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Published in:
Engineering Psychology and Cognitive Ergonomics

DOI:
10.1007/978-3-031-35389-5_17

Published: 01/01/2023

Document Version
Peer reviewed version

Please cite the original version:
Karvonen, H., Honkavaara, E., Röning, J., Kramar, V., & Sassi, J. (2023). Using a Semi-autonomous Drone Swarm to Support Wildfire Management – A Concept of Operations Development Study. In D. Harris, & W-C. Li (Eds.), Engineering Psychology and Cognitive Ergonomics: 20th International Conference, EPCE 2023 Held as Part of the 25th HCI International Conference, HCII 2023 Copenhagen, Denmark, July 23–28, 2023 Proceedings, Part II (pp. 235-253). Springer. Lecture Notes in Computer Science Vol. 14018 https://doi.org/10.1007/978-3-031-35389-5_17

Using a Semi-Autonomous Drone Swarm to Support Wildfire Management – A Concept of Operations Development Study

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Abstract. This paper provides insights into a human factors-oriented Concept of Operations (ConOps), which can be applied for future semi-autonomous drone swarms to support the management of wildfires. The results provide, firstly, an overview of the current practices to manage wildfires in Finland. Secondly, some of the current challenges and future visions about drone usage in a wildfire situation are presented. Third, a description of the key elements of the developed future ConOps for operating a drone swarm to support the combat of wildfires is given. The ConOps has been formulated based on qualitative research, which included a literature review, seven subject matter expert interviews and a workshop with 40 professionals in the domain. Many elements of this ConOps may also be applied to a variety of other swarm robotics operations than only wildfire management. Finally, as the development of the ConOps is still in its first stage, several further avenues for research and development are proposed.

Keywords: Drones, Concept of Operations, Human Factors, Firefighting, Wildfires.

1 Introduction

Due to global warming, wildfires are increasing around the world in their number, extent, and severity. To manage this increasing threat, we need more efficient tools for fighting wildfires. For example, up-to-date geospatial information on the fire event is needed to efficiently detect wildfires and to plan the suitable firefighting strategies. The currently used wildfire detection strategies combine satellite and in situ (e.g., aerial fire surveillance flights with small planes) methods to notice a fire and capture relevant data. Satellite observations can reliably detect large fires, but because of their limitations in spatial and temporal resolution, small and recently caught fires cannot typically be detected. Aerial fire surveillance flights made with planes can provide very good situational information also from smaller fires, but they can cost a lot and typically use fossil fuels as a power source.

Unmanned aircraft systems (UAS; also known as unmanned aerial vehicles, UAVs, or drones) may be disruptive, comparatively cheap, and environmentally friendly tools for real-time situational awareness regarding wildfires and which can greatly benefit their firefighting in all its related phases. The central phases of fighting wildfires include prevention, surveillance, and extinguishing activities [1]. Firstly, in the prevention phase, the occurrence of fires and limiting their consequences are sought after [1]. In this phase, the aerial remote imaging data collected by drones can be used to plan the related tasks. Secondly, the fire surveillance phase involves the activities performed to detect and monitor wildfires as early as possible and has up to four objectives: a) search of potential fires, b) detection to alert firefighters, c) diagnosis to get relevant data about the fire, and d) prognosis to predict fire propagation [2]. Drones as "eyes in the skies" for real-time situational awareness can naturally be of help in all these objectives. Thirdly, fire extinguishing involves not only the actions performed to put out the flames but also some supportive suppressing activities, such as creating firewalls, discovering the routes for entry and exit of vehicles, and finding nearby runways and heliports [1]. If not directly in extinguishing activities, drones can be used in this phase, for example, in finding information about the local roads for the fire trucks to arrive on site or natural sources of water (to be then used in ground-based extinguishing) near the site of the fire.

Considering the above examples, it is no wonder that drones are nowadays being deployed in various countries to support wildfire management activities. Currently, for example, a dedicated pilot with the fire brigade may operate a drone within a direct visual line of sight in a wildfire situation. The drone's sensors can provide a direct video feed from high above the fire for the pilot, who can then share the aerial footage results with, for example, the fire brigade commander to help in the coordination of the fire suppression efforts. In the foreseeable future, the usage of individual drones may be replaced with semi-autonomous drone swarms that can be monitored beyond visual line of sight (BVLOS) from a control centre, which is located possibly further away from the actual scene of the fire. In this paper, we report a study to develop a Concept of Operations (ConOps) for a semi-autonomous drone swarm to support wildfire management. This study is part of a three-year project called FireMan (Unmanned aerial systems based solutions for real-time management of wildfires).

The paper is structured in the following way: first, we present highlights from some relevant background literature on wildfire management with drone swarms and present earlier ConOps work related to the command and control of multiple drones in different domains. Second, we present the approach to our study case and a summary of our related interview and workshop results, which also describe the current operational activity of wildfire management practices in Finland. Third, we summarise the identified challenges and visions of drone usage in a wildfire situation from the study results. Fourth, we present the first version of our developed drone swarm based ConOps for wildfire management that is founded on the analysed results from the study case. Finally, we draw conclusions from our ConOps development study and discuss further research needs.

2 Background

There is a plethora of existing research regarding wildfire management with the help of drones. However, there is much less previous literature on how drone swarms could be used to detect and manage wildfire situations. This lack of research is understandable, as the research, development, and usage of non-military drone swarms, in general, is yet in its infancy. Next, we will first focus on some examples of the earlier literature on how drone swarms have been used in the context of wildfire management and then refer to a few earlier ConOpses in the context of command and control of multiple drones.

2.1 Wildfire management with drone swarms

The approaches of wildfire management with drone swarms in previous research can be divided into two different types of studies: 1) fire detection and monitoring studies and 2) fire suppression studies. Here, we will focus on some of the recent work on the former, as that is of more relevance to our study case in question.

Bjurling, Granlund, Alfredson, Arvola, and Ziemke [3] have studied drone swarms in forest firefighting, and especially the related multi-level human-swarm interaction. They describe a human factors-oriented case study conducted within two Swedish fire departments that regularly deploy UAS in fire responses. Based on their UAS usage in the forest firefighting context, the participating UAS operators and unit commanders envisioned a scenario that showed how the swarm and its capabilities could be utilised, given the constraints and requirements of a forest firefighting mission. Consequently, they developed a swarm interaction model that describes how the operators' interaction traverses multiple levels ranging from the entire swarm, via sub-swarms and individual Unmanned Aircraft (UA), to specific sensors and equipment carried by the UAs. Their results suggest, for example, that the related human-in-the-loop simulation studies need to enable interaction across multiple swarm levels, as this interaction may exert additional cognitive strain on the human operator(s) of the swarms [3].

Innocente and Grasso [4] have reported a study regarding the feasibility and potential of employing swarm robotics to fight fires autonomously with a focus on the self-coordination mechanisms for the desired firefighting behaviour to emerge. They developed a physics-based model of fire propagation and a self-organisation algorithm for swarms of firefighting drones with collaborative behaviour based on a particle swarm algorithm. They also conducted numerical experiments to demonstrate that the proposed self-organising system was effective, scalable, and fault-tolerant [4]. Other similar studies on autonomous fleet or swarm control strategies in fire detection or monitoring without human involvement have been presented, for example, in [5–9].

Additionally, some previous studies have suggested UAS swarm-based emergency management strategies. For example, Munawar, Gharineiat, Akram and Imran Khan [10] have developed a framework for a maximum area coverage of a disaster region during a bushfire event. They applied an Artificial Bee Colony (ABC) algorithm to the drone swarm to capture images and gather data needed for enhancing a disaster response. The collected images were used to produce maps of the burnt area, locate access points to the region, estimate the damages, and prevent the further spread of fire. The proposed algorithm aimed to optimise responses for exploration, exploitation, and estimation of the maximum height of the drones for the coverage of wildfires [10]. They also proposed a framework for emergency response by the State Emergency Services in Australia.

Furthermore, Bailon-Ruiz, Bit-Monnot and Lacroix [11] have reported an approach from the human control perspective to plan trajectories for a fleet of fixed-wing UA to observe a wildfire evolving over time. They presented a Situation Assessment and Observation Planning (SAOP) system, of which purpose was to monitor wildfires with a fleet of UAs to provide firefighters with real-time information on the fire perimeters and their evolution over time. The SAOP system operated along a Perception – Decision – Action scheme where the fire map and forecast were sent to the operators and subsequently used to define an observation plan that defines the optimal paths for the fleet to observe the fire. The resulting trajectories were sent to the UAs for execution, and the newly gathered information was used to update the fire map. In their SAOP system, supervision was playing the role of a thin abstraction layer issuing high-level commands to components. While this allowed for some operational autonomy, as it freed the user from the definition of low-level tasks or trajectories, the addition of a higher planning layer would call for more supervision capacities. This approach could, for example, allow the human operators to decide whether monitoring plans can allocate resources aggressively or conservatively and help them control the long-term fleet capacities jointly with the higher-level mission planner [11].

Finally, Saffre, Hildmann, Karvonen, and Lind [12] have presented the results of a systematic numerical methods (Monte Carlo simulation) investigation of drone swarm behaviour for the monitoring and cordoning of wildfires. They report on their insights into the influence of key simulation parameters, such as fire propagation dynamics, the surface area under observation, and swarm size, over the performance of an autonomous wildfire drone force operating without human supervision. Furthermore, they put special emphasis on using simple, robust, and realistically implementable distributed decision functions capable of supporting the self-organisation of the drone swarm in the pursuit of the collective goal. Their results confirmed the presence of strong non-linear effects in the interaction between the aforementioned key parameters, which can be closely approximated by using a specific empirical law [12].

2.2 Earlier Concepts of Operations work for the command and control of multiple drones

The notion of Concept of Operations has been introduced, for example, by Fairley and Thayer [13]. They stated that a ConOps document contains a description of the current system or situation, justification for and nature of proposed changes and/or new features, operational concepts for the new or modified system, operational scenarios for that system, a summary of organisational and operational impacts, and an analysis of the proposed system [13]. In previous research (e.g., in [14]), developing a ConOps has shown to be a useful and integrative element for different stakeholders in designing complex socio-technical systems. For example, a ConOps has been shown to mediate the interaction between people by presenting different illustrative perspectives to the socio-technical system under design and supporting cross-disciplinary communication of experts from various backgrounds.

Examples of related domains where ConOps work has been conducted include the military (e.g., [14, 15]), civil aviation (e.g., [16]), as well as U-space and UAS traffic management (e.g., [17, 18]) domains. There is also some earlier research reporting ConOpses specifically for multiple (semi-)autonomous drones. Next, we provide a few examples of this drone-related literature.

Cummings, da Silva, and Scott [19] describe the development of a new design requirements analysis method for deriving information and functional requirements that address the collaboration needs of UAS operators and the needs of stakeholders interacting with these operators. In their work, they extend an earlier developed requirements analysis method called the Hybrid Cognitive Task Analysis (CTA) method. The Hybrid CTA is extended by introducing analytic steps to identify task and decision-making dependencies between different UAS operations collaborators. The authors also utilise the notion of boundary objects, which is an analytic construct commonly used in the study of group work. Boundary objects are physical or information artefacts that cross the task boundaries between members of distinct groups. Therefore, a ConOps can also be considered as a one type of boundary object. Identifying boundary objects in complex task operations helps the analyst, for example, to identify task and decision-making dependencies between local and remote collaborators. Consequently, understanding these dependencies helps to identify information-sharing requirements that the UAS should support [19]. This conducted study is an example of a human factors-oriented holistic development of an UAS system by using boundary objects.

Furthermore, Pratt, Murphy, Stover, and Griffin [20] have defined a ConOps for UAS in mapping the destruction caused by Hurricane Katrina. Their study examines vertical take-off and landing (VTOL) small unmanned aircraft system (SUAS) operations conducted as part of an 8-day structural inspection task following the hurricane in 2005. From the observations, key findings are identified for the developed ConOps. Based on the findings and other observations, a crewing organisation and flight operations protocol for SUAS are proposed [20]. Therefore, the ConOps clearly includes also organizational and operational activity elements in addition to technical elements.

Finally, Väätänen, Laarni and Höyhtyä [21] have presented the development of a ConOps for a swarm of autonomous robotic vehicles (e.g., drones) in the military domain. Their target was to demonstrate how autonomous robotic swarms can be deployed in different military branches in the future. The proposed ConOps is also considered as a boundary object in the design, validation, or procurement of an autonomous robotic swarm system. In their approach, the ConOps should be maintained throughout the system lifecycle as an overview description and definition of overall goals and policies. This human factors-oriented approach is also well in line with our ConOps approach in this paper.

Although there clearly is some previous research regarding ConOpses for multiple drones in different domains where they have been applied successfully for specific applications, a systematic view to ConOps development seems to be still missing. In particular, the studied literature yet misses the details about how the work of the human operators is planned in detail, such as how they are to monitor and control the drones during the missions.

3 Study case approach

In our FireMan project, the ConOps document is used as a knowledge artefact that is created during the early stages of system development. Nevertheless, we see that it has the potential to be used at all stages of systems engineering. In practice, we consider the ConOps as a transitional design artefact, which plays a critical role especially in the requirements specification process. Additionally, we plan to use the ConOps in our project as a template that can be modified and updated as the development proceeds regarding specific user needs and use cases [21]. In the context of our study case, the term ConOps is used to indicate the design target that includes the work organisation, human activity and main tasks, and the related technologies, as it has been done in another previous similar earlier project as well (see [22]). It is, therefore, different from the ConOpses that are developed, for example, in the military domain, which typically describe what a joint force commander intends to accomplish and how it will be done using available resources, including the assumptions, enemy forces, operation phases, prioritised missions, and force requirements, deployment, and positioning [15]. Furthermore, our ConOps approach is distinguishable from those that every UAS operator needs to develop as the first step of Specific Operations Risk Assessment (SORA) processes [23] and similar activities, which are used to obtain a UAS operation authorisation. Nonetheless, our ConOps approach is close to the ones used in aviation, such as the U-space ConOps [17], which describes from a user's perspective how operations should occur in Very Low Level (VLL) airspace.

To develop a future Concept of Operations, it is necessary to understand the current operational practices in detail. To understand the current ConOps of wildfire (and especially forest fire) management in Finland, we organised altogether seven subject matter expert interviews (lasting 1.5–2 hours each) and a large online full-day workshop with 40 participants from relevant Finnish stakeholders (e.g., from fire departments, authorities, companies, research organisations). The approach of these interviews and the workshop was based on human factors research approaches, such as the Core-Task Analysis [24]. In practice, this meant that the questions in the interviews and in the workshop were oriented towards human activity-related practices than the technological considerations.

The interview questions and workshop themes included parts related to, for example, 1) current aerial forest fire surveillance practices, 2) current main activities in a wildfire management situation in a given scenario, 3) the current key actors/stakeholders and knowledge entities in a wildfire situation, 4) different challenges of drone usage in wildfire situations, and 5) future visions of drone usage in wildfire situations.

Based on the gathered information, a ConOps for using a semi-autonomous drone swarm to support wildfire management was developed. The developed ConOps aims to provide answers, for example, to the following questions:

- What kind of a Concept of Operations would work best for drone swarm-based wildfire management?
- What are the main elements of this ConOps?
- Who are the main stakeholders and actors?
- How are the basic operational activities organised?

- What are the characteristics of the operational environment, the human operator roles, their main tasks, and their tools used?
- What are the main system requirements and functions?

In our ConOps development work, it has also been essential to identify the relevant operational scenarios and have the associated human-swarm interaction requirements specified from the ConOps perspective. In practice, the developed ConOps of the human-drone swarm socio-technical system consists of easily understandable documentation, illustrations, and animations, which describe the characteristics and intended usage of the proposed swarm system from the viewpoint of its human users. From the human factors point of view, we have also evaluated and defined human operator roles, their main tasks, their interaction with the semi-autonomous drone swarm system and their cooperation with relevant stakeholders. Due to space restrictions, only the main elements of the future FireMan ConOps can be described in this paper in section 4.4.

4 Results

The results of the interviews and workshop can be divided into four thematic areas: 1) the current operational activity, 2) the potential challenges of drone usage in a wildfire situation, 3) participants' visions of drone usage in wildfire situations, and 4) first version of the developed drone swarm-based FireMan ConOps, which is based on the gained results. Here, we present the results of these areas in separate subsections.

4.1 Current operational activity

The basic operational activity in a forest fire situation clearly includes two distinct stages: wildfire detection and management. The current wildfire detection in Finland is typically conducted with aerial forest fire surveillance flights around the country when the forest fire weather index goes above a certain threshold during summertime. The study case results indicated that these flights include the following phases (in an actual wildfire situation): 1) Flight route planning, 2) Take-off, 3) Flying the planned route, 4) Smoke detection, 5) Locating the source of the smoke (reconnaissance), 6) Alerting the emergency centre (in case of a real wildfire), 7) Assessment of the fire area, 8) Mapping the roads, natural water sources, and guiding the fire brigade, and 9) Producing a situational picture for the incident commander on the ground as the fire proceeds. For each of these phases, the related detail-level tasks, main operational aims, and potential additional information were also defined in the interviews and workshop, but they are not described here due to lack of space.

After a real wildfire has been confirmed, different actors become relevant in response to the fire. In the study, we mapped the main actors and their main tasks during a forest fire situation. These actors in Finland include, for example, the relevant fire brigades, aerial surveillance pilots, the Finnish Defense Forces, The Finnish Border Guard, weather service providers, volunteers, machine contractors, municipalities, forest management associations, forest companies, the Ministry of the Interior (especially the duty officer), maintenance services, telecom operators, drone operators, sensor companies, satellite companies, electricity companies, police, and air traffic control. The task descriptions of these actors are excluded from this paper due to space limitations.

We also defined both static and dynamic information entities that are relevant in a forest fire situation. In addition, it has been described what this information typically includes, how it is received, and what its format is. Naturally, different tools to mediate these information entities are used, such as information systems, radio communications, human senses, maps, and shared physical artefacts. Examples of these information entities and types are listed in Table 1.

Table 1. Static and dynamic information entities in a forest fire situation.

Information entity	Information type
Fire's situational information	Dynamic
Prediction of the propagation of the fire	Dynamic
Weather information and forecasts	Dynamic
Road information	Static
Natural water source data	Static
Satellite observations	Dynamic
Topography data	Static
Map materials and positioning data	Static
Forest resource information	Static
Documentation to support the early fire management and flow of situational information	Dynamic
Quality of the mobile network communication connections in the area	Static
Sharing of common operational picture	Dynamic

After defining the basic information entities, an imaginary operational scenario (see the top part of Fig. 1) was presented to the participants in the workshop. The participants then started to jointly work on this scenario by defining the key phases, functions (i.e., operational activities), and main purposes (i.e., aims) of the fire rescue services in the situation by using a predefined notation approach. This definition was conducted using a functional situation model (FSM) approach, which has been previously used in analyses of operating practices in complex work (see, e.g., [25, 26]). The FSM approach connects the conducted operational activities with the main purposes arising from the domain in question. The formative FSM technique enables the analysis of operational activity from the perspective of way of acting, i.e., work practice. The aim of this approach is to promote the adoption of resilient work practices by analysing which ways of acting in a given situation are aiming for the general objective of safety [25]. The resulting model denotes a control situation from the point of view of its critical functions, which are endangered in the safety-critical situation. The related human activity is also depicted in the model and connected to these critical functions, which are aimed to be maintained.

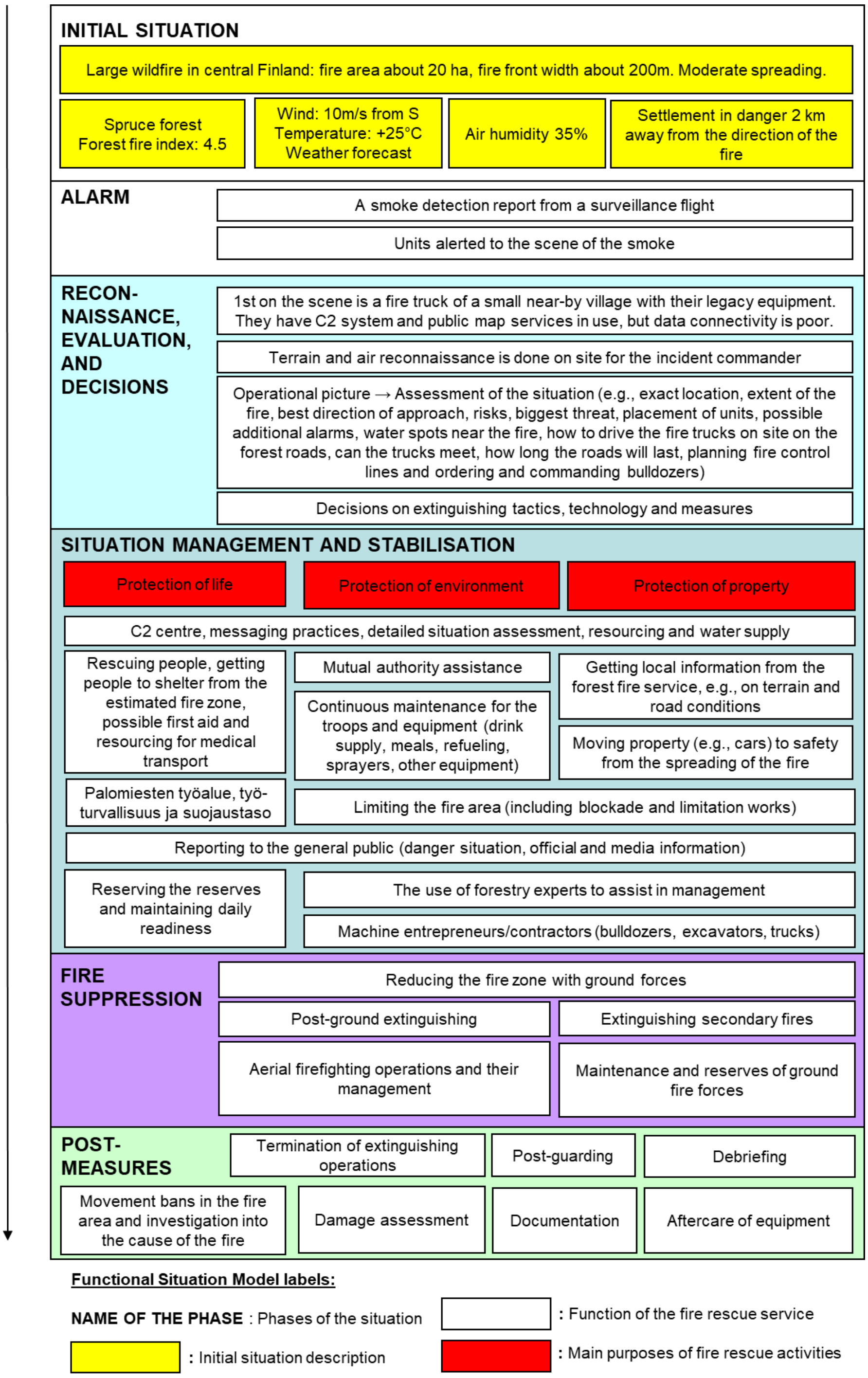

Fig. 1. Functional Situation Model of forest firefighting general level measures and phases

The FSM regarding the imaginary scenario we presented and worked through together with the experts in the workshop is presented in its finalised format in Fig. 1. From the FSM, it can be seen that the typical main aims of human activity in safety-critical environments are the protection of life, environment and property (the red boxes, [25, 27]). Similarly, the main priorities of safety, productivity, and health in the entire socio-technical safety-critical system have been identified in previous human factors literature (e.g., [28]). In addition, a broad range of weather-related technological and operational challenges have been studied and categorised previously [29, 30]. Finally, the operational activities in these types of environments are typically uncertain, dynamic, and complex, which requires keeping the operational focus on their core task at all conducted activities [24].

4.2 Challenges of drone usage in a wildfire situation

From the study case results, it became evident that several reasons may cause unexpected situations during drone flight missions in a wildfire situation. Firstly, problems with the drone due to fire and smoke are possible. For example, because of smoke, the drone pilot may lose direct eye contact with the drone, and it may accidentally hit the close-by trees and thus fall from the sky. Furthermore, if the drone is piloted too close to the wildfire, the heat may damage the materials, structures, electronics, navigation system, or sensors of the drone. The greasy smoke from the fire can also block the optical lenses used for remote sensing and thus prevent the planned drone-based operations and data acquisition. As a result, the situation awareness information from the drone cannot be utilised for coordinating the fire suppression efforts. Consequently, the drone should be piloted in such a way that it does not enter the airspace near the smoke, the flight altitude should be kept well above the surrounding trees, and the drone should be kept at a safe distance from the wildfire’s flames.

Secondly, the current power solutions for drones present challenges. The flight times of modern drones are not yet exceptionally long. If continuous aerial surveillance is to be organised to the site of the wildfire, there needs to be a backup reserve of drones to be sent to the sky once the batteries of the airborne drones run out. Furthermore, inadequate charging capacity for the drone batteries may shorten the flight times, and the needed recharging of the drones may cause extra delays if this is not considered at an appropriate level in advance.

Thirdly, the lack of adequate resources for the analysis and interpretation of airborne remote sensing data may prevent the achievement of benefits of drone-based operations. As typically all the fire brigade members are busy during a wildfire situation, there might not be time to analyse and interpret the gathered data from the drones, even though it would help the efficient extinguishing of the fire. Therefore, the missions should be planned beforehand in such a way that a sufficient and skilful crew is available, and the drone missions are not relying only on one person (who might be busy with other tasks in a wildfire situation).

Fourthly, the possible unintentional (e.g., due to lack of coverage) or intentional (e.g., due to jamming or spoofing) interruptions in GPS or data connections may delay or even prevent drone flights from being conducted. The positioning, navigation and communications solutions should therefore be resilient, redundant, and secure enough for the planned operations. Furthermore, there should be enough bandwidth and low latency connectivity available to transfer the information from the sensors and to avoid the loss of direct data link between the drone and the pilot in command.

Fifthly, as autonomy advances in the future, operations with a high level of autonomy and low level of human involvement need to be carefully designed from the human operator's perspective to avoid distractions and boredom during the operations. Therefore, the human operator tasks should include enough meaningful tasks to keep the operators vigilant and interested in the operations.

Finally, from the future operational perspective, one of the main challenges for an automated drone swarm system would be its integration into the systems operated by the aviation authorities and the rescue personnel. This integration requires novel U-space solutions to manage the drones and crewed aircraft in the same airspace. Furthermore, a lot of integration work is needed with the application programming interfaces (APIs) of the rescue information systems and other solutions used by the authorities for them to receive and present the collected situation awareness data from the drone swarm sensors and the sensor fusion platform.

4.3 Visions of drone usage in wildfire situations

Regarding drone usage in a typical forest fire situation, we defined three different time scales on which we held brainstorming sessions in groups of 5 to 10 persons. There were four groups altogether, and each had a dedicated facilitator and a secretary to write the results down. The used time scales were I) the current use of drones in a forest fire situation, II) the usage of drones in the foreseeable future (1–5 years), and III) the usage of drones further in the future (5–10 years). Regarding each timeframe, we went through the following topics in detail:

- What kinds of drones can be used?
- Who operates the drones, and what is the level of automation?
- What kind of a common operational picture can be provided with drones?
- What cameras/sensors can be used onboard the drones?
- How can the collected sensor data be analysed and processed by technological means?
- What types of telecommunications connections are available for data transfer?
- How can safe airspace management on the forest fire site be done?

In summary, the following information could be obtained regarding the participants' visions about drone usage in wildfire situations in the chosen time scales. I) In the current situation, light and cheap commercial quadcopters are flown low within Visual Line of Sight (VLOS), mostly by individual pilots with the fire brigade to provide video and thermal imaging camera material regarding the fire situation from the sky. This material is not currently analysed with automated technological means (e.g., with artificial intelligence, AI), but only by humans with the aim to detect the fire front and its spreading direction and speed. This information is utilised in commanding the fire crews in the field and their extinguishing activities. In general, real-time analysis of the forest fire situation is missing from the current operational practices. The data transfer in Finland is typically based on private (e.g., Terrestrial Trunked Radio, TETRA) or public mobile networks (e.g., 3/4G), which may also include coverage and bandwidth problems, creating a bottleneck effect. Basic airspace management can be done, for example, with temporary R (restricted) or P (prohibited) airspace areas. Autonomous systems are not in operational usage at the moment, but some automated solutions are used (e.g., for defining the flying waypoints of the drone beforehand automatically). One key challenge is the sharing of the situation awareness information efficiently from the drones to all relevant stakeholders.

II) In 1–5 years, the participants envisioned that heavier professional (both quadcopter and fixed-wing) drones could be flying semi-autonomously BVLOS and providing a good enough quality real-time situational picture with their advanced sensors from very high above. However, a lot of training for drone operations is needed for this situation to become a reality. In addition, even small airships or satellite-based remote imaging could be utilised for long-term aerial surveillance of the situation. Some participants also saw that even fire-extinguishing drones could be in operational use in a wildfire situation. In addition, drones could deliver essential equipment (e.g., tools or power banks) for firefighters in the field. On the analysis side, a real-time map view of the current fire situation and its predicted propagation could be provided for different stakeholders. Sensor fusion would also allow detailed analysis of the fire situation by combining different sensor information into an intuitive and coherent whole for humans. This would enable the efficient command and control of the fire crews to conduct appropriate predictive extinguishing activities. The data connectivity is expected to be provided through advanced and good-coverage private (e.g., VIRVE 2.0), public mobile (4/5G), satellite communications, and IoT networks. Airspace management could be done in habited environments with appropriate pop-up U-space solutions, air corridors, and automated detect and avoid (DAA) solutions.

(III) In 5–10 years, (semi-)autonomous swarms of drones could be used for the detection and monitoring of wildfires in large geographical areas. These swarms could be deployed automatically from drone base stations in 24/7 readiness spread around the country. The swarms could conduct automatic reconnaissance and detection of wildfires with enhanced machine vision and AI capabilities to provide intuitively understandable real-time situation analysis to relevant stakeholders. In addition to regular visible light RGB and thermal imaging, also hyperspectral and other advanced imaging from different angles could be combined with refined sensor fusion to provide appropriate situational awareness information. Furthermore, heavy-weight drones can provide different types of fire extinguishing activities and logistics to support fire crews. Centralised and semi-autonomous command and control of the drones and the related analytics have been established. Furthermore, holistic predictions could be conducted about the fire situation during certain future time intervals with the help of AI. The data connectivity in the fire area is provided via secured and robust 5/6G networks. The airspace management is conducted with advanced unmanned traffic management (UTM) solutions that allow crewed and uncrewed air traffic to operate safely in the same airspace.

4.4 The first version of the developed drone swarm-based ConOps

As described in section 3, we held a co-design session in the workshop with the participants to craft the basic building blocks of the first version of the FireMan Concept of Operations. Based on the received results and feedback about the envisioned ConOps, we developed the first version of the drone swarm-based FireMan ConOps. Next, we present the main elements of this ConOps on a general level.

Process description. A high-level process description of the operational activities when detecting and extinguishing a forest fire in the FireMan ConOps (estimated to be feasible in 5 to 10 years) is provided in Fig. 2 and explained in text format in the following. First, an aerial surveillance flight, drones, drone swarms, or a human on the ground detects a fire somewhere in the environment. Second, there needs to be a more detailed detection of the fire type (e.g., is it a real wildfire or somebody burning trashes controllably). A drone swarm with advanced detection capabilities could be used for aerial reconnaissance of the fire situation at this phase. Third, if it is a real wildfire, help should be alarmed, and the drone swarm would start monitoring the propagation of the wildfire from different angles. In practice, different remote sensing capabilities onboard both fixed-wing and quadcopter drones swarming in the air would be utilised. In addition, the fire brigade would arrive via ground routes to the site and start their needed operations.

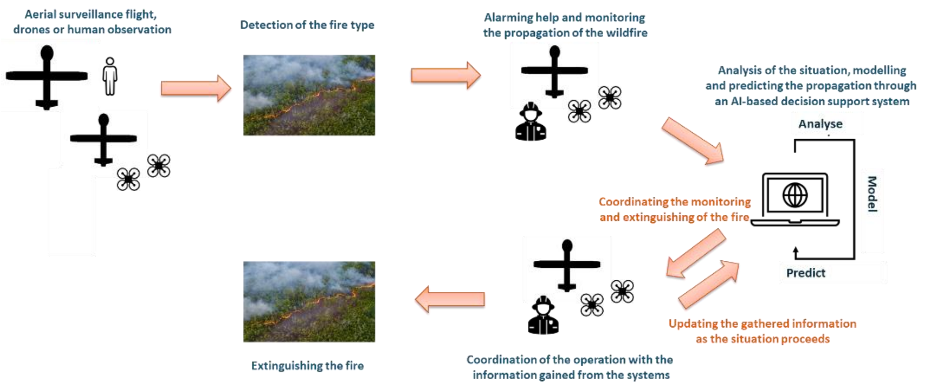

Fig. 2. High-level process description of the operational activities when detecting and extinguishing a forest fire in FireMan ConOps

Fourth, the collected information from the drone swarm's sensors is fed to a centralised AI analysis system, which models the fire and its propagation based on the received information in a digital twin. This digital twin would allow real-time automated analysis of the situation and the prediction of the fire's future behaviour. In this way, predicting the spreading of the fire (if no extinguishing actions would be conducted) between certain time intervals (e.g., 5, 15 and 30 minutes) could be done.

Fifth, this information is processed in an AI-based decision support system that can provide recommendations for the incident commander of the fire situation to guide the commanding of the fire crews and their extinguishing activities in the field. In addition, the analysis of the effect of these activities can be then utilised in coordinating the drone swarm's behaviour to provide better situational information. Therefore, an automated closed-loop behaviour of the drone swarm can be established here. Finally, the fire would be extinguished with the help of this intelligent decision support.

Mission and operational scenario. A detailed level future FireMan ConOps for operating a drone swarm during a forest fire situation is presented in a diagram format in Fig. 3. This situation would be estimated to be possible in operational usage in about ten years. The scenario and mission description considered here is similar to the Initial Situation described in the top part of the FSM in Fig. 1. A textual description of this ConOps is not provided here due to lack of space, but it is assumed here that the diagram is rather self-explanatory as a high-level model of the mission from the human factors perspective. The used symbols and colours in the diagram mean the following: the orange arrows are interactions and data flows between the different main elements (rounded rectangles) of the socio-technical system at hand. The blue colour indicates the human operators in the command, control and communications (C3) centre and their key outputs (the blue arrows).

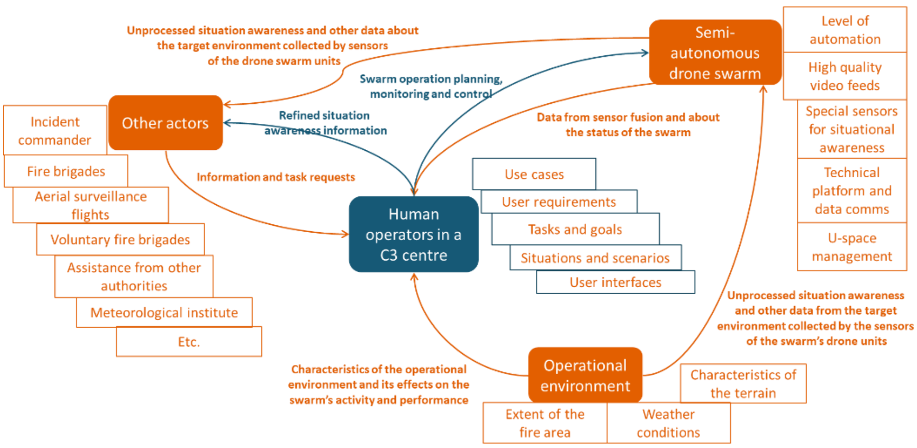

Fig. 3. ConOps diagram for operating a drone swarm during a forest fire situation (FireMan ConOps).

System requirements: The system consists of a semi-autonomous swarm of flying drones. The individual drones have a flight time of one hour, and they are equipped with various kinds of payloads (e.g., RGB, thermal, hyperspectral imaging cameras) for remote imaging purposes. The station for the drone swarm units with their launch pads is moveable, and it can be ordered by request to the site where the forest fire is occurring. The system also includes a swarm command, control, and communications (C3) platform through which the swarm's mission and actions can be planned and coordinated. This platform also allows human interventions if something does not go according to the predefined plans. A communications solution based on 5G-Advanced or

6G connectivity provides sufficient bandwidth for high-quality sensor feeds for different stakeholders. A pop-up U-space solution for safe airspace management of uncrewed and crewed aircraft in the same airspace is also utilised.

Main stakeholders. Public law authorities, such as fire and rescue departments, typically take the main responsibility of organising the drone swarm-based fire monitoring operation and the related C3 centre. However, it may also be possible to outsource this to be provided as a service by private organisations. Cooperation with other authorities (e.g., with the police), aerial surveillance flight operators, voluntary fire brigades, telecom operators, and the meteorological institute also plays an important role here.

The human operators at the C3 centre include a swarm operator, a data analyst, and a U-space operator. Below are their main tasks and responsibilities summarised in a list format.

<u>Swarm operator:</u>

- Communicates with the other C3 operators to plan, operate and end the drone swarm's mission
- Prepares and activates the swarm launches and plans the swarm's return to the launch pad
- Monitors the performance of the drone swarm (e.g., battery status, etc.)
- Operates and coordinates the semi-autonomous drone swarm's flying in the air

<u>Data analyst:</u>

- Analyses the provided sensor analytics from the drones of the swarm
- Monitors and uses AI-based analytics system of the situation
- Makes refined analyses of the situation and recommendations for action for the incident commander
- Communicates with other external stakeholders about the fire situation

<u>U-space operator</u>

- Establishes a U-space area for airspace management
- Monitors safe airspace usage and provides air traffic control for aircraft in the area
- Communicates with crewed and uncrewed aircraft pilots about airspace usage

On a more practical level, the following stages would be followed in conducting the drone swarm operation in a wildfire situation:

1. Planning the operation and defining the limitations and boundary conditions of the swarm's operation
2. Configuring the drone units of the swarm
3. Taking the drone units to their launch site
4. Monitoring the progress of the swarm operation
5. Interpreting real-time results and reacting to them accordingly

6. Responding to potential unexpected events and intervening with the automated operation of the drone swarm when necessary
7. Ending the operation

System interface. A user interface for the interaction between the human operators and the swarm units provides an intuitive and easy-to-use human-machine interface. A step-by-step main task progress example from the swarm operation system's usage perspective is provided below:

- The swarm operator selects the area to be monitored by painting the area from his map-based swarm C3 user interface.
- The swarm launches and spreads to the selected reconnaissance area automatically in such a way that it maximises the surveillance coverage while maintaining the connection between the different members of the swarm and the central control.
- When the swarm detects a fire, some of its members stay to monitor that area in question, and some continue to survey other areas.
- The decision support system combines the geospatial data of the area and the real-time data obtained from the swarm drones.
- For a wildfire situation, a simulation environment is used to guide the fire extinguishing activities with a virtual forest environment (as a digital twin) that matches the real environment as closely as possible. In this way, the fire progression can be modelled in different scenarios and time intervals.
- Fire incident commanders can examine this situation model from different perspectives and time scales in order to make more informed decisions about extinguishing activities.

5 Discussion, conclusions, and further research

Based on our results, swarm-based drone operations offer an attractive approach to wildfire management. Especially the detection and monitoring of wildfires could be enhanced with drone swarms because their use could enable a more comprehensive situational awareness, as a larger geographical area with various sensors and imaging angles are possible compared to single drone operations.

In addition to the technical aspects of the implementation of the developed ConOps, also the human factors aspects need to be addressed. Although swarm operations can be an effective tool for rescue teams, they should not require any additional effort or expertise away from the firefighting teams. Therefore, the system's use should be easy and the level of automation optimal. In an ideal scenario, dedicated operators could monitor the swarm, and the produced information would then help efficiently the extinguishing tasks, which require more direct human involvement. Therefore, drone swarms could also enable a more efficient management of the rescue team resources. In far-future use cases, drone swarms with the capability of fire extinguishing could also save lives if the number of firefighters on-site at the fire could be reduced in this way.

Stemming from our study results, a thermal imaging camera offers an excellent method for the detection of the fire front, as the sensor can detect the heat source even through smoke in the air. As this feature offers precise information regarding the exact location and progress of the fire front, extinguishing tasks can be accordingly planned and executed. The thermal imaging camera has already been utilised by the fire brigades in the monitoring of residential building fires, and it offers huge potential already when used in single drone operations.

A similar drone swarm, as the one envisioned in this paper, could also be utilised in other surveillance and monitoring missions, which require the surveying of large terrestrial areas. It is only a matter of teaching the AI algorithms correctly to detect relevant things from the ground. These other missions could include, for example, the search and rescue of a mission person, border patrolling (and detecting, e.g., humans and vehicles), or reconnaissance of enemy's locations in a military scenario.

Fixed-wing drones offer longer operational time windows compared to traditional quadcopters. Therefore, fixed-wing drone swarms with an efficient division of labour could support or possibly even replace aerial surveillance flights with crewed aircraft in the future. This would also enable more real-time data processing and AI-based analysis tools to be used in surveillance operations.

In general, we found out during this first ConOps development that the approach is useful for communicating various ideas and works efficiently as a boundary object for all the stakeholders in the design of complex socio-technical systems. Especially when different requirements need to be assimilated in the process, the ConOps offers a way to discuss their prioritisation with people from various backgrounds.

Finally, our future work will focus on the refinement and implementation of the presented high-level ConOps vision into more practical solutions. These will include the development of appropriate swarming algorithms, simulations of swarming behaviour, implementation of this behaviour to physical drones in a proof of concept, developing of AI solutions for the detection of fire and smoke from various remote sensing feeds, and to practical operational procedures for the related authorities.

6 Acknowledgements

This research is funded by the Academy of Finland (project grant numbers 348010, 346710, and 348008) and conducted as part of the Unmanned aerial systems based solutions for real-time management of wildfires (FireMan) project. In addition, part of the financial support was from the project 'Finnish UAV Ecosystem' (FUAVE, project grant numbers 337878, 337018, and 338080).

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