كلية الهندسة بشبرا
FACULTY OF ENGINEERING AT SHOUBRA
ERJ
PRINT ISSN 3009-6049
ONLINE ISSN 3009-6022

ENGINEERING RESEARCH JOURNAL (ERJ)
Volume (52) Issue (4)
October 2023, pp:**149-156**
https://erjsh.journals.ekb.eg

Enhancing Efficiency and Safety in Forest Firefighting: A Comprehensive Review of Drone Applications

Shahinaz H. Abdelraouf [1]*, Mohamed A. Ibrahim[2], M. Moawed[2], O.E. Abdelatif[2]

[1]Department of Mechatronics Engineering, Faculty of Engineering,6th of October City, Egypt.
[2]Department of Mechanical Engineering, Faculty of Engineering at Shoubra, Benha University, Cairo, Egypt.
* Corresponding Author
E-mail: shahenazhossam.eng@o6u.edu.eg., mohamedaly.eng@o6u.edu.eg, mmoawed28@feng.bu.edu.eg, osama.abdellatif@feng.bu.edu.eg

Abstract: Forests play a vital role in nature, purifying water, sustaining the land, cycling nutrients, regulating climate, and storing carbon. They also provide habitat for many species and contribute to economic wealth. This study involves an extensive survey of firefighters regarding the current issues facing their field of work and potential technology solutions. It also assesses the efforts made by the academy and businesses to use a variety of robot types for firefighting operations. The recommended technique consists of a few octa-copters that can not only visit waypoints and transport shipments on their own but can also carry out duties like monitoring, mapping, and observation. The three established operator positions task commanding officer, team leaders, and team members each have a unique information access role and mission-related duties. These operators make use of interfaces for virtual and augmented reality to easily gather scenario data and, in the instance of the mission chief, direct the drone swarm.

Keywords: Firefighting, Wildland, Fire management strategies, Multi-Robot Systems, **UVA**

1. INTRODUCTION

One of the most frequent events is forest fires, which pose severe dangers to humanity. They cause significant biodiversity losses in both plants and animals, as well as catastrophic losses of life and property. They also emit greenhouse gases, contributing to global warming. States create regulations for fire mitigation, early detection, and quick response. It is challenging to quantify the fires and their global effects. According to [1], published papers by the International Association of Fire and Rescue Services There were 4.5 million fires and 30,800 deaths in countries with 2700 million inhabitants in 2018, representing 1.7 fires per 1000 residents and 1.1 deaths per 100,000 residents. Even if these numbers do not account for the entire planet, ESA released the World Fire Atlas using ATSR-2 data to measure the magnitude of the problem. [2] and Sentinel-3 [3]; the National Aeronautics and Space Administration publishes the Global Fire Atlas [4]. Missions for fighting forest fires include prevention, observation, and suppression. Firefighters often use multiple vehicles and equipment to enhance efficiency and safety, but the use of robots and drones is uncommon. These self-governing systems could address some of the existing problems.[4]. This paper analyses the current issues in forest firefighting missions and the potential of robotic technologies to solve them. It poses two research issues: What are the primary challenges facing forest firefighting missions today, and how can robotic technologies aid their resolution? This study provides an operational approach for the use of drone swarms in fire prevention, observation, and suppression missions.

2Fire-Fighting State:

This section examines the current firefighting landscape. It describes operations and holds essential data. Statistics are used to identify major problems, and two surveys of professionals' opinions are presented. Fires burned 83,963 ha in Spain in 2019, with 7,290 affected by less than 1 ha and 3,593 by more than 1 ha. [5]. Spain experienced an annual average of 12,182 fires and 99,082 ha of forest area between 2009 and 2018, with the worst consequences occurring in

July and August when more surface area burned than any other time of year [6]. Firefighting is carried out everywhere throughout the year to both put-out and prevent fires. Fire reduction is an established set of operations aimed at reducing the likelihood of fires occurring and mitigating their effects if they do. In March, most fires were caused by incidental, negligent, or intentional use of fire in the northwest of the country. [7]. Between 2006 and 2015, more than half of the forest fires in Spain were started intentionally, while 28% of Fire prevention activities are divided into two categories: incidents and negligent behavior, 7% natural causes, and 12% unknown: prevention of causes and prevention of combustibles. Activities that aim to reduce hazards and have a social character, such as campaigns to discourage fire use and careless behavior and actions regarding land uses and plant distribution, create discontinuities that prevent the spread of potential flames. Fire observation is the action taken to detect fires quickly. Forest fire damages are highly dependent on detection and response periods, with an average incinerated surface of 7.10 ha and 30.66 ha when response time was greater than one hour. Reduced detection and response times are crucial for fire suppression. [5]

3Firefighting Robots:

Focusing on multi-robot systems and aerial robots for forest fire prevention, observation, and suppression, as well as other types of robots and urban but rather indoor scenarios, robotic and automation technologies are being applied to firefighting activities. Already, robots are indeed being designed to intervene in dangerous situations and combat fires. Firefighters are attuned when these technologies support their work and do not alter their conditions. According to prior research, New Jersey fire chiefs support these findings; however, budget, manpower, and regulatory concerns must be addressed. [8]. [9] This study examines public opinion on the use of drones for cargo, passenger, and commercial conveyance, including firefighting. Participants support the use of drones for cargo and commercial applications but prefer piloted aircraft for passenger transportation. [10] Public sentiment on drones is mixed, with most articles concentrating on a few specific tasks, which are classified as prevention, observation, and extinguishing. Ref. [11] distinguishes between activities preceding, during, and after the fire, such as vegetation mapping, observation, danger estimation, detection, extinguishment, browsing for flames, and hazard assessment.

3.1Protection:

Preventing the occurrence is the first stage of firefighting and includes two categories of actions: social activities to prevent fires and multiple operations on trees and shrubs to reduce fire risk, which also create discontinuities. Robots have the potential to enhance current outcomes in the latter operations, as prepping vegetation is a labor-intensive endeavor with insufficient management of human resources. Robotics can make this task more convenient in two ways. Drones can be used to capture aerial images to plan tasks such as identifying troubling areas, deciding on trees and shrubs, and planning extraction paths. Precision agriculture techniques can also be applied. [12], Detecting and identifying seeds and trees in greater images [13] LIDAR surveys are used to measure terrain accurately. Drones can capture multispectral images of the environment. Drones are a great alternative to satellites for many tasks, as they offer greater availability and cost savings and are less dependent on weather conditions. [16]. Ground robotics can help remove forest vegetation by bridging the gap between manual labor and heavy equipment, achieving a balance between firefighters' agility and accuracy and machinery's speed and efficiency. [17] Locomotion, localization, and planning are essential for navigating difficult terrain. [18]. In the SEMFIRE Experiment [19], A multi-robot mechanism is being developed to decrease forest fuel concentration and aid in landscape maintenance. It includes small hovering automatons for mapping trees and shrubs and large, measured mobile automatons for forest intercropping.

3.2Observation

Fire monitoring is the topic that receives the most attention in the literature on industrial robots for fire suppression. It involves Aerial robots are used to monitor forests from above, with up to four objectives associated with fire observation tasks. [20]. The complete analysis of a fire is essential for firefighting teams to organize their operations, such as the combustion source and crisis opportunities. [21]. Due to their strong range of movement, adaptability, and low risk, quadcopters with onboard vision systems can recognize and oversee wildfires. [22]. Observation systems should include a fleet of UAVs, sensor technology and image processing methods, algorithms, coordination and cooperation strategies, path planning algorithms, and ground control stations. [23]. UAVs must have a long flight time and accurate localization using Inertial Measurement Unit data, and the Global Navigation Satellite System provides stable, large, and powerful aircraft with high photo quality. [24]. Vision systems can be used to detect fires quickly and accurately. [25] Fire detection systems use visible hardware and sensors to detect fires on land, in the air, and via satellite. [26, 27], thermal [28, 29], multispectral [30, 31], and infrared [20, 32] Cameras and environmental sensors are used in interior scenarios. [33], but also proposed for forests [21].

Traditional algorithms [22, 34] compete with recent intelligence solutions. [35,36] Color, geometry, and motion are the most common features used to identify fires in aerial photographs. In isolated frames, color and geometry enable the detection of potential fires, whereas motion is required to validate these detection methods across an opening set. [22]. Algorithms must be able to adapt to different types of fires and scenarios, such as subterranean fires and interfacial bushfires. [37]. Consideration is also given to diverse and complex robot systems for fire observation. The work presented in [38] This paper proposes an air-ground robotic team in which unmanned ground vehicles compensate for the limitations of unmanned aerial vehicles in autonomy and payload. Unmanned Ground Vehicles serve as base stations for UAVs, centralizing their communications, processing data, and coordinating their tasks in the scenario. Additionally, unmanned ground vehicles serve as base stations for UAVs, integrating their communications, converting data, and organizing their actions in the scenario. [35] Fixed-wing UAVs are proposed as standard sizes to scan for fires, and rotary-wing UAVs are proposed for flight at different altitudes to check for detections. Verification is needed to avoid false alarms. [39], The use of multiple drones and features such as color and movement to detect fires in images is proposed to capture simultaneous information about every area.

3.3Extinguishing

Fire suppression is the final step of firefighting, occurring after fire detection and inspection. This task is executed with human-operated surface and airborne vehicles. However, due to the virulence of fires, the presence of humans can sometimes place them in perilous situations. To address this, two primary approaches are being explored: one for aerial extinguishing and the other for enabling ground activities. The purpose of starting fires with drones is to attack the fire in phases to prevent its spread. [40] The quadcopter is comparable to current firefighting helicopters, but its limited payload capacity hinders its performance. [41] The most important details are that an airborne hose-type robot can make direct contact with a fire source using a water jet and receive a constant supply of water to combat the fire. This eliminates the payload restrictions of traditional unmanned aerial vehicles but necessitates the proximity of a water source to the fire. The proposed vehicle is a quadcopter carrying a helium-filled balloon. [42]. Absorbent gas is used to decrease the oxygen content. The fire is sufficiently light to be transported by a quadcopter. Validate the scalability of this system concerning forest fires, such as the method for the exact balloon release. Additionally, fire suppression pellets are used to put out fires. [43]. These elements explode when exposed to elevated temperatures, emitting substances. Modules that put out a fire [44] highlight a quadcopter's ability to initiate a fire-extinguishing projectile at urban and wildfires. [45,46] The release mechanism should allow the drone to hurl multiple balls while maintaining its stability. [47] poses a fleet of UAVs capable of tracking and extinguishing fires demonstrates the scalable nature of fire extinguishing systems based on drones that launch balloons. Several co-systems are being intended for firefighting tasks; instead of constructing drones equipped with the capabilities of aircraft, instead of using multiple light robotics, [48] proposes a drone fleet and [49] A drone swarm necessitates fleet coordination and algorithmic proposals to allocate targets among drones to reduce the path length of each drone. [11] The team should share mission information and use an exchange system for allocating tasks. [50] Using deep learning, a newer algorithm for secure human-robot collaboration in wildfires overcomes the sensing, connectivity, and motion restrictions of drones. It can also monitor fires and provide firefighters with data. [51]. Drones monitor the evolution of flames, and a human safety module detects people near fires. [52] There are three types of drones for patrolling, confirming, and monitoring, together with a retardant model to predict the conduct of fires based on the data collected by these drones.

4 System Overview:

Drones in firefighting applications enhance efficiency and safety by providing high-resolution cameras and sensors for vegetation mapping, fire investigation, and observation tasks. They provide a bird's-eye view, detecting fires, assessing behavior, and monitoring flame spread, aiding situational awareness for firefighting personnel.

In extinguishing tasks, drones play a crucial role by providing critical information to firefighting teams Drones use specialized sensors to monitor fire progression, and temperature variations, and detect heat, aiding firefighters in resource allocation and deployment strategies. They also deliver lightweight resources, reducing risks to human firefighters.

The exceptional tasks carried out by drones involve risk mapping, fire investigation, and tracking. analyze topographical data to create risk maps, aid in preparedness, and monitor fire behavior for analysis. They also enable dynamic fire tracking and strategy adaptation.

Incorporating drones into outdoor firefighting applications streamlines operations, enhances situational awareness, and mitigates risks associated with traditional firefighting methods. Their ability to access hard-to-reach areas, provide real-time data, and assist in fire suppression makes drones an invaluable tool for firefighting professionals, ultimately contributing to more effective firefighting strategies and better outcomes in challenging outdoor environments.

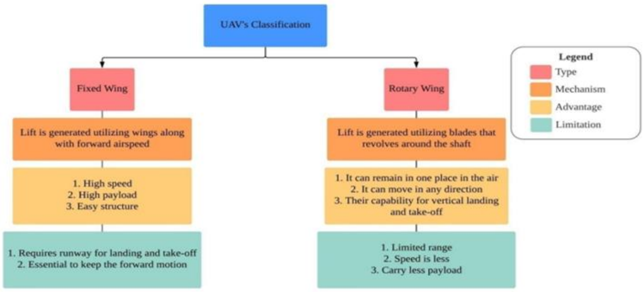

Fig 1:Classification of general-purpose UAVs

Fig 2:Different types of UAVs used in the last decades for various applications.

Elena Ausonio introduces a method using a swarm of collaborative UAVs to transport fractionated extinguishing liquid on fire fronts, simulating the rain effect. The system aims to detect and suppress fires, reducing human life risks. The study aims to estimate the impact of drones on forest fires, a complex phenomenon influenced by various factors. The drone system manages a swarm of UAVs and satisfies requirements, demonstrating its effectiveness in suppressing or containing low-intensity fires.

Wildland fire is studied. For this purpose, the critical water flow rate, i.e., the rate of water application required to arrest a certain number of linear meters of active fire front, is estimated. Based on fire parameters such as flame length, wind speed, moisture content, active flame depth, Fireline intensity, etc. Plant species are typically present in the Mediterranean.

A scrubland fire is chosen for low-height flames, minimizing tree foliage. A drone system is positioned at a distance, and a fire cellular automata propagation model predicts fire front modifications over time. [54]

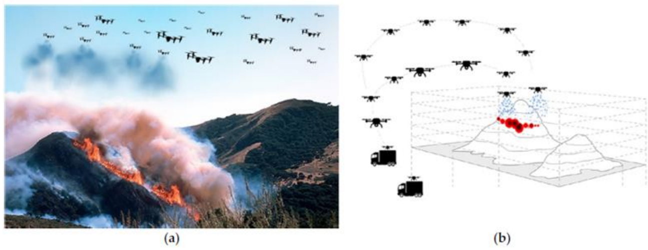

Fig3:(a,b) Representations of the proposed firefighting system based on the use of a swarm of collaborative UAVs.

We present an efficient operational principle for the application referring to drone crowds in firefighting missions, which is depicted in Figure 1 and explained in subsections such as mission, drone swarm, team, and infrastructure requirements. This concept is illustrated in Figure 3.

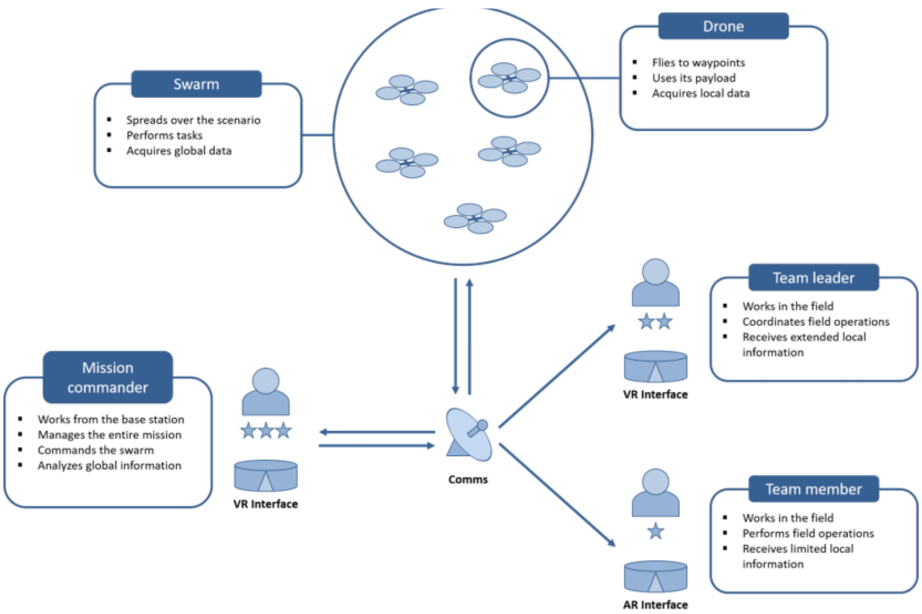

Fig 4:System overview

4.1 Mission:

The purpose has been developed with current fire suppression processes and data and to analyze in mind, but aerial extinguishment has been excluded due to the development of other types of drones. It evaluates tasks that might necessitate a drone swarm.

• Prevention: Drone technology aims to prevent fires and limit their spread by performing vegetation mapping and fire investigation after a fire has been detected. Only a small number of drones can do this.

• Observation: Drones are used to detect fires and alert fire-fighting crews promptly, using cameras, sensors, and drones.

• Extinguishing: Fire monitoring and fire assistance are provided by drones to capture data about firefighting teams and provide lightweight resources to firefighters.

4.2Drone Swarm:

A variety of aerial robot systems can be used to accomplish the mission. Heterogeneous fleets can optimize missions by allocating resources to distinct duties, while drone swarms are more scalable and have greater adaptability to changes in the scenario. They also have greater defect tolerance. [53] A "robot crowd" is a selection of simple automatons capable of performing complex tasks as a single expert system. A group of quadcopters is considered a "robot swarm" when the fleet consists of twelve robots, as individual robots are unable to cover the target scenarios and perform the tasks at hand. Quadcopters must have a minimum flight autonomy of 30 minutes, navigation using IMU measurements, visual odometry, GPS/GLONASS/GALILEO signals, control, a 5 km range for telemetry and video connections, and a payload of cameras, temperature, humidity, and hydrocarbon sensors. Similarly, the dimensions and strength of the drones were determined to strike a balance between versatility and load capacity. They must be lightweight enough to be transported by vehicle and deployed by a person in the field carrying as many as three cameras, environmental sensors, and communication devices. Moreover, autonomy is a crucial component of the system, as the longer the flight duration, the greater the system's viability in actual missions. Current high-quality commercial drones have a flight time of approximately 30 minutes. However, this may change in the coming years. The drones' route-planning capabilities are important to the system's operation. To achieve high precision and defect tolerance, multiple sources are used, including a high-performance IMU and GNSS receiver. Onboard cameras can acquire terrain features, which can be used to estimate drone motion. Multiple models, such as Kalman, are also used. [54] and particle filters [55], The most important details are that drones can integrate data from sources such as GNSS to determine the precise location of the drone and that connectivity is often a challenge when deploying drones in expansive and remote environments. To maintain this connectivity, it is recommended that vehicles maintain a constant data flow between agents, with robots serving as relays. Each quadcopter can fly to waypoints and use its payload, while the fleet can disperse across the scenario and carry out missions. Individual decisions are made using control and collaboration algorithms based on local data. Validation has been conducted on behavior-based algorithms for analysis, search, and monitoring. [53,56,57]. Behavior-based algorithms are comprised of multiple behavioral patterns that process input and generate potential actions, as well as a choice module that combines their outputs and computes the final action. Based on these behaviors, the drone swarm will execute generic tasks. [58]. Observation, intelligence gathering, location, monitoring, support, tracking, and transport all involve flying over an area of interest to locate targets. The search involves trying to fly above a location of interest to find targets; observation involves flying over an area of interest to acquire updated data; reconnaissance involves flying to a list of points of interest to acquire data; mapping involves To create a map of an area of interest by flying over it; monitoring involves flying over an event of interest to acquire data; support involves flying over teams to provide information; whereas tracking involves pursuing a mobile target to collect data. These generic responsibilities may be used uniquely or in combination to represent the duties associated with firefighting operations. For instance, fire observation is a combination of observation and reconnaissance, in which the targets are fires. The specific provisions and their respective generic duties are listed in Table 1.

Table 1. An array of responsibilities for firefighting missions.

c	Exceptional Tasks	Repetitive Tasks
Prevention	Vegetation mapping	Mapping
	Fire investigation	Search, Monitoring, Tracking
Observation	Risk mapping	Mapping
	Fire observation	Observation, Reconnaissance
Extinguishing	Fire monitoring	Monitoring, Search
	Firefighter support	Support, Transport

The task commanding officer, leaders, and crew mates are crucial to the success of missions and scenarios, each with their duties, connections, employer, and activities.

4.3Team

• The task commanding officer is responsible for overseeing and directing the mission from a base station. They have access to mission information, including drone telemetry and fire measurements, and control the drone swarm via high-level commands. They communicate with team leaders to establish work areas, duties, and resources.

• Team leader: A leader is responsible for coordinating the firefighting squad's field operations, receiving instructions from the task officer in charge, and managing local information. In the event of a fire, they also ensure interactions with the access point.

• Team members: Firefighters execute prevention, observation, and extinguishing tasks in a fire scenario. They own restricted access to regional data, which is relevant to routes and actions. To avoid distractions, the amount of information should be limited but sufficient to ensure safety.

4.4Infrastructure:

Components that support the autonomy of the swarm, facilitate communication between agents, and permit human-swarm interaction are the most crucial details. Autonomy is a significant impediment to firefighting missions, and charging stations can be dispersed. interactive and flexible user interfaces can improve situational awareness and decrease operator workload [59]. Interfaces adapt to mission state and operator preferences, using immersive technologies to enhance the perception of robots' working environment. Interfaces adapt to mission state and operator preferences, using immersive technologies to enhance the perception of robots' working environment. These interfaces have validated these results, thereby decreasing the amount of data and the operator's workload. [60].

This research examines the current state of firefighting missions and potential future technological applications. Two firefighters revealed a lack of human and material resources and the need for real-time intelligence about fire evolution. Firefighters support the use of drones to acquire pertinent data for fire prevention, observation, and extinguishing. They authorize the generation of maps that aid in the organization of vegetation preparation tasks and the identification of areas with the highest risk of fire. In the case of extinguishing, they believe drones can provide them with real-time data about flames to make their actions safer and more efficient.

A literature review has identified proposals for autonomous systems applied to firefighting responsibilities, but no suggestions for trees and shrubs preparation duties. There are multiple methods for extinguishing fires using autonomous drones, but fewer for helping firefighters stationed on the surface.

5 Conclusions:

This work provides a concept for the operational use of drone strikes. clusters to encourage prevention efforts, observation, and extinguishment efforts. It envisions a fleet of homogeneous quadcopters capable of searching, observation, special operations, charting, support, tracking, and transport. There are three distinct roles for operators: task commanding officer, team leader, and staff member. The system addresses many such issues with current firefighting operations and provides enhanced scenario information to professionals. Nevertheless, there are obstacles to overcome, such as scalability, operator training, and the present constraints of drone autonomy and correspondence. To configure, establish, and verify algorithms, we will create a simulation prototype and a minimum acceptable product using actual drones.

References

[1] Brushlinsky, N.; Ahrens, M.; Sokolov, S.; Wagner, P. *World Fire Statistics*; Technical Report 23; Center of Fire Statistics: Moscow, Russia, 2018.

[2] Mota, B.; Pereira, J.; Oom, D.; Vasconcelos, M.; Schultz, M. Screening the ESA ATSR-2 World Fire Atlas (1997-2002). *Atmos. Chem. Phys.* **2006**. [.]

[3] Xu, W.; Wooster, M.J.; He, J.; Zhang, T. First study of Sentinel-3 SLSTR active fire detection and FRP retrieval: Night-time algorithm enhancements and global intercomparison to MODIS and VIIRS AF products. *Remote Sens. Environ.* **2020**, *248*, 111947.

[4] Andela, N.; Morton, D.C.; Giglio, L.; Paugam, R.; Chen, Y.; Hantson, S.; Van Der Werf, G.R.; Randerson, J.T. The Global Fire Atlas of individual fire size, duration, speed, and direction. *Earth Syst. Sci. Data* **2019**, *11*, 529–552. [.]

[5] Los Incendios Forestales en España: Avance Informativo 2019. Technical report, Área de Defensa contra Incendios Forestales, Ministerio para la Transición Ecológica y el Reto Demográfico, Gobierno de España. 2020. Available Online: https://www.mapa.gob.es/es/desarrollo-rural/estadisticas/avance_1_enero_31_diciembre_2019_tcm30-537398.pdf (accessed on 31 December 2020).

[6] Los Incendios Forestales en España: Decenio 2006–2015. Technical report, Área de Defensa contra Incendios Forestales, Ministerio de Agricultura, Pesca y Alimentación, Gobierno de España. 2019. Available Online: https://www.mapa.gob.es/es/desarrollo-rural/estadisticas/incendios-decenio-2006-2015_tcm30-511095.pdf (accessed on 31 December 2020).

[7] Muñoz, R.V. *La Defensa Contra Incendios Forestales: Fundamentos y Experiencias*; McGraw-Hill Interamericana de España: Madrid, Spain, 2009.

[8] Russell, M.T. Fire Chief Perception of Unmanned Aircraft Systems: A Diffusion Study; New Jersey City University: Jersey City, NJ, USA,

[9] MacSween, S. A public opinion survey-unmanned aerial vehicles

for cargo, commercial, and passenger transportation. In Proceedings of the 2nd AIAA" Unmanned Unlimited" Conference and Workshop & Exhibit, San Diego, CA, USA, 15–18 September 2003; p. 6519.

[10] Aydin, B. Public acceptance of drones: Knowledge, attitudes, and practice. *Technol. Soc.* **2019**, *59*, 101180.

[11] Ghamry, K.A.; Kamel, M.A.; Zhang, Y. Multiple UAVs in forest fire fighting mission using particle swarm optimization. In Proceedings of the 2017 International Conference on Unmanned Aircraft Systems (ICUAS), Miami, FL, USA, 13–16 June 2017; pp. 1404–1409.

[12] Roldán, J.J.; del Cerro, J.; Garzón-Ramos, D.; Garcia-Aunon, P.; Garzón, M.; de León, J.; Barrientos, A. Robots in agriculture: State of art and practical experiences. *Serv. Robot.* **2018**.

[13] Valente, J.; Sari, B.; Kooistra, L.; Kramer, H.; Mücher, S. Automated crop plant counting from very high-resolution aerial imagery. *Precis. Agric.* **2020**, *21*, 1366–1384.

[14] Anders, N.; Valente, J.; Masselink, R.; Keesstra, S. Comparing Filtering Techniques for Removing Vegetation from UAV-Based Photogrammetric Point Clouds. *Drones* **2019**, *3*, 61. [.]

[15] Zhang, C.; Valente, J.; Kooistra, L.; Guo, L.; Wang, W. Opportunities of UAVs in orchard management. *Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci.* **2019**. [.]

[16] Barrientos, A.; Colorado, J.; Cerro, J.d.; Martinez, A.; Rossi, C.; Sanz, D.; Valente, J. Aerial remote sensing in agriculture: A practical approach to area coverage and path planning for fleets of mini aerial robots. *J. Field Robot.* **2011**, *28*, 667–689. [.]

[17] Bergerman, M.; Billingsley, J.; Reid, J.; van Henten, E. Robotics in agriculture and forestry. In *Springer Handbook of Robotics*; Springer: Berlin/Heidelberg, Germany, 2016; pp. 1463–1492.

[18] Aguiar, A.S.; dos Santos, F.N.; Cunha, J.B.; Sobreira, H.; Sousa, A.J. Localization and Mapping for Robots in Agriculture and Forestry: A Survey. *Robotics* **2020**, *9*, 97. [.]

[19] Couceiro, M.S.; Portugal, D.; Ferreira, J.F.; Rocha, R.P. SEMFIRE: Towards a new generation of forestry maintenance multi-robot systems. In Proceedings of the 2019 IEEE/SICE International Symposium on System Integration (SII), Paris, France, 14–16 January 2019; pp. 270–276.

[20] Yuan, C.; Liu, Z.; Zhang, Y. Fire detection using infrared images for UAV-based forest fire observation. In Proceedings of the 2017 International Conference on Unmanned Aircraft Systems (ICUAS), Miami, FL, USA, 13–16 June 2017; pp. 567–572.

[21] Bouabdellah, K.; Noureddine, H.; Larbi, S. Using wireless sensor networks for reliable forest fires detection. *Procedia Comput. Sci.* **2013**, *19*, 794–801.

[22] Yuan, C.; Liu, Z.; Zhang, Y. Vision-based forest fire detection in aerial images for firefighting using UAVs. In Proceedings of the 2016 International Conference on Unmanned Aircraft Systems (ICUAS), Arlington, VA, USA, 7–10 June 2016; pp. 1200–1205.

[23] Yuan, C.; Liu, Z.; Zhang, Y. UAV-based forest fire detection and tracking using image processing techniques. In Proceedings of the 2015 International Conference on Unmanned Aircraft Systems (ICUAS), Denver, CO, USA, 9–12 June 2015; pp. 639–643.

[24] Allauddin, M.S.; Kiran, G.S.; Kiran, G.R.; Srinivas, G.; Mouli, G.U.R.; Prasad, P.V. Development of an Observation System for Forest Fire Detection and Monitoring using Drones. In Proceedings of the IGARSS 2019—2019 IEEE International Geoscience and Remote Sensing Symposium, Yokohama, Japan, 28 July–2 August 2019; pp. 9361–9363.

[25] Barmpoutis, P.; Papaioannou, P.; Dimitropoulos, K.; Grammalidis, N. A Review on Early Forest Fire Detection Systems Using Optical Remote Sensing. *Sensors* **2020**, *20*, 6442. [.] [PubMed]

[26] Dang-Ngoc, H.; Nguyen-Trung, H. Aerial Forest Fire Observation-Evaluation of Forest Fire Detection Model using Aerial Videos. In Proceedings of the 2019 International Conference on Advanced Technologies for Communications (ATC), Hanoi, Vietnam, 17–19 October 2019; pp. 142–148.

[27] Barmpoutis, P.; Stathaki, T.; Dimitropoulos, K.; Grammalidis, N. Early fire detection based on aerial 360-degree sensors, deep convolution neural networks and exploitation of fire dynamic textures. *Remote Sens.* **2020**, *12*, 3177. [.]

[28] Valero, M.; Rios, O.; Pastor, E.; Planas, E. Automated location of active fire perimeters in aerial infrared imaging using unsupervised edge detectors. *Int. J. Wildland Fire* **2018**, *27*, 241–256. [.]

[29] Bosch, I.; Serrano, A.; Vergara, L. Multisensor network system for wildfire detection using infrared image processing. *Sci. World J.* **2013**, *2013*, 402196. [.] [PubMed]

[30] Veraverbeke, S.; Dennison, P.; Gitas, I.; Hulley, G.; Kalashnikova, O.; Katagis, T.; Kuai, L.; Meng, R.; Roberts, D.; Stavros, N. Hyperspectral remote sensing of fire: State-of-the-art and future perspectives. *Remote Sens. Environ.* **2018**, *216*, 105–121. [.]

[31] Carvajal-Ramírez, F.; Marques da Silva, J.R.; Agüera-Vega, F.; Martínez-Carricondo, P.; Serrano, J.; Moral, F.J. Evaluation of fire severity indices based on pre-and post-fire multispectral imagery sensed from UAV. *Remote Sens.* **2019**, *11*, 993. [.]

[32] Martínez-de Dios, J.R.; Merino, L.; Ollero, A. Fire detection using autonomous aerial vehicles with infrared and visual cameras. *IFAC Proc. Vol.* **2005**, *38*, 660–665. [.]

[33] Fonollosa, J.; Solórzano, A.; Marco, S. Chemical sensor systems and associated algorithms for fire detection: A review. *Sensors* **2018**, *18*, 553. [.]

[34] Zhang, L.; Wang, B.; Peng, W.; Li, C.; Lu, Z.; Guo, Y. Forest fire detection solution based on UAV aerial data. *Int. J. Smart Home* **2015**, *9*, 239–250. [.]

[35] Kinaneva, D.; Hristov, G.; Raychev, J.; Zahariev, P. Early forest fire detection using drones and artificial intelligence. In Proceedings of the 2019 42nd International Convention on Information and Communication Technology, Electronics, and Microelectronics (MIPRO), Opatija, Croatia,20–24 M2019; pp. 1060–1065.

[36] Jiao, Z.; Zhang, Y.; Xin, J.; Mu, L.; Yi, Y.; Liu, H.; Liu, D. A Deep Learning Based Forest Fire Detection Approach Using UAV and YOLOv3. In Proceedings of the 2019 1st International Conference on Industrial Artificial Intelligence (IAI), Shenyang, China, 23–27 July 2019; pp. 1–5.

[37] Burke, C.; Wich, S.; Kusin, K.; McAree, O.; Harrison, M.E.; Ripoll, B.; Ermiasi, Y.; Mulero-Pázmány, M.; Longmore, S. Thermal-Drones as a Safe and Reliable Method for Detecting Subterranean Peat Fires. *Drones* **2019**, *3*, 23. [.]

[38] Ghamry, K.A.; Kamel, M.A.; Zhang, Y. Cooperative forest monitoring and fire detection using a team of UAVs-Unmanned Ground Vehicles. In Proceedings of the 2016 International Conference on Unmanned Aircraft Systems (ICUAS), Arlington, VA, USA, 7–10 June 2016; pp. 1206–1211.

[39] Sudhakar, S.; Vijayakumar, V.; Kumar, C.S.; Priya, V.; Ravi, L.; Subramaniyaswamy, V. Unmanned Aerial Vehicle (UAV) based Forest Fire Detection and monitoring for reducing false alarms in forest-fires. *Comput. Commun.* **2020**, *149*, 1–16. [.]

[40] Qin, H.; Cui, J.Q.; Li, J.; Bi, Y.; Lan, M.; Shan, M.; Liu, W.; Wang, K.; Lin, F.; Zhang, Y.; et al. Design and implementation of an unmanned aerial vehicle for autonomous firefighting missions. In Proceedings of the 2016 12th IEEE International Conference on Control and Automation (ICCA), Kathmandu, Nepal, 1–3 June 2016; pp. 62–67.

[41] Ando, H.; Ambe, Y.; Ishii, A.; Konyo, M.; Tadakuma, K.; Maruyama, S.; Tadokoro, S. Aerial hose type robot by water jet for firefighting. *IEEE Robot. Autom. Lett.* **2018**, *3*, 1128–1135. [.]

[42] Ogawa, S.; Kudo, S.; Koide, M.; Torikai, H.; Iwatani, Y. Development and control of an aerial extinguisher with an inert gas

capsule. In Proceedings of the 2014 IEEE International Conference on Robotics and Biomimetics (ROBIO 2014), Bali, Indonesia, 5–10 December 2014; pp. 1320–1325.

[43] Aydin, B.; Selvi, E.; Tao, J.; Starek, M.J. Use of fire-extinguishing balls for a conceptual system of drone-assisted wildfire fighting. *Drones* **2019**, *3*, 17. [.]

[44] Alshbatat, A.I.N. Fire extinguishing system for high-rise buildings and rugged mountainous terrains utilizing quadrotor unmanned aerial vehicle. *Int. J. Image, Graph. Signal Process.* **2018**, *12*, 23. [.]

[45] Soliman, A.M.S.; Cagan, S.C.; Buldum, B.B. The design of a rotary-wing unmanned aerial vehicle–payload drop mechanism for fire-fighting services using fire-extinguishing balls. *SN Appl. Sci.* **2019**, *1*, 1259. [.]

[46] Manimaraboopathy, M.; Christopher, H.; Vignesh, S.; others. Unmanned Fire Extinguisher Using Quadcopter. *Int. J. Smart Sens. Intell. Syst.* **2017**, *10*, 471–481. [.]

[47] Sherstjuk, V.; Zharikova, M.; Sokol, I. Forest Fire Fighting Using Heterogeneous Ensemble of Unmanned Aerial Vehicles. In Proceedings of the 2019 IEEE 5th International Conference Actual Problems of Unmanned Aerial Vehicles Developments (APUAVD), Kyiv, Ukraine, 22–24 October 2019; pp. 218–223.

[48] Islam, S.; Razi, A. A path planning algorithm for collective monitoring using autonomous drones. In Proceedings of the 2019 53rd Annual Conference on Information Sciences and Systems (CISS), Baltimore, MD, USA, 20–22 March 2019; pp. 1–6.

[49] Innocente, M.S.; Grasso, P. Self-organising swarms of firefighting drones: Harnessing the power of collective intelligence in decentralized multi-robot systems. *J. Comput. Sci.* **2019**, *34*, 80–101. [.]

[50] Haksar, R.N.; Schwager, M. Distributed deep reinforcement learning for fighting forest fires with a network of aerial robots. In Proceedings of the 2018 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), Madrid, Spain, 1–5 October 2018; pp. 1067–1074.

[51] Seraj, E.; Silva, A.; Gombolay, M. Safe Coordination of Human-Robot Firefighting Teams. *arXiv* **2019**, arXiv:1903.06847.

[52] Sherstjuk, V.; Zharikova, M.; Sokol, I. Forest fire-fighting monitoring system based on UAV team and remote sensing. In Proceedings of the 2018 IEEE 38th International Conference on Electronics and Nanotechnology (ELNANO), Kyiv, Ukraine, 24–26 April 2018; pp. 663–668.

[53] Garcia-Aunon, P.; Roldán, J.J.; Barrientos, A. Monitoring traffic in future cities with aerial swarms: Developing and optimizing a behavior-based observation algorithm. *Cogn. Syst. Res.* **2019**, *54*, 273–286.

[54] E. Ausonio, P. Bagnerini, and M. Ghio, "Drone Swarms in Fire Suppression Activities: A Conceptual Framework," MDPI, Mar. 07, 2021. https://www.mdpi.com/2504-446X/5/1/17

[55] Al-Turjman, F. A novel approach for drone positioning in mission-critical applications. *Trans. Emerg. Telecommun. Technol.* **2019**, e3603.

[56] Wang, L.; Sanchez-Matilla, R.; Cavallaro, A. Tracking a moving sound source from a multi-rotor drone. In Proceedings of the 2018 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), Madrid, Spain, 1–5 October 2018; pp. 2511–2516.

[57] Garcia-Aunon, P.; Barrientos Cruz, A. Comparison of heuristic algorithms tasks using aerial swarms. *Appl. Sci.* **2018**, *8*, 711. [.]

[58] Roldán-Gómez, J.J.; Garcia-Aunon, P.; Mazariegos, P.; Barrientos, A. SwarmCity project: Monitoring traffic, pedestrians, climate, and pollution with an aerial robotic swarm. *Pers. Ubiquitous Comput.* **2020**, 1–17. [.]

[59] Roldán, J.J.; del Cerro, J.; Barrientos, A. A proposal of methodology for multi-UAV mission modeling. In Proceedings of the 2015 23rd Mediterranean Conference on Control and Automation (MED), Torremolinos, Spain, 16–19 June 2015; pp. 1–7.

[60] Roldán, J.J.; Peña-Tapia, E.; Auñón, P.G.; Del Cerro, J.; Barrientos, A. Bringing Adaptive and Immersive Interfaces to Real-World Multi-Robot Scenarios: Application to Observation and Intervention in Infrastructures. *IEEE Access* **2019**, *7*, 86319–86335. [.]

[61] Martín-Barrio, A.; Roldán, J.J.; Terrile, S.; del Cerro, J.; Barrientos, A. Application of immersive technologies and natural language to hyper-redundant robot teleoperation. *Virtual Real.* **2019**, *24*, 541–555. [.]