; challenges

1. INTRODUCTION

Large outdoor fires are challenging events that can result in significant property damage and injury. These events include fires in the wildland-urban interface (WUI), fires in an urban setting, and informal settlement fires [1, 2]. Large Outdoor Fire and the Built Environment (LOF&BE) is an international working group of the International Association for Fire Safety Science (IAFSS) formed to assess the current state of the art and evaluate potential areas for research to improve safety and community resilience [3]. One aspect of the working group is large outdoor firefighting (LOFF), which is focused on challenges that must be overcome by the firefighters to effectively control and suppress these types of fires.

In recent years, unmanned aerial systems (UAS) are being increasingly used by the fire service in fire safety missions. A UAS encompasses all aspects of the mission system including the unmanned aerial vehicle (UAV), ground controlling hardware/software system, communications, and operator [4]. This standard outlines a methodology for training, maintaining, and deploying a UAS. In a fire event, the mission of the UAS deployment needs to be clearly defined before the flight and the required number of UAS for the mission established. Trained UAS operators then execute the mission and provide acquired information to command control to support firefighting activities.

One large outdoor fire application for UAS is wildland fire, particularly at WUI. The WUI is the intersection between wildland fires and the built environment where people live. The conditions of wildland fires may change rapidly, threatening people’s homes and endangering them. In this application, UAS can watch the WUI to detect when a spot fire may occur or monitor where the fire is relative to the infrastructure. Spot fires are small fires caused by firebrands and commonly result in fires at locations far from the fire front away from firefighters [5–7]. Having UAS monitoring neighborhoods could provide early detection and suppression of these spot fires before they become large and result in significant property damage. In addition, UAS can be used to monitor weather and fire conditions around the WUI to provide an earlier warning that wildland fire conditions may be getting more severe. Fire condition data are currently updated roughly every day based on satellite and plane data to support forecasting the fire spread and potential for spot fires. However, wildland fires are known to create their own weather which can subsequently affect the fire spread patterns and hazards [8]. As a result, environmental conditions can change quickly and cause wildland fires to move in unexpected directions potentially toward the WUI and affect the evacuation and firefighting strategies [9]. Numerous UAS known as swarms can be used to monitor conditions around the WUI to provide more frequent updates to ensure evacuations occur and provide firefighting resources where needed to protect the WUI [10, 11].

There have been several recent papers reviewing the current state-of-the-art in the area of UAS system hardware and software as well as its application to wildland firefighting. Akhloufi et al. [12] provided a detailed overview of the sensing and perception systems used on UAVs as well as the organization of multiple UAVs to accomplish tasks. Kukreti et al. [13] explored the use of machine learning based systems to utilize imaging for fire detection and localization of fires to support suppression activities. Yuan et al. [14] used imaging along with algorithms based on optical flow and thresholding to detect and localize fires. The concept of using a swarm of several UAVs has been described in several papers. In UAV swarms, several UAVs can be used to accomplish a task not possible by a single UAV as well as increase the efficiency of performing missions through coordinated execution of tasks by multiple UAVs. Methodologies on using swarms of UAVs for wildland and urban firefighting have been reviewed and discussed elsewhere [10, 11].

One of the current challenges with the use of UAVs to support firefighting activities are the standards and regulations, which differ across the world. The major reason is that the UAV is still a new technology, and the pace of making regulation cannot catch up with its technology development. Moreover, countries and local authorities also have their own regulations on the use of UAVs for fire service related missions. For example, the National Fire Protection Association (NFPA) has recently published an international standard (NFPA 2400) for the use of small UAS by public safety entities including the fire service [4]. A perspective on the use of UAVs in Poland is provided by Balcerzak et al. [15] highlighting the regulations and policy in the European Union (EU). A new standard for the application of UAS in detecting and fighting wildfire is also under development in China, drafted by leading UAV manufacturers.

The focus of this paper is to provide an overview of the challenges currently faced in a broader usage of UASs by the fire service to support outdoor firefighting activities. A general overview of UAVs is provided followed by an overview of some standards and regulations that exist internationally. Some of the technical challenges with the use of UAS for firefighting activities is discussed including UAV technology and communication systems. Lastly, the existing operational challenges including training and policy are provided.

2. UAVS AND THEIR USE IN FIREFIGHTING

2.1 Historical Aspects

The usage of UAS is not really a new concept, particularly in military uses throughout human civilization. An interesting early use of unmanned aerial technologies was the use of hot air balloons during the US Civil War or the installation of cameras in kites during the Spanish-American War [16]. Yet, there are also historical accounts that pre-date these events by hundreds of years that have used the concept of unnamed aerial technologies for various purposes. Watts [17] has provided an interesting review of UAS development and its recent introduction to fire safety applications. In this section, some important aspects of the review in Ref. [17] are discussed as they are of direct relevance to this review paper related to UAS technologies for large outdoor fires. For readers interested in a detailed history of UAS systems for military applications, please refer to [18].

UAVs, autonomous aircraft with remote control, as important parts of UAS, has aroused wide attention around the world. To get a comprehensive understanding of UAVs' history and development, Fahlstrom et al. [19] have summarized the main points. A common discussion point is related to the precise usage of terminology for UAV systems. A term often used when associated with UAV is the term 'drone'. According to Watts [17], the term drone was coined by the US Navy decades ago to refer to UAV directed at military targets. As a result, the term drone has been associated with military strikes and, in many regions in the world, does not have a positive connotation. For these reasons, when discussing the use of UAV for fire safety applications, it is best to avoid the term drone. Clearly, fire safety applications of UAV technology for deployment to large outdoor fires do not have a military intent.

2.2 Types of UAVs

To better describe UAVs, the basic classification of UAV is introduced first. Considering the take-off and landing processes, UAVs currently in use are delineated into two types.

1) Vertical Take Off and Landing (VTOL): Consist of technologies that require no runway for take-off and landing. UAVs that use VTOL can only fly below 400 ft (120 m) AGL. Naturally, VTOLs have a major advantage in that take-off requirements are eliminated, but of course it is easy to imagine that this consumes significant power and limits the overall flight time.
2) Horizontal Take Off Landing (HTOL): UAVs that use HTOL primarily fly in a mountainous zone or a predefined low-risk zone, and they must fly higher than 500 ft (150 m) above ground level (AGL). Recent UAV regulations define nonintegrated airspace for flights below 400 ft (120 m) AGL to maintain flight safety. A flight level of 500 ft (150 m) AGL is half of the minimum flight altitude for transport aircraft operations [20].

UAVs can be categorized based on their endurance time, flight altitude, range, and mass [21, 22], as summarized in Table 1. The choice of UAV will depend on the mission objectives. The small close-range low-altitude UAVs are most common in civil utilization, which can be rapid deployed for lower altitude fire conditions assessment. Meanwhile, the medium-range and long-range UVAs are used potentially for missions requiring higher altitude, e.g., fire front mapping, wildfire detection, and overall fire hazard monitoring.

Table 1. A typical classification of UAVs [21, 22].

Types	Mass (kg)	Range (km)	Altitude (m)	Duration (h)
Nano	< 0.2	< 10	< 250	< 1
Micro	< 5	< 10	< 250	< 1
Mini	5 – 25	< 10	150 - 300	< 2
Close Range	25 - 150	10 - 30	3,000	2 - 4
Medium range	50 – 250	30 – 70	3,000	3 - 6
Long range	>250	> 70	> 3,000	> 6

The Micro or Nano UAVs consist of small dimensions, deployed at low altitudes, and flight times less than 30 min. Nano UAV is usually defined as extremely small and ultra-lightweight air vehicle systems with a maximum wingspan length of 15 cm and a weight less than 200 g. The weight of Micro UAV should be between 200 g and 2 kg. These are probably the most well-known to everyone as this technology is quite inexpensive and may be purchased easily. In addition, UAVs can be grouped into tilt-wing, tilt-rotor, tilt-body, ducted fan, helicopter, heli-wing and unconventional types [22].

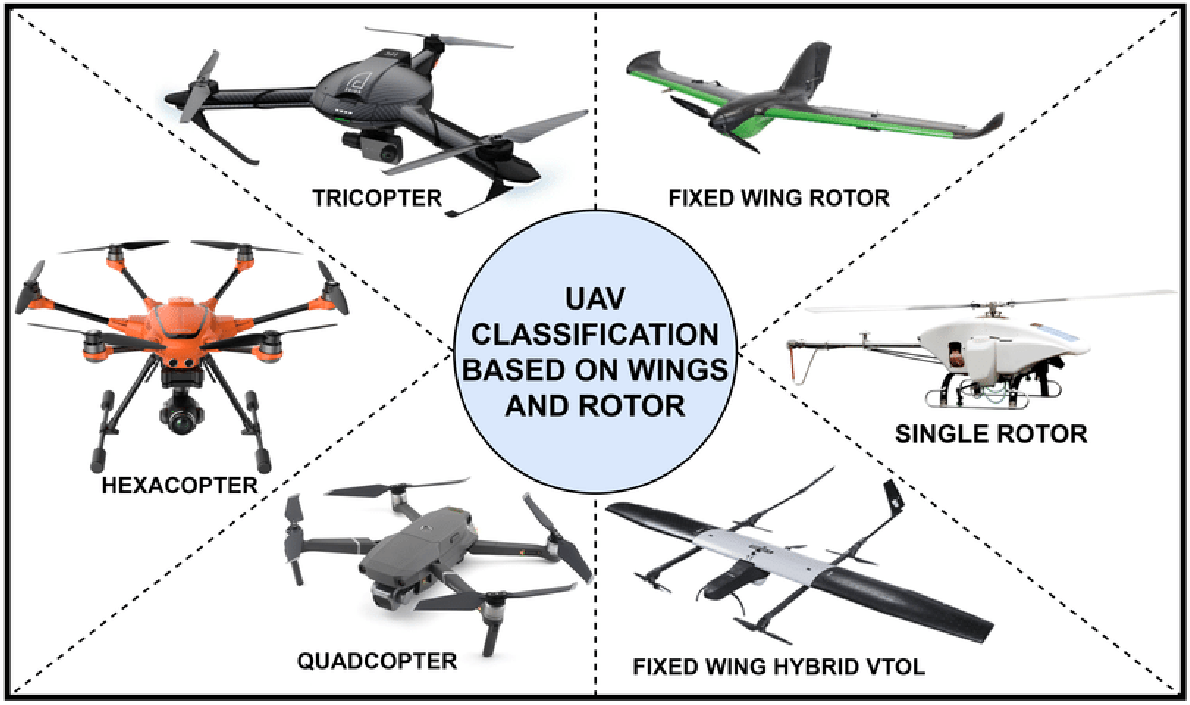

Figure 1. Common types of UAVs [23].

Defined by the way they fly, UAVs can also classified into fixed, multirotor and hybrid types, (**Error! Reference source not found.**). Fixed-wing UAVs need more space to be launched as their wings need forward airspeed to generate lift. Considering the endurance and cost of these UAVs, they are more likely to support operations in the open country. Multirotor UAVs use rotary wings to create lift and don't need much space to be launched. They are usually able to perform VTOL and they can also hover vertically, but have limited range, flight time and thus payload capacity [24]. The flexibility enables them to work well in buildings of cities. Hybrid UAVs encompass features of both fixed-wing and multirotor, for example, rotors to perform VTOL and wings to hover longer distances. However, they tend to be more expensive.

2.3. Firefighting UAVs

UAVs have been used to support responders in firefighting activities, which are actions that occur with a fire burning. There is no doubt that UAVs can play a key role in promoting the progress of different industries, which lays out for the framework of "UAV+". "UAV+" emphasizes the universality of UAVs to interact with researchers in different areas. Firefighting is such an area where firefighting UAVs are one of the most promising technologies to ensure the safety of fire fighters.

In wildland fire detection, monitoring and fighting, a view from higher elevations is desired to gain overall and unique fire information. Compared to a fixed camera network installed on mountain tops and fire watchtowers, the airborne monitoring system is more cost-effective and is not limited by the location of the pre-installed infrastructure. Airborne systems usually include high-altitude manned or unmanned aircraft [25, 26] and high-altitude long-duration balloons [27, 28]. As expected, the overall cost of unnamed aircraft and balloons is much lower compared to the manned system. Another important aspect is the risk of having people onboard aircraft during a mission. By using unmanned aircraft, you avoid putting a crew at risk. Aviation accidents account for 18% of wildland fire fighting fatalities between 2007-2016 [29].

UAVs perform well in the field of city resilience due to their flexibility when taking tasks in urban firefighting. Firefighting UAVs are undoubtedly one of the most promising technology to ensure the safety of fire fighters. UAVs can shorten the time of firefighting response and render rescue activities safer, faster and more efficient [30]. They have the ability to access hard-to-reach areas and help gather important data [31]. Besides, they can replace the role of helicopters and fixed wing aircraft, which may be disturbed by smoke, increasing the risk of pilots when putting out the fire. The ability to avoid human causalties, unnecessary obstacles and disturbance makes UAVs unique in firefighting.

The function of firefighting UAVs varies depending on the payload UAVs are equipped with. Usually, it can be divided into two types, the light UAVs for fire detection and monitoring, and the heavy UAVs that can carry fire suppression agents for direct firefighting. Fundamentally, UAVs are merely the vehicle to carry specific payload despite the difference in appearances and size in the field of firefighting. Normally, it could take extinguishing materials, pipes to transport suppression agents, and sensors, depending on its tasks.

There is no specific restriction on the sizes of UAV, but as for the weight, NFPA 2400 [4] regulated the weight of an unmanned aircraft should be less than 55lb (~25kg) as the take-off weight (referred to in the standard as small unmanned aerial systems, sUAS). Depending on the carrying weight, they are classified as either light-duty UAVs or heavy-duty UAVs. It is widely assumed that the lighter the weight of UAVs is, the longer the endurance time can be (see Table 1). However, in fact, heavier aircrafts have more endurance (e.g. they can carry more batteries and liquid fuels). Figure 2 summarizes some statistics of take-off weight and endurance time of commonly used commercial UAVs. The data are collected from several mainstream UAVs which are adopted in firefighting.

Light-duty UAVs whose weight is less than 4 kg usually bear the duty of taking photos and real-time information transmission. Heavy-duty UAVs carry more than 4 kg. Not only can they be equipped with some cameras, but they also carry other sensors at the same time. Utilizing them to transport fire hoses and other materials is possible. Although the amount of fire suppression agent carried by UAVs is much smaller than a typical firefighting helicopter and manned aircraft, UAVs can be deployed faster, enter a more complex landscape, get closer to the fire and drop the agent more accurately. These advantages make the UAVs very effective in controlling early stage outdoor fires.

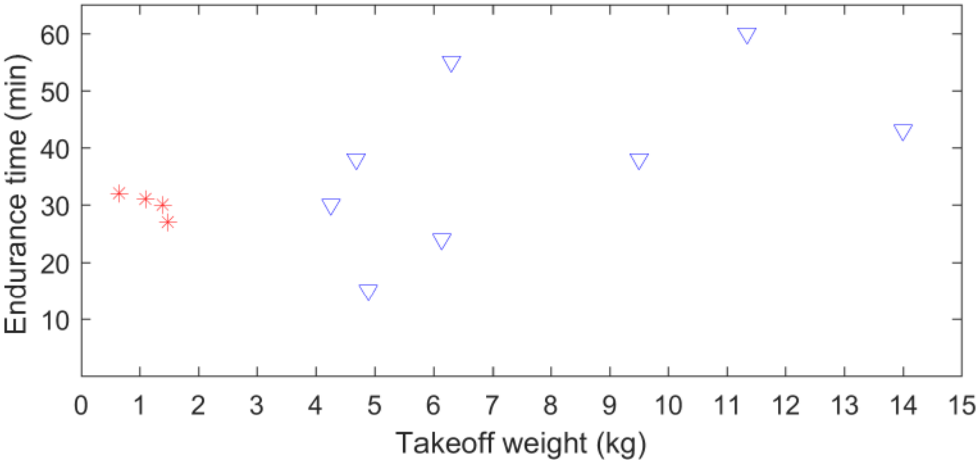

Figure 2. UAVs take-off weight (kg) and endurance time (min.) of commonly used commercial UAVs.

UAVs are typically not designed for extreme heat like hot fire smoke, and so if the chance of high heat exposure exists, some protection of the systems must be implemented. The DJI Matrice 300 RTK is rated for temperatures up to 50^{o} C; however, battery performance will always be degraded, and in the worse-case, a battery fire could result from high temperature operation. Some researchers and UAV manufacturers have demonstrated a UAV capable of operating after exposure to flame, using electric cooling technology to keep the critical electronics safe, e.g., KAIST [32]. However, operation in continuous fire environments has not yet been demonstrated. The assumption is that fire-hardened UAVs could be designed and built, but they have not reached maturity at this time.

Research suggests that UAVs can improve the effectiveness of firefighters during the emergency response in different situations, especially in fire extinguishment [33]. Two surveys conducted in 2021 revealed that the most common problems firefighters confront are the lack of human and material resources and the need for real-time monitoring of evolution of fires during extinguishing tasks [11]. The surveys demonstrated that firefighters support the use of UAVs which can help solve these problems. Generally, UAVs are used as an efficient tool for prevention, surveillance, and extinguishing activities in firefighting.

On the other hand, UAVs have already been put into practical use and research in the last decades. In 2014, the Roswell Flight Test Crew used RQCX-3 “Raven” hexacopter to finish a firefighting exercise [30]. Dubai Civil Defense bought 15 quadcopters for high-risk areas patrolling in case of fire disasters [34]. The firefighting department of New York City was also equipped with UAVs to monitor dangerous blazes in 2016 [35] and suppressed a fire with the help of UAVs for the first time on 7th March 2017. In April 2016, EENA (European Emergency Number Association) partnered with DJI Technology and chose four sites to evaluate the performance of UAVs in terms of emergency operations in Mid and West Wales Fire and Rescue Service (UK), Donegal Mountain Rescue (Ireland), Greater Copenhagen Fire Department (Denmark) and Reykjavik SAR Team (Iceland) [36].

A UAV has also been developed that carries extinguishing equipment for firefighting, and it is been in service for firefighting activities since 2017 [30]. For example, a semi-autonomous indoor firefighting UAV was proposed to help fire fighters seek survivors [37]. Not limited to the city, UAVs have also been tested in wildfires. As described in Ref. [38], researchers were entrusted by the fire department of Texas to come up with a fire-extinguishing ball technology and then applied it with UAVs in wildfire fighting. This technology was also utilized to detect and monitor wildfire to reduce false alarms, increasing the efficiency of fire fighters [39]. In 2021, a platform was proposed to manage a number of UAVs in order to spread suppressants on wildland fires [40]. Nowadays, several research teams have been focusing on frameworks of UAV swarms because a single UAV is not sufficient to address a big fire or wildfire [10, 11, 40, 41]. In other words, a single UAV cannot monitor the large-scale wildfire situation. Instead, large-scale wildfires require more UAVs cooperation to complete such the extinguishment task in wildfire, and such collaborative cooperation should be controlled by an intelligent algorithm rather than a group of human operators.

3. TECHNICAL CHALLENGES

3.1 UAV Endurance

Mini UAVs have already been adopted by multiple first responders for their daily tasks. They have proven a new valuable tool to get real time video or footage of small areas and more recently of indoor areas. However, these tools have range and endurance limitations, as well as lack the capacity to carry advanced payloads (such as gyrostabilized cameras or communication relay systems) for more demanding first responders' applications. Manned aircrafts are nowadays widely operated during emergency situations. However, this may change in the near future with long-endurance civil UAVs gaining increasing popularity.

Long endurance UAVs have already been extensively used in the military field. They have proven to be a valuable tool in replacing manned airplanes. The US Navy has nowadays a fleet of around 40% unmanned / 60% manned platforms [42]. Furthermore, it is expected that the tides are going to turn in the mid-term, expecting to have 60% unmanned / 40% manned platforms in the upcoming decade. Military systems are not suitable for the civil market, mainly because of its high cost and their complex operation. Moreover, most long-endurance UAVs are driven by conventional internal combustion engines with liquid fuel rather than heavy batteries. For wildfire-related operations, the falling of UAVs with liquid fuel can cause new ignition points and accelerate the fire growth, despite in the long term, a Li-ion battery pack also has a big concern of fire. A hydrogen fuel cell system has also been used for wildfire UAVs to increase their patrol range and fly duration, but its cost is much higher.

However, long endurance civil UAVs are starting to become a reality due to the following facts:

- Legislation changes: long endurance UAVs need to be operated Beyond Visual Line of Sight (BVLOS) or even Beyond Radio Line of Sight (BRLOS). Until 2020, these types of operations were completely forbidden in most countries. This has recently changed with the release of certification procedures in the USA and India and a new legislation in EU, all of them regulating these operations typology. The details of US regulations are provided in a later section.

- Communication technology advances: long range operations are only possible with long range control link communications. With the improvement of great coverage networks (4G/5G and satellite) together with its cost reduction, nowadays it is possible to stablish a control link of unlimited range between a ground control station and a UAV. Even real time images can be sent using bonding technology.

This has generated a renewed interest by manufacturers to start designing and producing new UAV systems that can take advantage of these recent changes. One example is the ones used in the IOPES project sponsored by the EU [43], in which a system with more than 24h+ endurance and 1.800 km range is operated to provide real time thermal and RGB imagery to first responders and very high resolution orthophoto maps in a few hours. High resolution orthophoto maps can be used to identify and geolocalize the sectors of the fire perimeter (i.e., head, tail, and flanks) and to determine the fire perimeter and flank length. The combination of several orthophotos can be used to derive the fire rate of spread following the approach presented in either Ref. [44] or Ref. [45]. This capability allows to increase the situational awareness of the deployed first responders' teams, thus enhancing their ability to effectively allocate the available resources and exercise supervision over them.

These types of UAVs have the capability to replace manned airplanes in some tasks: emergency surveillance in the short term, and fire suppression and rescue operations in the long term. Therefore, they can provide some key benefits compared to manned systems:

- Costs: UAVs have a lower cost than manned systems as shown in Table 2. This allows to either save resources for other consignments without downgrading the fleet or keep the same budget and increase the number of aerial systems available.

Table 2. Cost for operating manned and unmanned air vehicles.

Cost	**Manned** [46, 47]	**Unmanned**[1]
Acquisition	3.000-5.000k€	450-600k€
Operation	500-6.000€/flight h	250-500€/flight h
Maintenance	500-600k€ annually	25-50k€ annually
Environmental	360-420 L fuel/flight h	0.2 L fuel/flight h

[1] estimated based on experience and the market of 2022.

- Operation flexibility: Unmanned systems can fly in a more variety of conditions, such as during night or with bad weather conditions, being able to provide 24h air services over the emergency.
- No risk to pilot lives: Removing the pilot from onboard the UAV reduces the risk of losing human lives during an emergency. Furthermore, this also allows to push the system to the limit when required.
- Rescue support: Equip UAVs with infrared and thermic cameras to detect people lost or trapped in remote locations.

- Flexible landscape: Provide an aerial view of locations with difficult accesses by large manned airplanes.
- Quick response: UAVs can be sent quickly to assess the most affected areas so as to determine the safest access routes.

As demonstrated before, multiple benefits arise when using UAVs in the field of emergencies. Whereas they have become increasingly popular in the military industry for the last decade, similar tendencies may occur in emergency operations due to natural hazards such as wildfires, leading to a gradual replacement of manned airplanes by UAVs in those tasks that they prove useful, valuable and safe.

3.2 Operation in fire scene

In addition to the high temperature environment, the hot fire plume, uprising driven by buoyancy, can induced a wind, and such a wind increases with the scale of fire. For example, large-scale outdoor fires create hazardous weather conditions for drones as a result of turbulence from surface winds. For example, a wind speed over 20-30 m/s is widely observed in a wildfire. Moreover, large wildfire also causes a larger scale weather phenomenon such as rainfall, firebrand shower, haze, pyrotornadogenesis and pyrocumulonimbus cloud formation [48]. Unsteady surface winds are common around structures and terrain features whenever there is wind, but fire can greatly amplify surface winds and in turn, amplify turbulence. Emejeamara, *et. al.* [49] sampled wind speeds at 1 Hz from a roof-top sensor in Manchester, England, showing variations from 0.5 m/s to 14 m/s, with a 8 m/s velocity change in 1 second. Although sampling was not performed above 1 Hz, higher intensity and greater rates of change would be observed at higher frequencies, and fire would only make these conditions more extreme. Most common consumer-grade UAVs have a 8 m/s wind limitation, ruling out their applications near buildings, especially high-rise building. GPS degradation is another reality of flight that occurs whenever sky visibility is limited. This has the effect of reducing positional accuracy and amplifying the effects of wind turbulence on stable flight.

Fire-generated vortices (FGV) originate as a result of buoyancy-induced surface winds that create horizontal-axis vortices in the shear layer. Tilting of a horizontal vortex is possible, and then if it is ingested into an updraft it will form a coherent vortex [50]. Most FGVs are bounded in intensity to <10 m diameter, however large vortices may result (>100 m diameter), leading in some cases to pyrotornadogenesis as the vortex reaches cloud-height. Intense winds and wind gradients are created in FGVs and pyrotornados, much higher than the operational limitations of aircraft.

Pyrocumulonimbus cloud formation is the result of convective activity due to fire. These clouds originate from fire-generated air parcel buoyancy which moves warm, moist air to higher altitudes resulting in latent heat release and the start of classical cumulonimbus cloud formation. Severe weather commonly associated with these clouds then develops, including strong winds due to the intensity of the resulting updrafts, lightning and the possibility of pyrotornadogenesis. A pyrotornado developed from the Carr fire on 27 July, 2018 in California [51], with radar-measured winds of 230 kph (143 mph) and a height of 5200 m, qualifying as an EF-3.

Aircraft flying in the vicinity of a fire will experience elevated turbulence levels, with the possibility of loss of control due to micro and mesoscale winds and wind gradients. Loss of control resulting from an exceedance of control authority, and even structural failure are possible. Even without vorticity, straight line winds generated by fire-induced buoyancy is enough to challenge most aircraft that may need to maintain position near structures and terrain features of interest. Most commercial UVAs have a self-protecion mechanism to avoid approaching hot and unstable flow, while disabling that mechanism may cause an early crash. Both scenarios limit their ability to complete the missions related to firefighting.

Cybyk, *et. al.* [52] addressed aircraft design requirements with unsteady winds in mind, defining operational parameters that include "…minimum altitude, minimum and maximum airspeed, vehicle attitude angles limits, maximum wind speed, autopilot command schedules, and geographical no-go or stay-out zones. Vehicle design parameters or requirements may include control surface sizing, control actuator sizing and response, autopilot design, and overall vehicle sizing." Flight missions that occur on-demand with no opportunity to choose the day and time of the flight will expose the aircraft to unavoidable extreme conditions that potentially violate most operational envelopes. The challenge, therefore, is to select an aircraft with very high absolute and rate-of-change wind limits. Vertical takeoff and landing aircraft (VTOL) which include quad and hex-rotor designs have a significantly better resistance to gusty conditions than fixed wing aircraft, and so for close-in work where precision flying next structures and ground features is required, VTOL are functionally and aerodynamically preferred.

Smoke resulting from fire can be considered an impenetrable wall for drones, and if a flight mission steers the aircraft close to these areas it needs to have active sensing and control to avoid entry. Operating unmanned aircraft beyond visual line-of-sight (BVLOS) comes with added risk, and while the Federal Aviation Administration (FAA) is in the process of creating rules for such operations [53], they will most likely not approve low-altitude, zero-visibility operations within a fire zone. BVLOS operations outside of smoke are currently possible via waiver and will likely be approved without waiver in future rulemaking by the FAA. This allows longer duration flights at night, for instance, when manned aircraft are not flying.

Demonstrations of the utility of UAS in fire management occurred as early as 2006, where thermal imaging and radio repeating capabilities were flown to show the benefits of unmanned aircraft to the incident commander and firefighter [54]. Regardless of the line-of-sight requirement, regulations require at least three miles of visibility to operate drones that are not on an instrument flight plan. Lower smoke strata can obscure the ground environment which makes all sensing difficult from a higher altitude. The three-mile visibility requirement is enforced at the aircraft position so on-board visibility sensing may be required when flying in areas where smoke is present. The recent large-scale fires in the US west coast have driven UAV operations to very low altitudes and limited range due to the reduced visibility from smoke. In the Dixie fire in California in 2021, flights along powerlines were conducted over short segments only to effectively inspect for spot fires.

High wind and temperature levels do not prevent the use of UAV in wildfire management, but they must fly far away from the fire head and flanks in areas with less wind and lower temperatures. This potential limitation can be compensated with the use of cutting-edge cameras with enlarged zoom capabilities (such as 30x zoom). Moreover, it is important to remark that fixed wing systems have much more resistance to wind in cruise mode, and they can currently fly at wind speeds of 15 m/s or more. To be closer to the fire environment, the UAV must be designed to operate at higher temperatures. As recommended in Ref. [32], this would require the UAV to be manufactured with or reinforced with fire-resistant materials. This type of fire hardened UAV may be helpful for some types of suppression approaches discussed later or for different types of near field surveillance. However, as mentioned previously, these types of fire hardened UAVs have still not been fully developed and tested for field use, and the standard for fire hardened UAVs is not available yet.

Once a large-scale wildland fire is established and tanker operations commence, the FAA will put in place temporary flight restrictions (TFR) to keep non-cooperative air traffic out of the flight area. These are most commonly directed at drone flights which in the past have disrupted aerial firefighting by grounding tanker operations due to a flight hazard risk. The most notable example of this is when the Dixie fire was nearly contained before it spread to the second largest in California’s history. Late in the day, when a helicopter was making water drops due to the proximity of a river, a UAV was spotted which shut down flight operations until it became too late (after sunset) to continue flying. The fire grew to 500 acres overnight and was out of control from that point on [55]. So far, it is extremely unsafe to deploy UAVs and manned aerial vehicles or even multiple UAVs simultaneously.

3.3 Communications with UAVs

Communication is a significant challenge for UAVs in outdoor applications. These challenges include distance of communication with the UAV, bandwidth availability on dedicated emergency responder bands, latency in communication, and speed to enhance the amount of information that can be collected by the UAV.

As mentioned previously, radio repeating using UAVs in wildland fire management was tested in 2006 to enhance tactical firefighting capability where line-of-sight communications would not be possible [56]. These situations occur beyond ridgelines that block VHF communications of handheld radios transmitting on the public safety frequency bands (150 - 174 Mhz). The tests conducted proved the flexibility of deploying an aircraft with a repeating node that could be adaptively moved to re-broadcast transmissions between firefighters in remote areas, adjusting to the crew’s movement. Krawiec, et. al. [57] demonstrated an adaptive repeating node that uses a terrain model as the basis for optimal radio repeater positioning, resulting in extended comms coverage limited only by the endurance of the UAV.

In urban areas, 5G networks are being deployed and the AT&T FirstNet public safety coverage using a 20 MHz bandwidth of Band 14 promises expedited emergency communications for all emergency responders. Low Earth orbit technology like Starlink may also provide communication support for UAVs to detect remote wildfires. Although no specific applications have been demonstrated, the future of urban firefighting will probably rely on IoT capability where UAVs, static sensors and the crew interact together with low latency and high resolution information.

One method for augmenting communications between personnel as well as with aircraft would be using multiple UAS. As mentioned in Ref. [58], this could be accomplished by leveraging research from previous UAS integration projects and UAS traffic management programs.

3.4 UAS User Interface

A significant part of the UAS is the user-interface between the operator and the UAV. UAVs can be operated by a human, semi-autonomously with a human in the loop, or completely autonomous with a human overseeing the operation. In most instances for first responders, operations are typically operated by a human or in a semi-autonomous fashion. As a result, the operator needs to be able to process the information collected by the UAV and generated by other software to support decisions on how to proceed. This can create an information overload on the operator, which can reduce how effectively the mission proceeds. Current research is exploring optimal user-interfaces that provide the user with the needed information in a concise way so that it can be rapidly processed to support in-mission decision making. This is particularly true for cases where there may be multiple UASs.

One recent example of this is the RESPONDRONE project where a user interface was developed for operations with multiple UASs [59]. The user-interface development was based on the results of field interviews with first responders and workshops. Based on these results, the on-site command system (OSCC) had one display while the field operators had another display based on information located in a cloud-based system. The OSCC provided more high-level information about the disaster area and locations of the deployed UAS and first responders in the field. For the field operators, their displays were mainly focused on monitoring the UAS through a ground control system (GCS) to ensure low risk, safe flight. This application used highly automated UAVs that fly without a pilot, but a safety pilot supervises the UAVs during their pre-planned flight routes as well as take-off and landing (semi-autonomous). The system also allows for communication between the GCS and OSCC to support updates and receive additional tasks. The system was evaluated by eight participants through an online system.

Additional development of user-interfaces with the first responder in the design loop need to be conducted to ensure the critical information for operations is being provided in an efficient, effective manner.

3.5 Fires Suppression Capacity

A wide variety of robotic designs are being pursued for the suppression of outdoor and structure related fires. These include UAVs (primarily quad or hex rotors), track/wheeled ground vehicles, biomimetic type robots (snake-like [60] and bug [61]), and humanoids [62]. One of the primary considerations for the use of UAS in suppression operations is the payload of the UAV. Due to the low payload of UAVs, suppression has been primarily done through tethers attached to the UAVs that supply the suppression agent to the UAV for fire suppression. One of the applications of using this approach is for exterior façade fires on tall buildings. In recent years, combustible exterior façades have resulted in large exterior fires that are difficult to suppress. As seen in Figure 3, multiple UAVs have been developed to suppress these types of fires with water [63]. According to Ausonio *et al.* [40], a swarm of hundreds of UAVs is able to generate a continuous flow of extinguishing liquid on the fire front, simulating the effect of rain, but it has not been demonstrated in the large outdoor fire.

Figure 3. A demonstration for using multiple UAVs to suppress exterior façade fires on a structure [63].

A number of different techniques have been used to suppress and extinguish fires. Water, is the most available and most used fire suppressant for most applications [64]. However, it is not effective in some challenging types of fires, such as fuel pool fires, industrial fires where flammable chemicals are involved, enclosure fires, etc. Inert gases, such as carbon dioxide are used in some of these fires, as well as chemical foams. Aqueous film-forming foams (AFFF) have found widespread use [65], [66]. AFFFs coat a pool of hydrocarbon fuel with a layer of foam, which acts as a thermal and evaporation barrier to suppress and, to eventually extinguish the combustion reactions. In the last two decades, the fluorinated surfactants that are used in all current AFFF formulations have undergone environmental scrutiny. The fluorocarbon surfactant in these foams degrades to perfluorooctyl sulfonate (PFOS), a chemical which has been identified by the US CDC as environmentally persistent, bio-accumulative, and toxic (PBT) [67–69]. In addition to suppression, some agents are applied onto surfaces to prevent ignition or slow the spread of fires. Non-fluorinated foams have also been proposed to prevent the ignition of Class A materials, including home exteriors and vegetation [70]. Chemicals, such as fire retardants dropped onto vegetation in wildland fires, are also used to prevent the ignition and slow the spread of wildland fires [71]. Aerial application of agents is currently done by manned aircraft, but the use of UAVs for agent application has been demonstrated [72]but not broadly used.

Suppression concepts are also being developed using inert gas agents (nitrogen) to suppress outdoor fires. The effectiveness of liquid nitrogen was first demonstrated in bench-scale experiments [73–76] as shown in Figure 4, which also included a thermocouple tree at the center of the fire. These preliminary experiments involved a fire over a shallow (1 cm) pool of iso-propyl alcohol in a 20 cm diameter pan. A quantity of 2 mL of liquid nitrogen, thrown from a distance, successfully extinguished the fire. A cloud of nitrogen gas at low temperatures, being heavier than the air covered the pool. The extinction of this flame appeared to be nearly instantaneous, i.e., on the order of a second. In addition, the insert of the thermocouple readings in Figure 4 confirmed that the fire was extinguished. This was also demonstrated for larger pool fires at CSIRO, Australia in tests that involved fires with two different fuels (propanol or diesel oil) in a one square meter pool, 2.5 cm deep.

The effectiveness of liquid nitrogen was also evaluated for extinction of wood crib fires at FM Global as shown in Figure 5 [77]. In some tests, the wood crib reignited after flame extinguishment due to the wood still smoldering. As a result, wood-based materials may also require surface cooling with water to suppress the smoldering wood for complete extinction. These tests established that liquid nitrogen delivered within the base of a source fire can efficiently extinguish a pool fire. However, for cellulosic fuels additional water application would be required to prevent reignition.

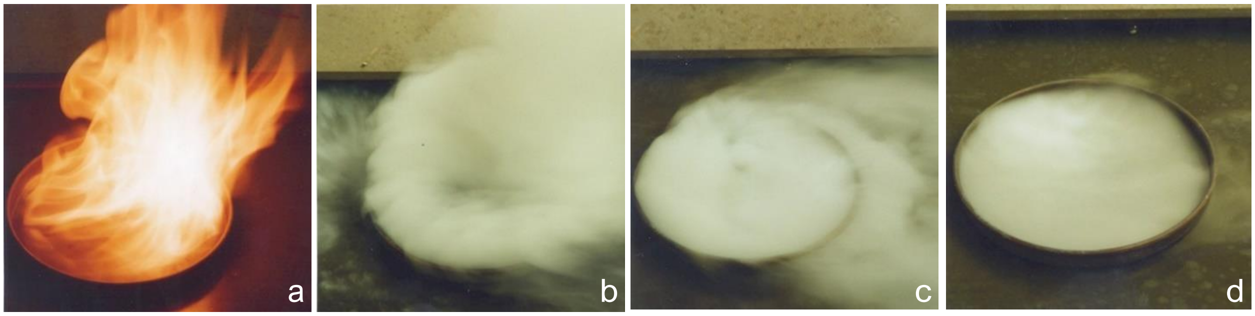

Figure 4. Extinguishment of liquid pool fire 20 cm in diameter by using 2 ml of liquid nitrogen. [73–76].

Figure 5. Extinguishment of wood crib fires by one liter of liquid nitrogen. In some of the tests the wood crib kept smoldering and slowly reignited after flame extinguishment [77].

The application of a liquid fire extinguisher by throwing capsules, filled with the liquid, in the fire has been explored [78–80]. The capsules can be transported with either piloted or remotely controlled helicopters or more preferably by a single UAVs [80], see Figure 6. The use of UAVs is possible because of their increased payload capability [81], the projected small quantities of liquid nitrogen required thrown in capsules [78–80], and the availability to guide and direct the UAV to critical situation for fire extinction or prevention of flame spread. In the case of cryogenic fluids, capsules need to be insulated. Prior research by the authors [78–80], showed that in the case of forest fires it may be advantageous for the capsules to have a particular shape as shown in Figure 6. This would facilitate the gradual dispersion of the cryogen onto burning trees and, thus, address all vertical sections of the fire, i.e., the crown, the mid-level, and the ground level. To implement aerial delivery of the cryogen to a wildfire, the capsules need to be insulated, and initially covered with vented lids to minimize loss of the cryogen by spilling or evaporation during transport. Upon reaching a destination, the capsules will be released. The capsules can be fluted to impart rotation during their descent to the fire, see Figure 6. The rotation will enhance ejection of the cryogen onto the fire as the capsules descend [79].

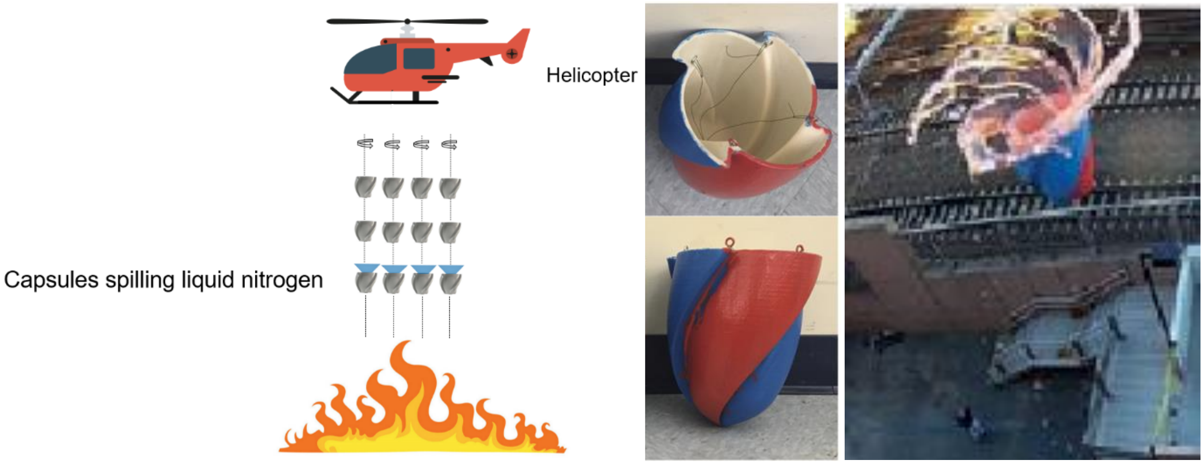

Figure 6. On the top a sketch of UAV delivery is shown. On the bottom left, photographs show a fluted capsule prototype. On the right, the capsule filled with colored water is released from a height, it spins as it descends and spills the liquid fire extinguisher to a large radius [78–80].

Finally, the application of swarm of UAVs, as suggested recently in Ref. [40], from which Figure 7 has been taken, would provide a means to combat fires that span over larger regions. Ideally, these types of UAV operations would occur before a wildland fire transitions to a crown fire where significant surface cooling may also be required.

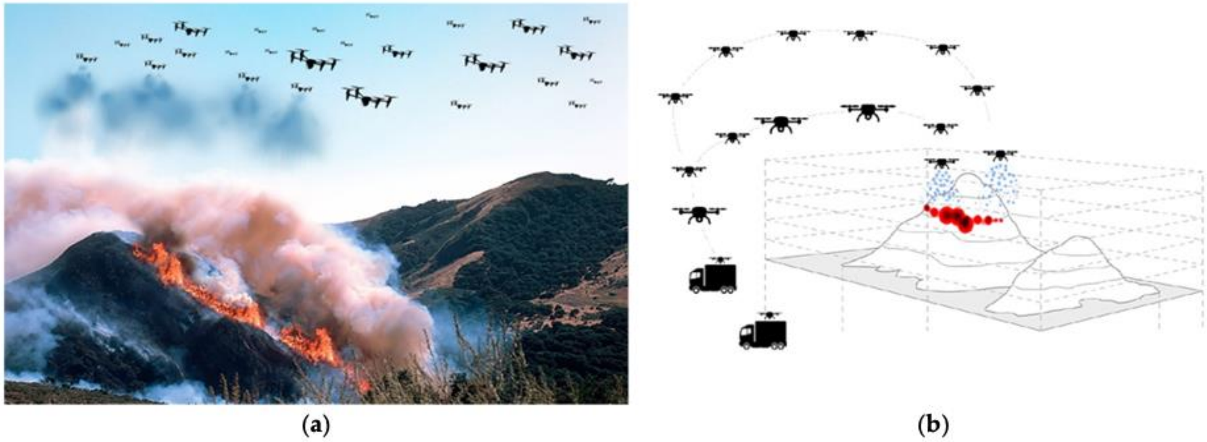

Figure 7. Application of liquid nitrogen for forest fire extinction using a swarm of UAVs [40].

4. OPERATION, TRAINING AND POLICY

According to the International Association for Fire Chiefs, UASs could be used in a variety of applications including structure fires including tall buildings, wildland fires, rescue, hazard materials events, emergency medical services, and disaster response [82]. The broader use of UAS has resulted in a number of standards and policies to provide guidance on the safe operation of UAS for emergency responders. An overview of the standards and guides that are used across the world is described. Following this, an example of the training and policy required in the United States (U.S.) is provided to give a sense of the considerations for the use of a UAS in large outdoor firefighting (LOFF).

4.1 Standards Overview

There are numerous regulations and standards around the use of UASs, primarily due to safety issues with respect to interference with other aircraft as well as the potential for UAVs to fall onto people located on the ground. Due to the significant advantages of using UAVs in support of public safety related operations, protocols have been developed as guidelines for UAS missions.

International regulations around global interoperability have been taken on by the International Civil Aviation Organization (ICAO) composed of members from 193 governments around the world [83]. However, the majority of regulations and standards for the use of UASs are still provided by other standards making bodies and national government organizations. Standards, best practices, and regulations exist for the general use of UASs as well as for public safety organizations including the fire service.

NFPA 2400 [4] is an international standard providing guidelines on the use of UAS with small UAVs (<25 kg). The scope of this standard is to provide operation, deployment, and implementation of small UAS (sUAS) for public safety related missions. The policies and procedures in the standard cover overall program management, operational procedures, personnel requirements (qualifications, training, certifications), safety, and care/maintenance of the UAS. For deployment of a sUAS, several aspects of the mission need to be specified and approved prior to flight including data collection, mission objectives, risk assessment, availability of resources, and definition of UAV operation zone (take-off, landing, drop zones). The operations team is composed of a remote pilot, visual observer and remote pilot in command (RPIC). The RPIC has the authority over the sUAS and may or may not be the actual pilot. The visual observer assists the RPIC/remote pilot in avoiding other air traffic and objects. There is also guidance provided on the use of multiple aircraft operations. In this case, there are multiple RPICs which are overseen by a UAS coordinator. The entire team must be trained in multiple sUAS operations. In addition, each of the personnel must have the appropriate professional qualifications/training/certifications to perform the role in the mission.

The United States Forest Service also have a standard for the use of UAS on lands that it manages [84]. Information on the use of UAS for a variety of potential missions are provided including natural resource for non-fire, wildland fires, emergency support/search and rescue/all hazard response, law enforcement, wilderness and scenic river, cooperatives with state and national (including universities), and hobbyist/recreational. Detailed documentation is provided on the administrative structure and authorities to approve these different missions. Similar to NFPA 2400, the document provides general guidance on the type of operators and support personnel that maybe involved in the mission. However, it is more specific in the types of training and permits (e.g., FAA licenses for pilots) as well as the specific regulations that need to be followed to perform different types of missions.

An overview of the general use of UAS in the European Union (EU) is provided in Ref. [83]. Within this paper, they indicate that more general policy that can be used at both the state and national levels could assist in the broader use of UAS. These types of policies that provide a clear definition of what is required to operate a UAS are being developed in the EU. For example, Article 4 – IRs EU 2019/947 has provided more general operation classifications compared with the other standards mentioned above based on the risk of the UAS activity. The categories include Open (low risk), Specific (medium risk), and Certified (high risk). Risk is based in part on UAS weight, flight altitude, visibility of UAS, payload hazard / dropping of payload. For Open, a non-licensed operator is allowed without any approvals. However, as the risk increases the requirements for operator licenses, the number of personnel involved, planning, training, etc., all increase. This type of approach could provide emergency responders with a more rapid response to fire events where time is critical. Balcerzak et al. [15] provided an overview of the European Union (EU) standards and regulations related to the operating UAS for firefighting. This paper also highlights the need to ensure that regulations allow sufficient flexibility for the rapid operation of UAS to support time critical firefighting activities.

The National Wildfire Coordinating Group has provided a concise, easy to use document on the use of UAS in wildfire operations [29]. This is more specific than the standards above but contains many of the same elements including operational requirements, mission planning, airspace requirements, flight procedures, safety, and training. The advantage of this type of document is that it is specific to the firefighting application, making it more clear on how to conduct operations.

Numerous other countries around the world also have regulations for the use of UASs in general as well as for public safety events. For example, Fire and Disaster Management Agency (FDMA) of Japan published guidance on how to use UAS for firefighting and disaster prevention purpose [85]. As a result, the operation of a UAS around the world varies and it is also dependent on the region where the operation will occur. Based on the above, the larger the region the regulation covers may promote the broader use of UAS since training and operation can be streamlined.

4.2 Training

A significant challenge for UAS operations in support of LOFF is determining the training requirements. As specified in NFPA 2400 4.1.4.11, training is one of the key elements of a UAS program for LOFF [4]. A recommended course of action is to keep training requirements system-agnostic, while incorporating best practices of successful training programs.

Initial training for operators should cover the following subjects to build and refresh expertise and awareness: 14 CFR Part 107 [86] refresher, weather, crew resource management, aircraft technical review, selecting an ideal location for launch and recovery, conducting a risk assessment, and flight training. The goal of these general classes should be to produce proficient operators who are confident about basic operation of their selected UAS and are safety-oriented.

LOFF operations will require additional considerations for UAS operator training. Some potential training courses are filing a Notice to Air Missions (NOTAM), obtaining clearance from local authority, determining direction of fire travel, and efficiently tracking firefighting crews [87, 88]. This advanced portion should be more flexible, given the potential for various techniques and tactics employed by different organizations. For example, research has been conducted into the deployment of multiple mixed-type UAS (different sizes and altitudes), multiple heterogenous UAS, and various levels of automation in the UAS [89–91]. In order to accommodate these tactics with manned firefighting aircraft, operators would have to be trained on communicating with air traffic control, other aircraft (both manned and unmanned), and incident commanders; maintaining safe vertical and horizontal separation; and identifying zones of increased risk.

In addition, recurrent training decisions are part of this key challenge. For trained operators, this means both proficiency training and currency requirements. Proficiency training implies the demonstration of basic and essential skills for both flight and tactical decision-making by the operator. Each organization will have to determine how to select evaluators, tasks, conditions, and standards. The goal of currency training is to maintain perishable skills and knowledge. One example could be requiring the operator to perform three launches and three recoveries every 90 days with their selected UAVs. Flights conducted for real missions would count towards these requirements.

4.3 Policy

One of the biggest challenges facing UAS LOFF operations is ensuring compliance with federal regulations. The main desire to deploy UAS in firefighting operations is for “dirty, dull, and dangerous” missions [92]. Due to the geographic spread of the fire and the danger it poses to the operator, these missions would be best executed as beyond visual line of sight (BVLOS). The U.S. Federal Aviation Administration (FAA) is still working to define methods by which BVLOS can be safely conducted. In order to plan and conduct a safe BVLOS flight, the UAS operator must account for three safety concerns not typically required in a standard 14 CFR Part 107 [86] flight: Detect and Avoid (DAA), Command and Control (C2), and Operations Over People (OOP). DAA systems to address 14 CFR Part 107.37 are still in research and development. At this time, only a few have been approved, but they have been short range solutions not scalable for routine operations which has left a gap for UAS in LOFF operations.

Long-range C2 for BVLOS flight requires reliable connection that will not create undue burden on spectrum management. Currently, the choices are between licensed band, unlicensed band (ISM and LTE), and experimental. The FAA has taken a stance against using experimental or standard ISM for long-range BVLOS flights, but has accepted LTE as a licensed spectrum option. The Federal Communications Commission (FCC) is researching the viability of expanding spectrum use to L band and C band in the future, but testing and validation will have to be done first [93].

Since the UAS operator will be unable to clear the ground underneath the BVLOS aircraft, an assumption must be made that it could be overflying nonparticipants at any given time. This requires the operator to take extra precaution to mitigate ground risk. Currently, the choices are to adhere to the new operations over people (OOP) rule released by the FAA [94] or to file a waiver request to 14 CFR Part 107.39. The OOP rule offers three different categories of operation, based on potential for injury, and also a type certification category that is based on the proven reliability of the UA. Many UAS that are able to both fly long distance and carry a mission-capable payload exceed the potential injury limitations required in the rule and for 14 CFR Part 107 waivers. Possible solutions currently offered are pursuing 14 CFR Part 91 authorization as a public aircraft, or obtaining Special Authority for Certain Unmanned Systems (Section 44807) [95]. As of this writing, no UAS manufacturer has received a type certification under the newly-leveraged streamlined process in the OOP rule.

Another option available is the Special Governmental Interest (SGI) process, which is granted in response to natural disasters or other emergencies. Operations that are included under this provision include firefighting, law enforcement, and search and rescue [96]. Applicants must already have a UAS pilot with Part 107 certificate or their organization must have an existing certificate of authorization (COA) [96]. This process benefits UAS LOFF operations because of the speed and flexibility it offers; requests are considered immediately, and in some cases granted in as quickly as five minutes [97].

Further policy challenges are operating a UAS in a temporary flight restriction (TFR), and the process for requesting a special use COA. Although these airspace restrictions present barriers to flight, they can also be leveraged to the operator’s advantage. Authorized flight in a TFR or special use COA may relieve the operator of standard BVLOS operational concerns (DAA and spectrum use). Also, UAS in the National Airspace System (NAS) are confined to lower altitudes, so utilizing a medium-altitude or high-altitude UA will likely require authorization outside of 14 CFR Part 107.

5. CONCLUDING REMARKS

The use of UAS by the fire service is expanding particularly for applications where firefighters are put into hazardous situations or where their job needs to be enhanced in a cost-effective way. Despite the operational and economic advantages, there are safety concerns around conducting operations with UAS. As a result, there are numerous operation guides, regulations, and standards that need to be considered prior to use. These vary widely from country to country as well as locality where the operation will occur. Therefore, users must consider the locality where the operations may occur and ensure that their UAS teams are adequately certified and trained according to local regulations. In addition to the training and policy standards, UAS hardware and software are still evolving to make these systems more useful and effective.

For outdoor fire events that are typically large and may cover wide regions, the use of multiple, coordinated swarms of UASs is desirable. In addition, the ability of the UASs to maintain control in outdoor extreme environments continues to be a challenge. This includes the impact of weather conditions as well as fire induced effects on environmental conditions. More improved sensors for improved visibility and navigation in smoke filled environments are needed along with temperature hardening to enhance the UAS close to the fire front. These topics are still active areas of research. In addition, policy has been evolving around the use of UAS and developments for the rapid use of UAS in specific time critical emergency still need to be refined. However, new risk based approach such as those in the EU may provide this needed flexibility as long as specified operating conditions are met.

Despite all of these challenges above, the impact of incorporating UAS into firefighting activities is expected to grow due to large upside for using this technology to limit firefighter exposure to hazardous conditions. The UAS technology is able to provide firefighters with rapid, remote, real-time observations of the fire front, smoke movement, and presence of firebrands. This can assist firefighters with suppression planning, spread mitigation, and evacuations. In addition, UAS could be used to monitor conditions around the WUI where there is potential for wildland fires to cause spot fires. Spot fires are difficult to identify early and suppress before significant damage occurs. UAS can provide this early detection by being able to continuously be on watch for spot fires in the WUI. Since these fires typically start small, there is also potential for UAS to suppress these fires with onboard systems such as inert suppression systems like the nitrogen capsules described in this paper as well other light weight suppression alternatives such as water mist sprays. Swarms of UASs are also being explored for suppression of larger, difficult to access urban fires on exterior facades of tall buildings. These concepts may also be able to transitioned to the WUI and settlement fires where the fire has become larger and firefighters are not able to easily reach the location. Overall, UASs provide firefighters with the ability to view and act rapidly in areas they have not be able to previously. This will continue to improve the effectiveness of firefighting and reduce losses from fires.

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