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Use of unmanned vehicles in search and rescue operations in forest fires: Advantages and limitations observed in a field trial

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ABSTRACT

Search and Rescue (SaR) in forest fires is usually applied in a broad area, under foggy or smoky conditions. It mostly involves location of entrapped fire crew or people in between fire fronts, as well as, safely removing them away from the dangerous zone. Moreover, SaR is applied in evacuation of rural residential areas due to heavy smoke impacts, or fire front approaching. Experiences achieved during a field trial, in which unmanned aerial and ground vehicles were deployed and used in a simulated forest fire SaR scenario, are presented. For planning and running the field trial a number of parameters were taken into consideration; logistics, safety plan, contingency plan, different agencies cooperation, time frames and ethical issues. Advantages of using unmanned aerial and ground vehicles in SaR operations include capability of planning and monitoring the operations, integration with the manned resources, connectivity with command and control centers, as well as, coordination of the different unmanned aerial and ground vehicles' platforms. Significant increase of personnel safety is possible through the capabilities of air quality monitoring and search over dangerous areas. Current limitations include limited heat resistance of vehicles and limited flying capability in strong winds and turbulence. Failure of communications is also possible due to rough terrain (autonomy limitations). Against all the limitations, a number of unmanned vehicles already exist that can be adapted successfully for SaR operations in forest fires.

1. Introduction

Search and Rescue (SaR) can be applied in different terrains: ground, sea, mountain and urban areas. It can also be practiced in different environments (e.g. forests, rural residential areas, extreme weather conditions). In all SaR operations time is the most critical parameter; the first hours have the highest possibility for survival [1]. However, SaR operations have different characteristics depending on terrain and environment. For example, urban Search and Rescue (USaR) involves victim localization indoors, i.e. under the debris of a collapsed building and extrication. SaR in forest fires on the other hand, is usually applied in a broad area, under foggy or smoky conditions; it mostly involves location of entrapped fire crew or people in between fire fronts and safely removing them away from the dangerous zone. This type of accidents has been described in literature [2]. SaR is also applied in evacuation of rural residential areas, due to heavy smoke impacts or fire front approaching. SaR operations are characterized by procedures and regulations. Maritime SaR for example is regulated (IMO) [3]. Also, a number of standards are provided by INSARAG for USaR operations [4]. However, it seems that SaR in forest fires is not strongly regulated, despite the fact that recommendations and guidelines provided by various relevant organizations, exist. Recently, guidelines for the defense of rural populations, local communities and municipality leaders have been prepared in the framework of the Council of Europe, Network of Specialized Euro-Mediterranean Centers [5]. The response to a SaR incident usually proceeds through a sequence of five stages; awareness, initial stage, planning, dispatching/SaR, reporting/debriefing.

The present work aims at presenting different issues related to forest fire SaR stages, based on the lessons learnt from a recent research project (FP7 security project DARIUS) that focused on SaR operations using manned and unmanned resources [6]. More

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Table 1
Recent research projects and their contribution in regard to unmanned vehicles, SaR operations and crisis management.

Title of project	Type of project	Contribution to unmanned vehicles/SaR operations/crisis management
DARIUS (Deployable SAR Integrated Chain with Unmanned Systems)	FP7-SEC-2011	DARIUS project aimed at providing unmanned platforms for Search and Rescue operations (maritime, urban, forest fire scenario), as well as at enhancing the interoperability performances of unmanned systems at procedural and technical levels.
CRISMA (Modeling crisis management for improved action and preparedness)	FP7-SEC-2011	CRISMA Integration Project focused on large scale crisis scenarios with immediate and extended human, societal, structural and economic, often irreversible, consequences and impacts. Typically, these crisis scenarios cannot be managed alone with regular emergency and first responder resources, but require multi-organizational and multi-national cooperation including humanitarian aid.
AIRBEAM (AIRborne information for Emergency situation Awareness and Monitoring)	FP7-SEC-2010	The major AIRBEAM objective was to propose a situation awareness toolbox for the management of crisis over wide area taking benefit of an optimized set of aerial (unmanned) platforms, including satellites.
AIROBOTS (Innovative aerial service robots for remote inspections by contact)	FP7-ICT-2009	The main objective of the AIRobots platform design process is to develop aerial prototypes which meet basic engineering principles in terms of expandability and flexibility.
OPARUS (Open Architecture for UAV-based Surveillance System)	FP7-SEC-2009	The goal of this project was to elaborate an open architecture for the operation of unmanned air-to-ground wide area land and sea border surveillance platforms in Europe.
CLOSE-SEARCH (Accurate and safe EGNOS-SoL Navigation for UAV-based low-cost SAR operations)	FP7-Galileo-2008	The goal of CLOSE-SEARCH was to integrate in a small Unmanned Aircraft (UA), a thermal imaging sensor and a multi-sensor BA/RINS/GPS-EGNOS-based navigation system with an Autonomous Integrity Monitoring (AIM) capability, to support the search component of search-and-rescue (SAR) operations in remote, difficult-to-access areas and/or in time critical situations.
DITSEF (Digital & innovative technologies for security & efficiency of first responder operations)	FP7-ICT-SEC-2007	DITSEF aimed at increasing the effectiveness and safety of First Responders by optimal information gathering and sharing with their command levels.

specifically, this work will present experiences achieved during a field trial in which unmanned vehicles were deployed and used in a simulated forest fire scenario, where both location and rescue of entrapped personnel, as well as, evacuation of rural residential area took place. In this paper, possible risks from forest fires are also highlighted; especially, smoke impacts when the fire front expands to rural residential areas and/or possible threats in case the forest fire front reaches territories contaminated with chemicals [7], or unexploded ordnance areas [8]. In this framework, advantages and current limitations of using unmanned aerial and ground vehicles in Search and Rescue operations during forest fires are examined.

2. Risks when forest fire front expands

In recent years, huge forest areas have been destroyed by large-scale forest fires; over 1,400,000 ha in total have been burnt in five Southern Member States in the last five years [9]. Severe forest fires can cause a number of environmental, health, security and safety impacts [10,11]. First priority is suppression and control of the fire, even though severe SaR incidents may occur. Usually, SaR operations are applied when firemen or people are trapped in between fire fronts, or when areas may need to be evacuated from residents. In most countries, emergency operating protocols were evolved over the years to meet the specific demands of such incidents. However, most of these do not provide consistent procedures and hence, a number of problems might be encountered; limited control, difficulties in the communication flow among agencies, safety risks for SaR personnel. The last is more significant especially when there is no sufficient prior training of personnel or protection equipment. Additionally, incompatible communication systems and in general lack of interoperability, may complicate situations. In these cases there is a need to survey large areas, which are very difficult to be approached by manned resources. There are particular risks when the forest fire front expands outside the forest to different nearby areas, such as rural fields, rural–urban interface, illegal waste or landfills; plastics, fertilizers, pesticides, and fungicides, wastes can also be burned together with the forest fuel and hence, the resulted smoke may have additive or synergistic toxicity impacts [7]. Forest fire smoke has significant impacts, such as visibility impairment and health effects on the exposed population and the fire fighters [12–14]. It is a chemical mixture consisting of substances that can cause acute, short-term and long-term health implications. More specifically, a number of respiratory irritants, such as aldehydes (e.g. acroleine), asphyxiants (e.g. carbon monoxide) and carcinogens (e.g. benzene, benzo (a)pyrene) are some of forest fire smoke components. Particles also contained in forest fire smoke are hazardous, especially the fine ones, such as nanoparticles (with diameter less than 100 nm) and respirable particles (with diameter between 0.1 and 10 μm). It has to be noted that smoke inhalation can be more aggressive especially for vulnerable groups of population, such as infants, children, pregnant women, the elderly and people with health problems [11,15]. Data regarding health impacts of population and hospital admissions, correlated with large scale forest fires can be found as a case study in literature [16].

3. Unmanned vehicles in SaR operations

Using unmanned vehicles in SaR operations combined with manned resources is currently an option. It can be applied in complicated situations, where fast response and protection of personnel from possible risks is necessary. A number of representative research projects relevant to unmanned vehicles, SaR operations and crisis management that have been implemented the last years, are shown in Table 1 [6,17–22].

There are also cases in which real field deployments of robots have been recorded in order to improve disaster preparedness, prevention, response and recovery (CRASAR) [23]. Focusing on SaR cases in large scale forest fires, unmanned vehicles can have a number of missions [24]; fire detection by locating fire spots, fire front surveillance and monitoring. The support of SaR operations is also possible. In addition, potential missions include location of entrapped crew or people, supporting of the evacuation process of an area, providing with first aid kits to victims, monitoring air quality and detecting toxic compounds.

In the following paragraphs, a brief presentation of different types of unmanned vehicles is given, focusing on Unmanned Aerial Vehicles (UAVs) and Unmanned Ground Vehicles (UGVs), which are mainly of interest in case of forest fires.

Moreover, currently available payloads for unmanned platforms that can be used in SaR operations during a forest fire are presented and described, focusing on sensors.

3.1. UAVs

UAVs have been recently used in a number of research projects, as shown in Table 1, for coping with disasters. Platforms could be categorized according to a number of different criteria. According to the OPARUS project [20], the different categories are formed according to their Maximum Take-Off Mass (MTOW), the range of action, endurance, altitude and maximum payload mass; Lighter Than Air (LTA: aerostats, airships, hybrid airships), Vertical Take-Off and Landing (VTOL) or Rotary Wing (RW), Fixed Wing (FW), MALE (Mean Altitude Long Endurance UAV), the multirotors (e.g. quad-rotors), HALE (High Altitude Long Endurance UAVs) [25].

In forest fires, UAVs missions could include surveillance, location, air quality monitoring, dispatching of first aid kits, supporting evacuation of residential areas, guiding personnel to safe zone.

3.2. UGVs

UGVs have been used for years in real SaR operations; a characteristic application was that of 11/09/2001 [23]. Out of this experience a number of proposals has been made [26]; UGVs should have among other rapid deployment, capability to use camera that automatically zoom in, capability to manage with various types of surfaces, to be waterproofed, and also capability to operate around and over different shapes and sizes of rubbles.

UGVs can be assigned different missions in forest fires; mapping, reconnaissance, damage inspection, acting as a repeater for transmissions. In addition, they can be used for medical assessment of victims, as equipment and first aid kits transporters. One important thing is that they can operate in harsh environments, and hence can be used for the detection and identification of hazardous compounds, as well as for air quality assessment and smoke monitoring.

3.3. Payloads for unmanned vehicles used in forest fires

The recent years, a number of different payloads have been developed for unmanned systems in the scope of copying with disasters; earthquakes, explosions, forest fires, etc. Based on the operational needs of each mission, these payloads may include sensors, communications or medical aid. It should be emphasized that a number of invaluable data can be provided to commanders through payloads of unmanned vehicles, so that to increase situational awareness at different levels and support operational management. In this work, a special attention is given to sensors, as payloads engaged with unmanned aerial and ground vehicles.

In brief, sensors may include electromagnetic spectrum sensors, such as visual, infrared, or near infrared cameras, as well as, radar systems. Additionally chemical sensors can also be used for monitoring chemical compounds that are hazardous for human health or the environment. Other sensors may also include mobile phones detector, as well as location, or environmental sensors. A list of sensors that may be used as payloads for unmanned vehicles engaged in forest fire SaR operations, is presented in Table 2, together with basic principles of operation and possible applications.

It must be noticed that use of chemical sensors seems to be quite important for the safety of personnel in forest fires. They can alert inside the harsh environment of forest fire smoke and can also provide with air quality monitoring, facilitating decision making (evacuation of an area or not). Chemical sensors that can be used as payloads of unmanned systems in forest fires can monitor air quality; smoke components such as permanent gases, volatile organic compounds (VOCs), semi-volatile organic compounds (SVOCs), and particles [11,27]. Electrochemical sensors are usually used for measuring permanent gases, such as carbon monoxide (CO), while spectroscopic chemical sensors are mainly

Table 2
Sensors used as payloads for unmanned vehicles in forest fire SaR operations – Principles and possible applications.

Sensor	Principles/Applications
Visible camera	Device that forms an image using visible light Video (motion, still); forest fire front expansion; identification of new fire spots; damage of infrastructures; weather assessment; location of people entrapped in fire or smoke; evacuation progress of an area
Infrared camera	Device that forms an image using infrared radiation (also called thermal camera) Video (motion, still); detecting people and animals at night; detecting lost people in foliage, thick fog or smoke; location of fire spots in smoldering fires
Radar	Device that measures the reflection of electromagnetic waves if they meet an obstacle in the propagation direction. Types of radars are Synthetic Aperture, Real Aperture, Moving Target Indicator, Laser Detecting people in vegetation under all weather conditions; detecting animals in motion under trees and foliage
Chemical sensors	Devices that transform chemical information originated from a chemical reaction of the analyte, or from a physical property of the system investigated, into an analytically useful signal Detection of toxic chemical compounds; smoke detection; air quality monitoring
Mobile phones detector	Device that locates transmission sources Detection of mobile phones signal, carried by trapped people beyond fire smoke
Light Detection and Ranging (LIDAR)	Device that measures the reflection of a laser pulse that meets a target Detection of clouds of emissions; see through the fire smoke
Location sensors	GPS for providing coordinates and mapping
Environmental sensors	Devices that provide meteorological data such as P, T, RH%, wind speed and direction

used for measuring CO_2 and VOCs, such as benzene [28,29].

4. Unmanned vehicles used at SaR operations in forest fires: a field operational scenario

In a recent project (FP7 Security project DARIUS) [6], the use of unmanned systems for copying with disasters, such as forest fires has been tested and evaluated, focusing on Search and Rescue operations (SaR). More specifically, a number of heterogeneous unmanned platforms were tested mainly regarding their capability to communicate and share recorded information and data, such as images, videos, chemical data, among different interested parties or organizations, and at different command levels (strategic, tactical, operational).

In that framework, a field operational scenario has been prepared for realistic simulation of forest fire and smoke crisis situation and is presented in this work. In addition, a number of lessons learnt relevant to organizational and safety issues recorded are described in the following paragraphs.

4.1. The forest fire operational scenario

A forest fire operational scenario has been prepared, based on the four phases of a typical forest fire; *pre-ignition, flaming, smoldering, and glowing phases*. In brief, during *pre-ignition* phase, heat from an ignition source or the flaming front evaporates water and the low molecular weight volatiles from the fuel, and the process of pyrolysis begins. During *flaming* phase, combustion of the pyrolysis products (gases and vapors) with air takes place. The heat from the flaming reaction speeds the rate of pyrolysis and produces greater quantities of combustible gases, which also oxidize, causing increased flaming. The *smouldering* phase is a very smoky process occurring after the active flaming front has passed. Combustible gases are still produced by the process of pyrolysis, but the rate of release and the temperatures are not high enough to maintain flaming combustion. Smoldering generally occurs in fuel beds with fine packed fuels and limited oxygen flow. In *glowing* phase, most of the volatile gases have been burned, and oxygen comes into direct contact with the surface of the charred fuel. As the fuel oxidizes, it burns with a characteristic glow, until the temperature is reduced so much that combustion cannot be continued, or until all combustible material is consumed [11].

Taking into consideration the aforementioned phases of the forest fire, the scenario was prepared including five operational stages; (1) early warning surveillance and fire detection (pre-ignition phase of the fire), (2) alert and initial action of forces (flaming phase of the fire at its growth) (3) large scale action planning of forces (flaming phase of the fire at its fully developed stage) (4) SaR operation in the field and area evacuation (smouldering phase of the fire) and (5) monitoring of the area, ending of forces field deployment (glowing phase of the fire).

According to the scenario, cooperation of manned firefighting ground vehicles and unmanned vehicles took place in order to cope with the risks from a devastating forest fire that burst out in a hot zone and expanded towards a territory, contaminated with chemicals or unexploded ordnance (restricted area). Three unmanned aerial vehicles (FW, VTOL and multirotor) were used for surveillance, fire propagation monitoring, mapping new fire spots, situation awareness, as well as for cooperation with two UGVs and the manned ground vehicles for SaR operations. The last included locating entrapped crew or people beyond smoke and guiding them safely to a secure area, away from the hot zone (evacuation). In Fig. 1, a snapshot of the SaR operation that took place in order to locate fire-fighters trapped beyond fire smoke is shown (smouldering phase of the fire).

Fig. 1. Unmanned vehicles used at SaR operations in a forest fire scenario.

We need to emphasize that in order to run the fire scenario in the most controllable way, it was decided to simulate the forest fire by using a specified fuel bed; minimize the risk of possible expansion to nearby areas by accident, as well as the safety risks imposed for the involved personnel. This bed, as shown in Fig. 2, has been constructed to create realistic fire conditions in regard to the different phases of the forest fire, as well as, to achieve sufficient smoke generation, so that to perform the scenario in its five operational stages described above.

A thorough study was carried out prior the field trial to decide on the dimensions of the bed, as well as to consider other parameters; weight, height, packing ratio, slope, moisture content and meteorological conditions (e.g. wind speed, relative humidity), so as to calculate possible fire expansion rate.

More specifically, the bed consisted of vegetation representative of the Mediterranean flora, mainly resulted from shrub clearing and tree branches pruning (e.g. *Pinus halepensis*, *Eucalyptus sp., Phoenix sp.*). The fuel moisture content, based on samples taken in the field and dried in an oven for 48 h at 104 °C, was 11% for the broadleaved species (*Eucalyptus sp.*, *Phoenix sp.*, etc.) and 28% for the pinus halepensis needles, respectively. The dimensions of the bed were chosen to be $15 \times 30\ m^2$ (width × length). The depth varied between 50 and 90 cm with an average of 70 cm. The fire spread for about 20 min, counting from

Fig. 2. Forest fuel bed to create realistic conditions of a forest fire for running a SaR scenario, using unmanned platforms.

the ignition until the flames reached the end of the fuel bed; the blowing wind had an average speed of 15 km/h. The fire was mainly carried by the fuels at the top of the fuel bed and continued burning in the deeper fuels, as smouldering fire, well after the flames, reached the end of the fuel bed, for about an hour.

Generally, it can be stated that burning of the fuel bed created realistic conditions in terms of forest fire different phases. There was sufficient smoke generation and visibility impairment for running the SaR operation and evacuation, according to the scenario. The use of UAVs and UGVs in the scenario, having the missions previously described, reduced personnel risks imposed in a harsh environment of high temperatures and smoke, and provided with the broad picture “behind the hill”, facilitating operational management.

4.2. Organizational and safety issues: the lessons learnt

For planning and running a large scale forest fire operational field scenario, with the participation of manned and unmanned aerial and ground vehicles, a number of organizational and safety issues should be taken into consideration.

Significant role in a successful organization plays the continuous cooperation among all the different parties involved, not only in the preparatory phase but also in the implementation phase, during the field trial; in our case, a number of different authorities, such as the fire brigade, the police, health agencies and the relevant municipality worked together to achieve this goal. A number of permissions were needed to be gathered in due time, provided by the responsible authorities. More specifically, permission for running the trial was initially required and given by the fire brigade headquarters, since vegetation prescribed burning was included in the scenario; complementary support by the local traffic police unit was also offered. Moreover, permissions of flights were required for the UAVs involved; a special notice to airmen (NOTAM) was issued by the Aviation Authority for the selected date and area of the trial, as well as for the specific duration of UAVs flight, for safety reasons. A special permission for running the scenario at the specific field site was also provided by the relevant Public Properties Company. Finally, since a number of volunteers participated in the scenario, special care was given to address any ethical issues in terms of personal data protection. Permission by the Data Protection Authority was given for keeping the personal data file of the participants, in the framework of the particular field exercise; everybody signed a consent form prior the trial, where details of the scenario, including safety issues were thoroughly described.

Another organizational issue to take into account when running such a field trial is the logistics. In our case, logistic sheets for all the involved unmanned platforms were collected. These sheets included useful information, such as details about packaging and transportation of the platforms to the field, based on their dimensions and weight. In addition, necessary consumables in regard to power supply, fuel type and batteries needs of the platforms, were considered. Storage of the platforms, in terms of size and waterproofing of the storage space, was also taken into account. Finally, complementary equipment (peripherals) needed, such as number of tables, chairs were included.

In large scale field exercises special attention is definitely needed in regard to the safety of people involved, as well as the equipment used. In the field trial presented here, an experienced fire safety officer had been assigned to overview the whole operation in regard to hazards and safety concerns. The field has been divided into discriminant zones; a safety perimeter of the field sites, where unmanned aerial and ground vehicles were deployed and moving, was defined. In addition, personal protective equipment was used by all the participants. Fire brigade vehicles and an ambulance were present during the trial.

Moreover, a contingency plan is necessary to record possible risks against the implementation of such an exercise, as well as to prepare the relevant preventive and mitigation measures for coping with them. An indicative example of risks concerning our scenario is accidental injure in the field, or breathing problems encountered due to smoke inhalation during vegetation burning. Other risks also include improper weather conditions for running the scenario, such as heavy rain, strong winds, as well as, unmanned platforms failures while operating, or an uncontrolled fire.

5. Conclusions

Through the experience of the aforementioned trial, a number of advantages when using unmanned aerial and ground vehicles at SaR operations in forest fires can be pointed out. Planning and monitoring of the operation, as well as receiving and exploiting of data recorded by the sensors, are possible. Unmanned vehicles can be integrated with the manned resources having good synergisms. Connectivity of unmanned aerial and ground vehicles with command and control centers is also feasible; unmanned vehicles from different agencies can be coordinated based on compatibility (interoperability) of the platforms.

In addition, different payloads carried by unmanned vehicles can provide with different type of information and data that can be combined to provide situation awareness in a broad area. Finally, significant reduction of risks for SaR personnel can be achieved; air quality monitoring, search over critical or dangerous areas, as well as medical kits dispatching to entrapped victims are possible without any SaR personnel exposed to the respective risks.

On the other hand, the harsh conditions prevailing in forest fires, especially those of large scale, restrict the operational capabilities of unmanned systems; strong winds and turbulence, thick smoke, low visibility and high temperatures (usually in the range of 400–1000 °C) create a hostile environment. Currently, unmanned vehicles are not constructed heat resistant for such temperature range, and micro UAVs (small in size) cannot fly under conditions of strong winds and turbulence. In addition, forest fires usually extend to broad areas including various topologies, such as rough terrain and mountains where communications may fail, and hence, autonomy of unmanned vehicles becomes questionable.

However, a number of unmanned vehicles that already exist can be adapted for operations in forest fires. It seems that Fixed Wing UAVs, capable of flying in moderate winds, can be used effectively in forest fires and especially in SaR operations. Moreover, enhancements of VTOL and multirotor UAVs will allow for better adaption in forest fires operations. UGVs on the other hand, can be used today in such operations, providing data and images, but still there is a need to make them fire proof.

It can be said that against current limitations, using unmanned vehicles in forest fires operations is generally for operational managers' benefit. Successful adaptation of existing unmanned vehicles will greatly push forward the efforts for advancing technology in SaR operations.

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