Drone Swarm for Post-Wildfire Hot Spot Detection: Technology Assessment and PoC Demonstrator

Micha Sende[*]
Lakeside Labs GmbH, Klagenfurt, Austria
sende@lakeside-labs.com

Christian Raffelsberger
Lakeside Labs GmbH, Klagenfurt, Austria
raffelsberger@lakeside-labs.com

Samira Hayat
Lakeside Labs GmbH, Klagenfurt, Austria
hayat@lakeside-labs.com

Armin Köfler
JOANNEUM RESEARCH
Forschungsgesellschaft mbH, Digital,
Graz, Austria
armin.koefler@joanneum.at

Alexander Almer
JOANNEUM RESEARCH
Forschungsgesellschaft mbH, Digital,
Graz, Austria
alexander.almer@joanneum.at

ABSTRACT

Post-wildfire hot spots are a severe problem for fire fighters since they are hard to detect and can reignite fires. The tedious search can be greatly improved by using drones. However, developing and controlling an autonomous drone swarm is a challenging task. An assessment with domain experts reveals the suitability of drone swarms for hot spot detection. We develop a heterogeneous multi-drone system that can support fire fighters by creating thermal and visual aerial images and automating the hot spot detection process. During a joint exercise with a fire fighter brigade we demonstrate that the proposed system is able to autonomously search, detect, and report hot spots. Therefore it is able to speed up the search process while reducing the required number of personnel.

Keywords

Drone Swarm, UAV Swarm, Wildfire Hot spots, Technology assessment, PoC Demonstrator

INTRODUCTION

The critical nature of disaster response missions make them ideal use cases for drone swarms. With climate change, the number and intensity of natural disasters is rapidly increasing. According to the "World Disasters Report – Trends in Disasters" 2022, the number of geological disasters increased from 19 in 2020 to 33 in 2021 (International Federation of Red Cross and Red Crescent Societies, 2022). According to a European Commission's report on wildfires, the number of wildfires in the EU increased by 48 % from 2021 to 2022, while the affected area increased by 86 % (Joint Research Centre, 2023). With an increase in number and intensity, wildfires are causing an increased havoc on the environment, human health, and infrastructure (United Nations Environment Programme, 2022).

Fighting wildfires requires a coordinated effort by fire fighters, emergency management, and specialized aircraft teams. In recent years, drones also known as unmanned aerial vehicles (UAVs) equipped with visual and thermal

---

[*] corresponding author

sensors have been used to support these efforts. Drones offer a cost-effective solution, compared to traditional methods for visual overview, such as using satellite imagery or aerial photography using helicopters. Fire departments equipped with drones may have a lot more flexibility in terms of operation time to generate and analyze such overview images. Additionally, drone swarms reduce the overall mission time significantly when compared to search using watch towers, ground robots, or ground personnel.

After wildfires are extinguished to a significant degree, fire fighters must search the affected area for hot spots that may be hidden inside burned tree trunks or buried out-of-sight. Sparks flying from these hot spots may lead to future fires. Therefore, the post-disaster phase of detecting hot spots, which may span over multiple weeks, is very important to prevent reignition. Currently, hot spot detection is mostly performed manually by fire fighters that are equipped with handheld thermal cameras. They may be supported by drones which are manually steered and do not provide automatic hot spot detection. These efforts require a lot of personnel. In this paper we describe a multi-drone system to aid fire fighters in hot spot detection in the post-disaster phase of wildfires.

Our proof of concept (PoC) system implementation uses a fixed-wing drone equipped with a visual camera, four multirotor drones equipped with thermal cameras, visual cameras, and communication interfaces (WiFi mesh and LTE/5G), two ground control stations (GCSs) for human interaction, and three servers for computing and data storage. The system is scalable in terms of the number of drones, and is designed with clear interfaces between humans and drones, while requiring minimum intervention from humans.

The system design takes into account feedback from first responders and emergency management experts gathered through questionnaires and expert interviews. It is noted from the feedback that current usage of drone imagery for hot spot detection puts a strain on the resources, requiring two persons per drone, a pilot and one person to analyze the images. The developed PoC by design requires two persons for the operation of the entire swarm. The purpose of this work is to demonstrate that an autonomous swarm is a feasible solution in terms of optimal resource usage in post-wildfire hot spot detection. The system is able to autonomously identify hot spots from the air over large areas, leaving the fire fighters free to tackle the task of extinguishing the fires. The focus of this paper, however, is not to provide quantitative results comparing the efficiency of manually-operated versus autonomous drones for hot spot detection.

The mission starts with the fixed-wing drone flying autonomously to generate a real-time aerial overview image of large areas. This provides the ground personnel with an up-to-date situation overview image to identify regions of interest (ROIs) for closer inspection. The ROIs can then be assigned to one or more multirotor drone swarms, which cover less area but provide greater detail. A single pilot can track the swarm status using a GCS. To synchronize takeoff in a swarm, the swarm pilot gives the mission start command. The swarm takes off, flies, searches, and lands autonomously. During search, the drones detect hot spots and transfer images and hot spot information to the ground, where they are geo-referenced. The location and intensity information of the hot spots is passed to the fire fighters who take necessary action to extinguish them.

Communication plays a critical role for successful swarm operation during the mission. The drones must avoid collisions autonomously. The swarm pilot must be able to track the swarm mobility and the hot spot images, and information must arrive in real-time manner at the GCSs. To support actions that benefit from device-to-device connectivity, e.g., collision avoidance, we use WiFi mesh; to support high-throughput real-time image transfer, LTE/5G networks are used. Thus, we are able to demonstrate a fire fighting mission aided by a drone swarm which makes the best use of two different communication technologies.

Our main contribution is the demonstration of a distributed swarm robotic system integrated from several sub-systems in a realistic environment including stakeholders. Compared to state of the art drone operations in wildfire scenarios, our system reduces the required ground personnel count while increasing the speed at which the situation overview is generated.

The rest of the paper is organized as follows: First, we list related work and report the outcome of the technology assessment. Then we describe the system architecture and its components, followed by details of the proof of concept demonstration and a conclusion.

RELATED WORK

There is no shortage of research work focusing on drone swarm or multi-drone use for search and rescue (SAR) (Arnold et al., 2020; Dominguez et al., 2017; Dong et al., 2021; Guo et al., 2019; Mbaitiga & Shosaku, 2022; Quan et al., 2019; Scherer et al., 2015; Steinhäusler & Georgiou, 2022). A small number of these focus on real-world system implementation (Dong et al., 2021; Lauterbach et al., 2019; Quan et al., 2019; Scherer et al., 2015; Steinhäusler & Georgiou, 2022; Terzi et al., 2019). Some work on system implementation highlights the necessity for seamless integration of different technologies (Scherer et al., 2015; Tinetti & Riveros, 2021), which is a challenging task. The task becomes further complicated when using an autonomous drone swarm. In this paper, we present a multi-drone system to aid fire fighters. The drones fly completely autonomous to search an area and detect hot spots while avoiding collisions.

A drone swarm may support a team of fire fighters in many ways. One of the biggest advantages of using drone swarms is their ability to generate large-scale, near real-time, visual situational awareness by 3D area mapping (Lauterbach et al., 2019). The drones may additionally collect other valuable sensor data such as the levels of hazardous plumes in the air and reduce the risk to the fire fighters' lives (Seiber et al., 2018). Drone swarms are also ideal for victim detection and localization (Dong et al., 2021; Quan et al., 2019; Scherer et al., 2015; Steinhäusler & Georgiou, 2022) as they provide a much faster area search as compared to ground personnel or robots. Finally, they help locate sources of disaster such as fires or toxic plumes (Seiber et al., 2018; Viseras et al., 2019). In our proposed system, the autonomous drone swarm locates hot spots in the post-disaster phase. Locating and extinguishing the hot spots mitigates the risk of future fires.

The increasing number of wildfires in recent years has seen an increased interest among the drone research community to develop systems aiding fire fighters. Pasini et al. developed a framework for cooperation between aerial and ground robots (Pasini et al., 2022). A drone is used to gather a visual overview of the area of interest while identifying hot spots. The overview image is transferred to a ground station, which generates a path to the identified hot spots for a rover. Viseras et al. performed a measurement campaign with three drones to collect visual and thermal images of wildfires and hot spots (Viseras et al., 2019). Hot spots with a minimum size of 15 cm could be identified during image analysis from a height of 90 m. Unlike the above two works, in our system, the drones are equipped with visual and thermal cameras to autonomously identify hot spots in a real-time manner during flight. Dong et al. used a similar approach for survivor detection post-disaster using YOLOV3-MobileNet on a single drone (Dong et al., 2021). However, the drone swarm system implementation was not the focus.

The agents in a drone swarm may make autonomous flight decisions either using visual information (Schilling et al., 2022) or using communication (Scherer et al., 2015). In this work, we rely on WiFi mesh communication for flight decisions due to the small drones' payload limitations. The drones are also equipped with 5G modems for sensor data transfer. The use of 802.11s mesh network to operate a drone swarms has been proposed in (Scherer et al., 2015), with related measurement campaigns performed in (Hayat et al., 2015). It was shown that in a multi-sender scenario (two drones generating traffic and sending to a ground station), the network offered fairness and an average throughput of 10 Mbit/s up to a distance of 450 m from the ground station. Scalability of wireless mesh networks is a known concern, mostly caused by link sharing (Lei et al., 2022). How mesh technologies such as WiFi fare in real-world drone swarms with more than ten agents depends on the amount of traffic needed to be exchanged among the agents, and is still an open topic.

For the transfer of high-throughput real-time payload data such as visual and thermal images, 5G networks are ideal. Experimental campaigns report drone-to-ground station throughput of up to 50 Mbit/s, with latency as low as 47 ms in a suburban environment (Fakhreddine et al., 2022). The average latency has been shown to vary with signal-to-interference and noise ratio, with its variance strongly impacted by handover frequency in both urban and suburban scenarios in (Luo et al., 2022).

TECHNOLOGY ASSESSMENT

In order to identify the most important application scenarios for a drone swarm and to gather initial requirements, we asked first responders and emergency management experts from Austrian ministries to complete a questionnaire. In total 33 experts replied. The majority (57.6 %) have more than 15 years of experience, 42.4 % are in senior command, 30.3 % in mid-level command and 24.2 % in operational service. Such a technology assessment is important, since it helps to determine the feasibility and suitability of the system for the specific needs and requirements of the first responders. The questionnaire introduced the general idea of autonomous drone swarms, equipped with different sensors, to support the emergency response. It contained questions to assess the experts' opinions concerning the suitability of such a system in different scenarios and specific use cases, the anticipated risks, dangers, advantages and disadvantages, both with closed Likert scale and open answers.

Due to space constraints, we only provide selected results of the user survey. In a series of questions, we asked the experts whether they a) believe that such a system introduces risks, b) disturbs the work of first responders, and c) brings them more disadvantages than advantages. Figure 1 shows the results for four application scenarios: wildfires, other natural disasters, person monitoring (e.g., at large events), and monitoring critical infrastructure. The majority of the experts agreed that a drone swarm introduces risks in person monitoring and wildfire scenarios. Most experts disagreed that such a system introduces risks for other natural disaster responses and monitoring

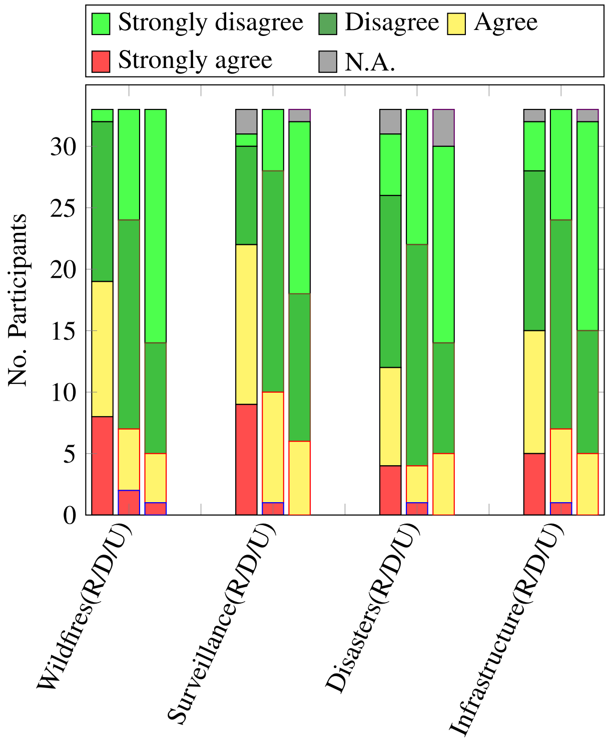


Figure 1. Does a drone system introduce more risks (R), dangers (D), or more disadvantages than advantages (U) to the use cases?

of critical infrastructure. The majority disagreed that a drone swarm disturbs the operation or introduces more disadvantages than advantages. It is safe to say that drone swarms are seen as beneficial in all scenarios.

We also asked the experts about specific use cases for drone swarms in the wildfire scenario, such as: detection of wildfires (e.g., after lightning strikes), monitoring the actual wildfire response, hot spot detection, and the post-disaster damage assessment. Figure 2 shows that hot spot detection and damage assessment are seen as the most suitable use cases to be supported by drone swarms.

The experts were also asked to identify the three most important/useful and the three most problematic/risky/negative factors when using such a system. Many experts mentioned cost as an important factor, both as a strength and as a weakness. Some experts were concerned with the initial investment costs, while others saw the potential for future cost savings due to a reduction in the number of first responders required. Similarly, the complexity of the system was seen as a crucial factor. While some experts were concerned with initial and ongoing training needs to operate the system, others saw a high degree of autonomy as a potential. Legal restrictions on the operation

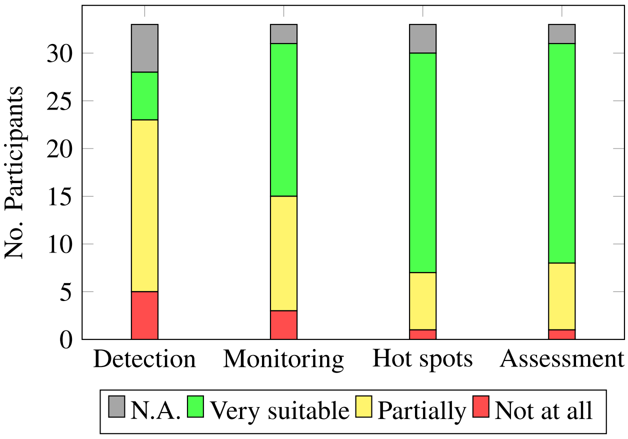


Figure 2. Is a drone swarm suitable for specific use cases in a wildfire scenario?

of autonomous drones and the impact of weather were seen as the biggest risks. Improved assessment times and situational awareness were cited as the biggest potential benefits.

Subsequent to the PoC demonstration, an evaluation was conducted to collect feedback from the first responders. The outcomes of this evaluation are elaborated in the proof of concept section.

Requirements

The experts were also asked about requirements towards such a system. The answers included: ease of use, both when controlling the system and when analyzing the gathered data; providing data interfaces to existing systems; well-defined safety regulations to ensure the safety of the personnel on ground and air forces. Furthermore, they mentioned important aspects such as flexibility (e.g., adapt the size of the swarm), quick setup, real-time monitoring, and robustness. Interestingly, there were conflicting opinions about the costs of such a system. While some experts see such a system as a way to reduce the response costs, other expect the system to increase costs.

SWOT Analysis

Based on the answers we performed a SWOT analysis with the following results.

Strengths: The system is seen to handle resources efficiently and hence to reduce cost regarding acquisition, operation, and maintenance. It can increase the speed of a mission, create increased situational awareness, and allow early detection of incidents. Its versatility allows it to be adapted and used for different applications.

Weaknesses: The complexity of the system is seen as its main weakness. This complicates the integration into existing systems, hence limiting its acceptance. Due to the complexity it might also be prone to failures and require regular maintenance, e.g., in changing weather conditions or crowded air space. Operating such a complex system requires training which could drive up costs, while current legislation does not allow a single swarm pilot but requires one pilot per drone.

Opportunities: The system can exploit already existing interfaces of other systems as well as existing, well-defined safety regulations to boost its acceptance. It can play out its flexibility in the challenging and changing conditions of rescue operations.

Threats: Outside influences that can threaten the system operation include incompatibilities with other systems, badly educated personnel, hacking attacks, external disturbance (e.g. interference on the communication channels), and mid-air collisions.

Concluding the assessment, we can say that most experts agree that drone swarms are a suitable technology for hot spot detection in wildfire scenarios. Therefore, we target this scenario with our drone swarm system. To address the concerns regarding system complexity we design our system with a focus on autonomy. Most steps, including mission execution, swarm coordination, communication, image analysis, and feature detection are automated to ease the system operation. This includes a collision avoidance algorithm to minimize the aforementioned risk of collisions in the air.

SYSTEM

In this work we propose a system consisting of several sub-systems that are interconnected using different technologies. An overview is given in Figure 3.

System Components

The proposed system can be organized into three technical sub-systems plus a user interface (UI) for interaction with users, i.e., pilots and fire fighters. The sub-systems are: the fixed-wing drone, the multirotor drone swarm and the server infrastructure for off-board analysis and storage.

The first subsystem consists of a fixed-wing drone (Skywalker EVE-2000) equipped with a visual camera (Sony IMX249 sensor with 2.3 megapixel mounted on a 1D gimbal for roll compensation) that creates an aerial image, a map server based on the open source implementation GeoServer[1] to store that image, and a custom build GCS that controls the mission of the drone and visualizes the progress (Fanta-Jende et al., 2023). The drone is controlled by a Pixhawk 2 flight controller running the Ardupilot firmware and localizes using a Cube Pilot Here3 RTK GPS. The onboard computation is performed by an NVIDIA Jetson Xavier NX. The drone has a maximum takeoff weight of 4.6 kg and a cruise speed of 75 km/h.

---

[1] https://geoserver.org/

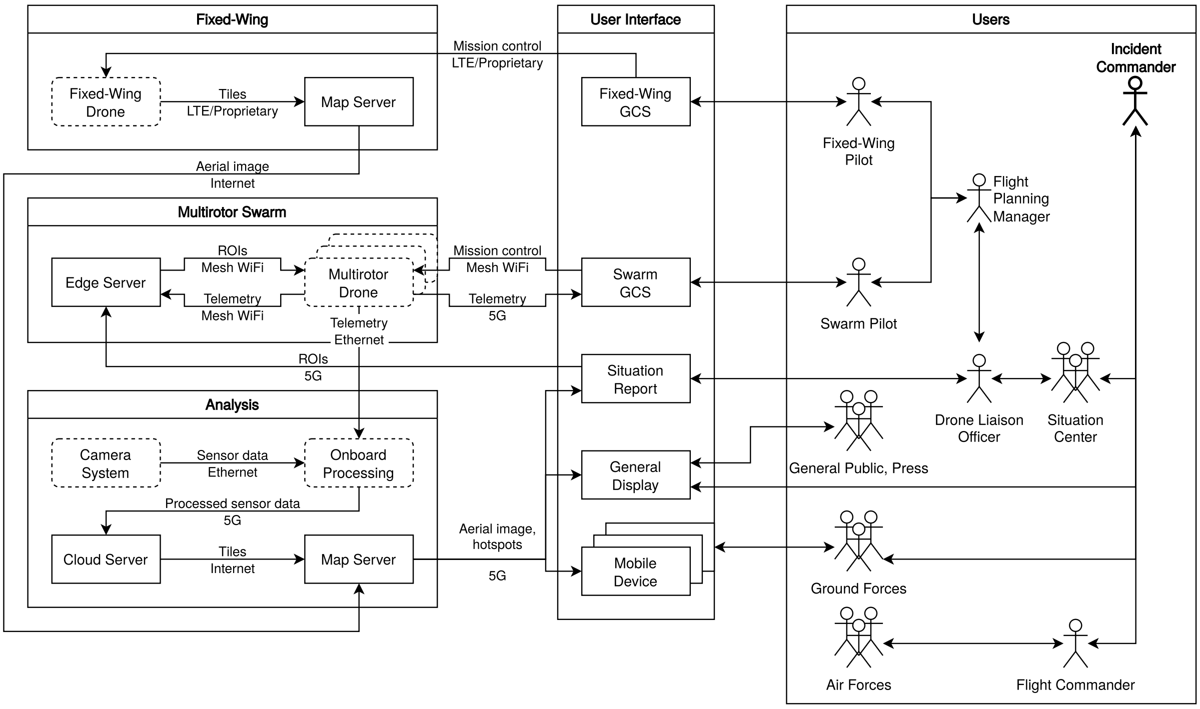


Figure 3. System Architecture with aerial components marked by dashed lines.

The second sub-system, the multirotor drone swarm, comprises several multirotor drones (twinFOLD KAT, twinFOLD GEO, twinFOLD SCIENCE)[2], an edge server that computationally supports the drone swarm, and a GCS for controlling the drone swarm. The drones are controlled by algorithms running in the Robot Operating System (ROS) on a Raspberry Pi 4 B connected to a Pixhawk flight controller that runs the Ardupilot firmware.

The third sub-system includes the components related to image analysis. Its main task is to locate the hot spots and provide a map server that manages the recorded images and the results of the hot spot detection. Onboard the multirotor drones are the following sensors: an RGB camera (Ximea CMV20000), two thermal infrared cameras (custom built by LEADER Photonics) and a GNSS/INS sensor (SBG Quanta). An NVIDIA JETSON AGV Xavier board is used for controlling the sensors and pre-processing sensor data onboard the drones. A custom built trigger box ensures that all sensor data (images and pose) is collected synchronously. The setup is shown in Figure 4. The takeoff weight including batteries for a flight time of roughly 15 min is around 14 kg. It should be noted, that the component weights have not been optimized, hence providing significant potential to extend the flight time. For further analyzing the sensor data, a cloud server allows computing intensive post-processing tasks.

The user interaction happens through the UI sub-system. Both fixed-wing drone and multirotor swarm have a GCS to control and monitor the mission. The main mission results are presented through the situation report terminal. It is a web front end that shows base maps, the real-time aerial image collected by the fixed-wing drone, the locations and state of hot spots and the location of fire fighters' ground forces and multirotor drones. It can also be used to define and send ROIs to be mapped by the swarm or to send commands to first responders that carry smart phones with a dedicated Android app. Additionally, there can be a non-interactive terminal (general display) to inform the general public about the mission.

The user side reflects the hierarchy of the fire fighter personnel. The main interaction points to the technical system are the pilots (fixed-wing and swarm) which are coordinated by the flight planning manager. He interacts with the drone liason officer who gets his information from the situation report terminal and gives instructions for the drone missions.

Communication

The system components are interconnected using different technologies. Communication between the fixed-wing drone and the GCS may use different technologies (Fanta-Jende et al., 2023). In most situations, 5G/LTE mobile networks provide sufficient bandwidth and a stable connection for transmitting the payload data to the GCS. For

---

[2] https://www.twins.co.at/en/multirotorsystems/

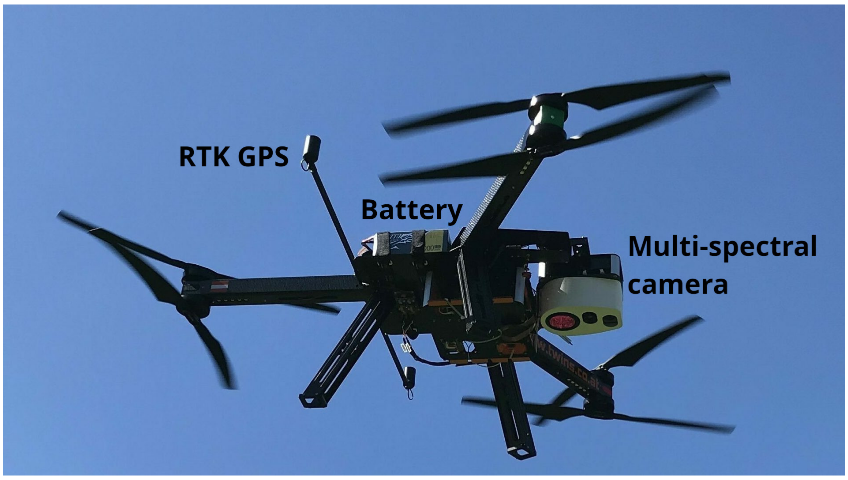


Figure 4. Multirotor drone setup (the processing boards are underneath the drone).

this purpose the drone and GCS are equipped with LTE routers (Teltonika RUT240 on the drone and RUTX11 on the GCS). Alternatively, a WiFi 802.11n network using a tracking antenna or a proprietary data link may be used. This alternative is important, as there may be a lack of mobile network coverage in the area of operation. Communication is used to control the mission from the GCS and transmit the recorded images to the map server on the ground. Coordination with the multirotor swarm is not needed at this stage since the fixed-wing drone mission is separated in time from the multirotor swarm mission.

The multirotor swarm uses a combination of WiFi mesh and LTE/5G mobile networks. Communication and coordination within the swarm is based on WiFi mesh to increase robustness in the absence of infrastructure. The mobile network is used to transmit payload data to the cloud server for processing and returning the result to the ground stations, and for receiving the ROIs to be searched.

Algorithms

The drones are programmed and controlled using ROS version 1[3]. Many of the software components are available as open source and links are given in the following.

A typical mission begins by fire fighters defining the mission area. The fixed-wing pilot enters it into the GCS which is a custom implementation connected to a locally running ROS master. When the fixed-wing pilot starts the mission, the drone autonomously surveys the mission area using its onboard camera to create an aerial image. It records images and performs visual simultaneous localization and mapping (SLAM) to localize itself while creating the aerial image. Being connected to the ROS master on the GCS, it transmits individual tiles of this aerial image to a map server located on the ground allowing the GCS to continuously update the visualization of the aerial image in real-time. This includes the steps of densification and stereo reconstruction[4], surface generation, semantic labeling[5], orthorectification[6], tiling[7][8], and object detection[9] (Fanta-Jende et al., 2023). Once the aerial image is complete, the fire fighters can define ROIs that should be covered in greater detail.

In the multirotor swarm, each drone, the edge server, and the swarm GCS run individual ROS instances that use the CPSwarm libraries[10]. They are connected using the swarmio bridge[11] (Sende et al., 2021) that forwards selected topics using the the ZeroMQ Message Transfer Protocol (ZMTP) over a (wireless) network. This increases the robustness of the system in unreliable networks. Hierarchical finite state machines (FSMs)[12] are used to model and implement complex behaviors controlling the drone from the onboard computer (Sende et al., 2021). The ROIs are received by the edge server that automatically assigns them to the available drones following a first-come,

---

[3] https://www.ros.org/
[4] Plane sweep library based on CUDA: https://developer.nvidia.com/cuda-downloads
[5] Open neural network exchange: https://github.com/onnx/onnx
[6] OpenREALM: https://github.com/laxnpander/OpenREALM
[7] Tiled map service: https://wiki.osgeo.org/wiki/Tile_Map_Service_Specification
[8] MapTiler: https://epsg.io/3857
[9] YOLOv5: https://github.com/ultralytics/yolov5
[10] https://github.com/cpswarm
[11] https://github.com/cpswarm/swarmio/
[12] FlexBE: https://github.com/FlexBE/

first-served policy. As soon as a drone receives an ROI it computes a coverage path following a Bustrophedon back and forth pattern to search the given ROI[13]. The spacing between the different legs of this path is computed considering the characteristics of the camera system, i.e., field of view and altitude above ground. The swarm pilot uses the GCS to monitor the state of the drones and control the mission. He issues commands to start or stop the mission. For safety reasons, the drones wait for the mission start command before taking off.

After take off, a drone moves to the assigned ROI, activates the sensors and begins to autonomously search the ROI. Controlled by the onboard processor, the drone jointly captures thermal infrared and visual images and synchronizes them with its current pose.

The thermal images are analyzed on board and hot spots are detected if the temperature difference to the surroundings passes a given threshold. There can be an upper as well as a lower threshold. Hot spot detection using deep-learning neural networks or other AI approaches were dismissed due to the unavailability of suitable training data sets. The results are very small text-based data samples. Enriched with additional information such as temperature, size, and shape, they are sent to the cloud server for post-processing. The cloud server performs the more computationally expensive tasks of referencing the hot spots spatially and grouping neighboring detections using a morphological opening operator that also cleans up the data to smooth the detected polygons. The hot spots are labeled and linked with the meta data. Over the course of a mission, information about a hot spot is received multiple times in different image frames. This time series information is used for a scene analysis to improve and update the detection results.

The visual image data cannot be processed on board due to limited computing hardware and is instead transmitted to the cloud server for processing. For saving bandwidth, it is compressed losslessly on board the drone using the JPEG 2000 standard to guarantee that the transport does not influence the processing result. The cloud server generates a sharpened, orthorectified aerial image, both visual and thermal, containing the hot spots and their state (e.g., detected, assigned, extinguished). The result is stored on the map server which provides it to the user interface for further processing by the fire fighters.

While we also process the visual images on the cloud server for detection of humans and objects with YOLO deep-learning algorithms, it is not further described in this paper because it is out of its scope.

When a drone finishes the search, it returns, marks the ROI as completed and waits to be assigned to another ROI.

PROOF OF CONCEPT

To demonstrate the functionality of the proposed system, we performed a common exercise with the fire fighters in a closed stone quarry with an area of approximately 10 ha. The focus of the demonstration lies on the drone swarm component of the system which provides the main novelty and carries the greatest challenge. Besides showcasing the system capabilities to the main user group, the reason for the joined demonstration exercise was to test its usability during wildfire fighting missions. We assume the mission area to be a sub-part of the overall incident region surveyed by the fixed-wing drone. Compared to the fixed-wing drone, the multirotor drones cover a smaller area in greater detail. This helps firefighters deployed in the field to capture their direct surrounding at high detail without exposing them to the strain and risk involved in traditional, foot-based reconnaissance. While single-drone systems are already used for wildfire fighting, they are very personnel demanding (for each drone the fire fighters currently require one pilot and one person for mission planning and image observation). Our demonstration showed that a single operator can control four drones simultaneously by simply providing ROIs. Once the ROIs have been sent, the drones operate autonomously, executing their tasks without further human intervention. Due to resource limitations only four drones have been utilized for the demonstration. However, it is fair to assume that this number can be scaled up, as we performed mixed-reality experiments with simulated and physical drones to evaluate the coordination algorithm using up to 16 drones.

For this demonstration, the fire fighters created several hot spots of different types (burning wood or charcoal) shown in Figure 5a. For safety reasons the hot spots were deployed on rocky ground and not within forests. If hot spots provided a lower temperature footprint due to tree or bush cover, the detection threshold could be adapted accordingly.

Following the mission approval by the incident commander, the drone liaison officer defined four ROIs within the mission area using the situation report terminal, see Figure 5b. They cover a region of roughly 2 ha and are located at a distance up to 370 m from the command center. The ROIs were automatically transferred to the edge server and assigned to the four multirotor drones shown in Figure 5c. Once commanded from the flight planning manager, the swarm pilot started the mission using the swarm GCS. The drones computed flight paths as shown in Figure 5e to autonomously search the assigned ROIs. The drones then autonomously took off (Figure 5d) to altitudes between

---

[13] https://github.com/cpswarm/swarm_functions/tree/noetic-devel/coverage_path

30 m and 60 m and started moving to their designated ROI while autonomously avoiding collisions with other drones. Flying at a speed of 3 m/s and having a 30° camera field of view, they could cover an area of approximately $72\,\mathrm{m}^2/\mathrm{s}$ while detecting all different types of hot spots. The low flying speed was selected for safety considerations, such as accommodating communication delays or outages that negatively impact collision avoidance. However, there is potential to increase the speed, particularly during ROI approach. During flight, the status of all drones could be monitored through the situation report terminal (blue symbols in Figures 5b and 5f) as well as the swarm GCS (red arrow in Figure 5e). The detected hot spots were visualized in the situation report terminal (warning triangle in Figure 5f) and reported to the incident commander. He then assigned them to individual fire fighters using a smart phone app shown in Figure 5g. The fire fighters moved to the location, confirmed (Figures 5h and 5i) and extinguished the hot spots (Figure 5j).

Based on the results of the initial survey and discussions with experts (see the technology assessment section), a second questionnaire was developed. The focus was on social science inquiries as well as the potential benefits of future market-ready systems based on the swarm technology.

The experts identified several advantages of the system. Most experts consider the demonstrated system highly useful because it is anticipated to enable faster detection of hot spots, particularly through its autonomous operation. A (partially) autonomous swarm of drones will fundamentally expand the capabilities of the first responders by providing a larger and more valuable set of real-time mission data. This enables more precise planning of operations, more efficient firefighting procedures, and enhanced protection for emergency personnel, third parties, nature and wildlife. Two advantages have been named: 1) it accelerates the firefighting efforts, as a larger area can be searched in less time and 2) it reduces the need for manpower, as a single pilot can control multiple drones at once. In this sense, the system has been seen as an extension (not a replacement) of first responder personnel, which can be assigned with different tasks. The coordinated mission execution and the precision with which hot spots were detected are seen as an impressive demonstration of the system's strengths. Standard systems transmit images and videos, which lack the support for orientation. The presented system directly determines GPS positions of events (i.e., hot spots on the images are geo-referenced) and can lead emergency personnel straight to the point of interest.

Several disadvantages were identified. A significant risk is the potential for damage to third parties or objects due to faulty behavior. The greatest danger remains an uncontrolled crash, which can cause harm to people and materials. The lack of a legal framework for the deployment of a drone swarm is another weakness, mentioned by the first responders. Drones are already a substantial aid to all emergency services in dangerous and time-critical operations. However, the legislation and product maturity are seen as big challenges to be overcome. For efficient operation, comprehensive training of the emergency personnel is necessary. There is also a risk in a lack of acceptance of such systems by the emergency personnel themselves and in terms of public acceptance (e.g. privacy concerns).

CONCLUSION

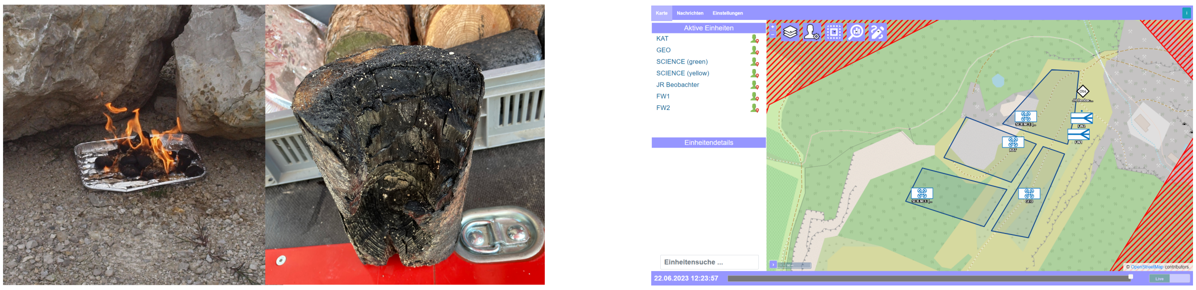
In this paper we present a heterogeneous multi-drone system to support fire fighters with post-wildfire hot spot detection. According to a survey among domain experts, hot spot detection is a suitable application for such a system. They see the advantages in reduced mission time and increased situational awareness; the main disadvantage in its complexity. The system is still in an experimental phase and not yet ready to be deployed as a product. The system could be demonstrated in a controlled environment, with operation mainly performed by the research team, indicating a technology readiness level (TRL) of 4. It falls short in usability, reliability and security, which are critical aspects for effective oepration in actual fire fighting missions. Despite these limitations, we were able to demonstrate the system's capability to autonomously search for, successfully detect, and report hot spots in given ROIs. This outcome is encouraging and suggests potential for significant improvements in firefighting missions, particularly in addressing the increasingly pressing issue of forest fires.

ACKNOWLEDGMENTS

We would like to thank the volunteer fire fighter brigade Gumpoldskirchen, Austria for their support and IFR Ing. Richard Feischl for the task settings and the tactical and operational coordination.

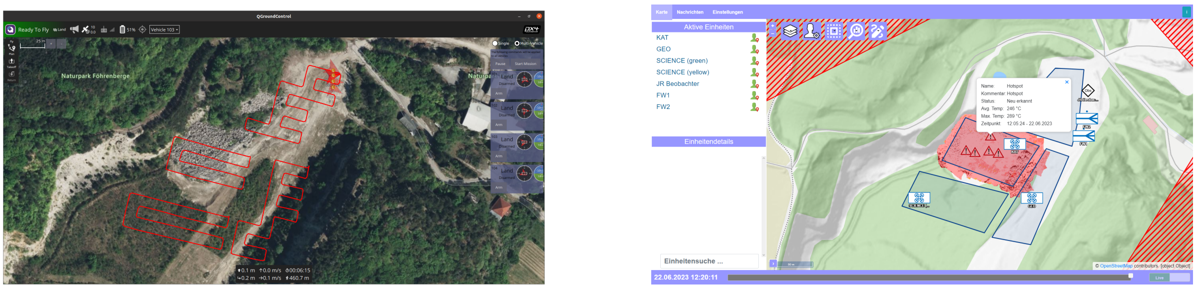
This work received funding by the security research program KIRAS of the Austrian Federal Ministry of Finance (BMF) under grant agreement no. 879682 (UASwarm).

During the development of the communication system and the coordination and control algorithms, we used infrastructure provided by the 5G Playground Carinthia, which is funded by the Carinthian Agency for Investment Promotion and Public Shareholding (BABEG). The 5G Playground is operated by BABEG and financed by means of the Austrian Federal Ministry for Climate Action, Environment, Energy, Mobility, Innovation and Technology (BMK) and the government of the Carinthian provincial.

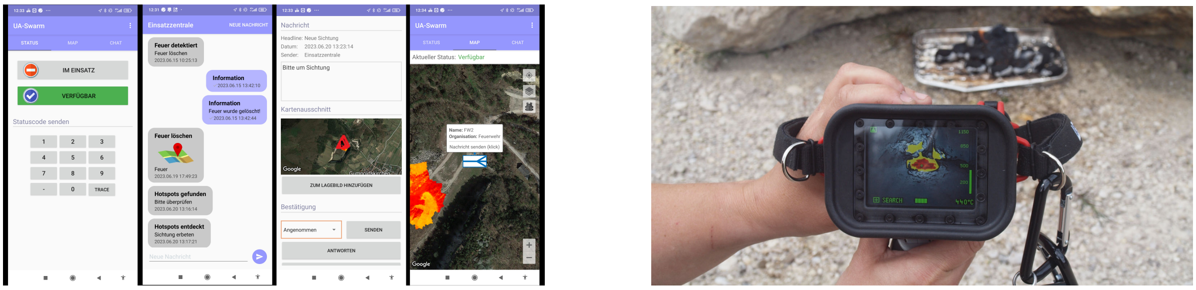


(a) Two different hot spots: Charcoal and wood. (b) ROI definition.

(c) Multirotor drones before takeoff. (d) Flying multirotor drones.



(e) Search path of the multirotor drones. (f) Detected hot spots.



(g) Assigned hot spot on the mobile device. (h) Hot spot confirmed with thermal camera.

(i) Hot spot confirmed with thermal camera. (j) Hot spot being extinguished.

Figure 5. Photos and screenshots from demonstration exercise.

REFERENCES

Arnold, R., Jablonski, J., Abruzzo, B., & Mezzacappa, E. (2020). Heterogeneous UAV Multi-Role Swarming Behaviors for Search and Rescue. *Proceedings of the Conference on Cognitive and Computational Aspects of Situation Management (CogSIMA)*, 122–128. https://doi.org/10.1109/CogSIMA49017.2020.9215994

Dominguez, M. H., Nesmachnow, S., & Hernández-Vega, J.-I. (2017). Planning a Drone Fleet using Artificial Intelligence for Search and Rescue Missions. *Proceedings of the International Conference on Electronics, Electrical Engineering and Computing (INTERCON)*. https://doi.org/10.1109/INTERCON.2017.8079646

Dong, J., Ota, K., & Dong, M. (2021). UAV-Based Real-Time Survivor Detection System in Post-Disaster Search and Rescue Operations. *IEEE Journal on Miniaturization for Air and Space Systems*, *2*(4), 209–219. https://doi.org/10.1109/JMASS.2021.3083659

Fakhreddine, A., Raffelsberger, C., Sende, M., & Bettstetter, C. (2022). Experiments on Drone-to-Drone Communication with Wi-Fi, LTE-A, and 5G. *Proceedings of the Globecom Workshops (GC Wkshps)*, 904–909. https://doi.org/10.1109/GCWkshps56602.2022.10008743

Fanta-Jende, P., Steininger, D., Kern, A., Widhalm, V., Apud Baca, J. G., Hofstätter, M., Simon, J., Bruckmüller, F., & Sulzbachner, C. (2023). Semantic Real-Time Mapping with UAVs. *PFG – Journal of Photogrammetry, Remote Sensing and Geoinformation Science*, *91*, 157–170. https://doi.org/10.1007/s41064-023-00242-2

Guo, F., Wei, M., Ye, M., Li, J., Mechali, O., & Cao, Y. (2019). An Unmanned Aerial Vehicles Collaborative Searching and Tracking Scheme in Three-Dimension Space. *Proceedings of the Annual International Conference on CYBER Technology in Automation, Control, and Intelligent Systems (CYBER)*, 1262–1266. https://doi.org/10.1109/CYBER46603.2019.9066685

Hayat, S., Yanmaz, E., & Bettstetter, C. (2015). Experimental Analysis of Multipoint-to-Point UAV Communications with IEEE 802.11n and 802.11ac. *Proceedings of the Annual International Symposium on Personal, Indoor, and Mobile Radio Communications (PIMRC)*, 1991–1996. https://doi.org/10.1109/PIMRC.2015.7343625

International Federation of Red Cross and Red Crescent Societies. (2022). *World Disasters Report – Trends in Disasters*. Retrieved February 23, 2024, from https://web.archive.org/web/20240223104446/https://www.ifrc.org/sites/default/files/2023-01/20230130_2022_WDR_DataAnnex.pdf

Joint Research Centre. (2023). *The EU 2022 Wildfire Season was the Second Worst on Record*. Retrieved February 23, 2024, from https://web.archive.org/web/20240223104923/https://joint-research-centre.ec.europa.eu/jrc-news-and-updates/eu-2022-wildfire-season-was-second-worst-record-2023-05-02_en

Lauterbach, H., Koch, C. B., Hess, R., Eck, D., Schilling, K., & Nuchter, A. (2019). The Eins3D Project — Instantaneous UAV-Based 3D Mapping for Search and Rescue Applications. *Proceedings of the International Symposium on Safety, Security, and Rescue Robotics (SSRR)*. https://doi.org/10.1109/SSRR.2019.8848972

Lei, L., Tang, A., & Wang, X. (2022). Analysis on the Scalability Issues of Wireless Mesh Networks: Key Factors and Potential Solutions. *Proceedings of the International Conference on Mobile Ad Hoc and Smart Systems (MASS)*, 586–591. https://doi.org/10.1109/MASS56207.2022.00087

Luo, J., Zhao, P., Zheng, F.-C., & Li, L. (2022). Delay Evaluation for Cellular-Connected Drones: Experiments and Analysis. *Proceedings of the Vehicular Technology Conference (VTC-Fall)*. https://doi.org/10.1109/VTC2022-Fall57202.2022.10012989

Mbaitiga, Z., & Shosaku, T. (2022). Assessment of Multi-Drones using City Information for Search and Rescue Operations. *Proceedings of the International Conference on Intelligent Informatics and Biomedical Science (ICIIBMS)*, 379–381. https://doi.org/10.1109/ICIIBMS55689.2022.9971612

Pasini, D., Jiang, C., & Jolly, M.-P. (2022). UAV and UGV Autonomous Cooperation for Wildfire Hotspot Surveillance. *Proceedings of the MIT Undergraduate Research Technology Conference (URTC)*. https://doi.org/10.1109/URTC56832.2022.10002208

Quan, A., Herrmann, C., & Soliman, H. (2019). Project Vulture: A Prototype for Using Drones in Search and Rescue Operations. *Proceedings of the International Conference on Distributed Computing in Sensor Systems (DCOSS)*, 619–624. https://doi.org/10.1109/DCOSS.2019.00113

Scherer, J., Yahyanejad, S., Hayat, S., Yanmaz, E., Andre, T., Khan, A., Vukadinovic, V., Bettstetter, C., Hellwagner, H., & Rinner, B. (2015). An Autonomous Multi-UAV System for Search and Rescue. *Proceedings of the First Workshop on Micro Aerial Vehicle Networks, Systems, and Applications for Civilian Use (DroNet)*, 33–38. https://doi.org/10.1145/2750675.2750683

Schilling, F., Soria, E., & Floreano, D. (2022). On the Scalability of Vision-Based Drone Swarms in the Presence of Occlusions. *IEEE Access*, *10*, 28133–28146. https://doi.org/10.1109/ACCESS.2022.3158758

Seiber, C., Nowlin, D., Landowski, B., & Tolentino, M. E. (2018). Tracking Hazardous Aerial Plumes using IoT-Enabled Drone Swarms. *Proceedings of the World Forum on Internet of Things (WF-IoT)*, 377–382. https://doi.org/10.1109/WF-IoT.2018.8355118

Sende, M., Schranz, M., Prato, G., Brosse, E., Morando, O., & Umlauft, M. (2021). Engineering Swarms of Cyber-Physical Systems with the CPSwarm Workbench. *Journal of Intelligent & Robotic Systems*, *102*(83). https://doi.org/10.1007/s10846-021-01430-1

Steinhäusler, F., & Georgiou, H. V. (2022). Detection of Victims with UAVs during Wide Area Search and Rescue Operations. *Proceedings of the International Symposium on Safety, Security, and Rescue Robotics (SSRR)*, 14–19. https://doi.org/10.1109/SSRR56537.2022.10018756

Terzi, M., Anastasiou, A., Kolios, P., Panayiotou, C., & Theocharides, T. (2019). SWIFTERS: A Multi-UAV Platform for Disaster Management. *Proceedings of the International Conference on Information and Communication Technologies for Disaster Management (ICT-DM)*. https://doi.org/10.1109/ict-dm47966.2019.9032923

Tinetti, F. G., & Riveros, O. C. V. (2021). Combining Technologies for Aiding Search Missions with Drones. *Proceedings of the International Conference on Computational Science and Computational Intelligence (CSCI)*, 1617–1622. https://doi.org/10.1109/CSCI54926.2021.00013

United Nations Environment Programme. (2022). *Spreading like Wildfire: The Rising Threat of Extraordinary Landscape Fires*. Retrieved February 23, 2024, from https://web.archive.org/web/20240223105515/https://www.unep.org/resources/report/spreading-wildfire-rising-threat-extraordinary-landscape-fires

Viseras, A., Marchal, J., Schaab, M., Pages, J., & Estivill, L. (2019). Wildfire Monitoring and Hotspots Detection with Aerial Robots: Measurement Campaign and First Results. *Proceedings of the International Symposium on Safety, Security, and Rescue Robotics (SSRR)*, 102–103. https://doi.org/10.1109/SSRR.2019.8848961