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Scenario and system concept for a firefighting UAV-UGV team

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***Abstract*—This work presents a scenario and a system concept for an Unmanned Aerial Vehicle (UAV) teamed with an Unmanned Ground Vehicle (UGV) and a base station for firefighting tasks. Based on a detailed scenario description, we investigate tangible design choices regarding relevant hardware and algorithms based on today's technology. We conclude that the implementation of a functional prototype appears feasible.**

***Index Terms*—Unmanned Aerial System; Unmanned Ground Vehicle; cooperation; firefighting; system concept**

I. Introduction

In the evening of 15 April 2019, a fire broke out beneath the roof of the Notre-Dame de Paris cathedral. Due to its sheer height, the firefighters had trouble seeing where their water jets were landing. Drones were launched to obtain a bird's eye view [1] and instructions for aiming the deluge guns where then radioed from the drone pilots to the firefighters. This is one many examples showing the steadily increasing use of Unmanned Aerial Vehicles (UAVs) for public safety applications. At the same time, Unmanned Ground Vehicles (UGVs) for firefighting tasks have also seen significant improvements and more widespread use. Common models, such as Shark Robotic's "Colossus"[1] or Magirus' "Wolf R1"[2] drag a fire hose behind them and disperse the water from an adjustable nozzle. Another approach (better suited for indoor scenarios) is to use foam or powder stored on the robot itself, as exemplified by the "D4" robot developed by colleagues of ours [2]. During missions, these robots can encounter the same visibility problems as humans. It is therefore only natural to investigate a similar approach: using a drone to supply a better perspective. The work at hand proposes a system in which a UGV is enabled to efficiently fight fires by using sensor data from a supporting UAV. Teaming aerial with ground robots has been the subject of numerous previous studies as UAVs can be seen as complementary to UGVs, which are slower and ground-bound, but can carry heavier payloads. For example, in studies such as [3] a UAV tracked and followed a fiducial marker mounted on the UGV to providing a third-person perspective for the teleoperator. In studies such as [4] one or more UAVs are launched from a "carrier UGV" to investigate points of interest. The authors of [5] proposed a system for the autonomous exploration of disaster sites similar to ours, consisting of a UAV, a UGV, and a ground station. But to the best of our knowledge, no previous study considered the peculiarities of using this setup for firefighting. The work at hand attempts a first step in closing this gap.

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[1]https://robots.ieee.org/robots/colossus/

[2]https://www.magirusgroup.com/de/products/special-vehicles/wolf-r1/

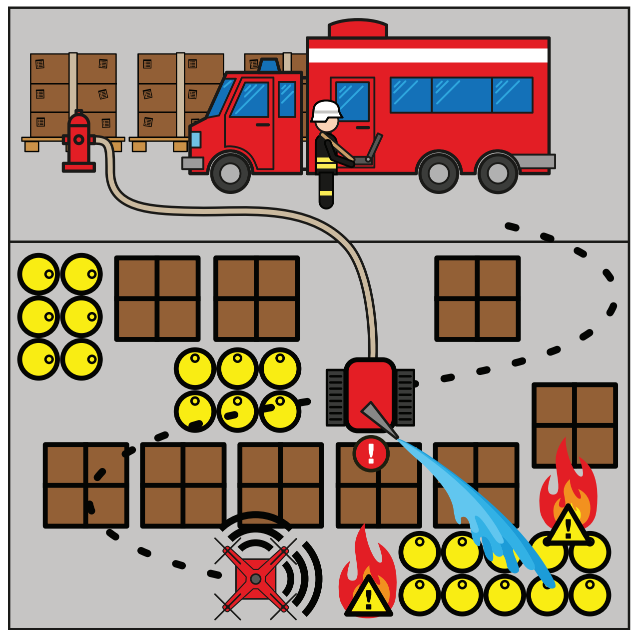

Figure 1. Illustration of a typical mission. A fire was reported at a logistics facility. Due to the presence of hazardous materials (represented by yellow barrels), the incident commander decides to employ the robotic system. The UAV explores the mission site and locates the fire. The UGV navigates towards and fights the fire, dragging a hose behind it. The water's trajectory is tracked by the UAV and optimized.

II. Scenario description

This section sketches a typical application scenario (illustrated in fig. 1) for the envisioned system. Numerous variations are imaginable, but we aim to develop a baseline first before adding more complexity. We conducted a semi-structured interview with a member of the *Institute of Fire Service and Rescue Technology* (IFR, associated with the Dortmund

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Fire Department[3]), to include an end-user's perspective and validate our concept's practicality. Additionally, some insights were transferred from our previous research into UAV swarms for emergency mapping scenarios [6]. The system's main purpose is to efficiently fight fires. Ideally, it shall offer the following advantages over human firefighters: Reduced risk of burns, smoke poisoning, trauma, and other injuries for human personnel; faster fire extinction; and minimized water usage. With today's technology, outperforming human firefighters in any and all scenarios is certainly not a realistic goal. But utilizing such a system may be preferable if one or more of the following conditions are met: 1) The mission is too dangerous for humans, e.g., if toxic or explosive substances are present. 2) The mission site is (at least partially) known a priori, drastically reducing the time needed for exploration. 3) The system is a permanent installation near the mission site and can react to developing fires earlier than humans.

Condition 3 would imply that fire prevention officers are willing to invest heavily into installing and operating a new system that is only useful in the relatively rare event of a fire. This approach can be of interest in some cases (e.g., at warehouses) and is already targeted by our colleagues working on the aforementioned D4 robot [2]. In contrast, we believe our system proposal is better suited as a mobile task force for a wider range of scenarios—especially those containing hazardous materials (condition 1). For example, Germany has seen several wildfires at military training and explosives disposal sites in recent years, where undetonated ammunition posed a tremendous threat [7]. Conversely, a mobile system makes meeting condition 2 (access to maps) more difficult. However, we see a couple of options to obtain a priori created map data. One could be the utilization of publicly available Digital Surface Models (DSMs).

A. Main components and capabilities

Centerpiece of the system is a robotic team of one ground and one aerial vehicle. Future iterations may employ additional robots to increase the system's efficacy. The UGV shall be capable of navigating in semi-structured environments and disperse a fire extinguishing agent from an adjustable nozzle. For the remainder of this paper, we assume the extinguishing agent to be water drawn from a hose dragged behind the vehicle. The UAV shall feature sensors suitable for exploration and fire detection. The system furthermore requires an interface for the human operators. This interface shall double as a Ground Control Station (GCS) to coordinate and support the robots.

B. Mission procedure

While traveling to the mission site, the system is booted and given a geographic boundary of the mission, as well as regions of interest (ROIs—e.g., suspected fires). The system downloads, processes, and fuses available map data into a usable format. Arriving at the scene, the UAV is launched first. It explores the area prioritizing the ROIs. The gathered data is used to refine the map and localize fires. Once a fire has been identified, the UGV navigates to a position from where it can fight the fire. Naturally, the water's ballistic trajectory may not intersect any obstacles. The system shall trace and optimize the water jet's trajectory using the UAV's data.

C. Requirements

Following the expert interview, we derived a set of high-level system requirements. The functional requirements stem directly from the scenario description outlined above and are omitted for brevity. In the following, we would like to elaborate on some of the identified *non-functional* requirements.

a) NF0 Autonomy: The desired benefits of the proposed robotic system over conventional approaches can only emerge when it operates at a sufficiently high degree of autonomy. However, our expert reported that a typical firefighter's acceptance of a new system increases dramatically if supporting functions are optional, rather than mandated (to keep the human in full control at all times). Hence, the system shall offer multiple *levels* of autonomy, from assisted teleoperation to "full" automation.

b) NF1 Flexibility: No fire department would purchase a costly system that is only applicable in a limited number of cases. Hence, the system needs to operate in various environments (e.g., forests, industrial sites, residential areas) and weather conditions. Next to firefighting, future iterations shall support additional use cases (e.g., sample collection).

c) NF2 Extensibility: Future results in robotics research may exhibit significant improvements over the state of the art. Our system needs to be designed in a modular fashion that supports the integration of new technologies to increase its efficacy and open up new use cases. This applies to both the hard- and software.

III. System concept

In this section, we attempt to develop a rough system concept and discuss tangible choices for key hard- and software components, based on the available literature and previous works of ours.

A. System architecture

Deciding on a system's architecture has a huge influence on its overall reliability, extensibility, and other aspects. As already advocated in a previous paper of ours, we propose to use an adaptation of the Operator Controller Module (OCM)[4] [8]. In essence, the OCM consists of three hierarchically strongly separated layers (as shown in fig. 2) with differing timing constraints: the *cognitive operator* layer, the *reflective operator* layer, and the *controller* layer. The *controllers* on the lowest level are directly connected to a robot's sensors and actuators (motor loop), requiring hard real-time compliance. Indispensable are the *motion controllers* to process the robots' movements in our scenario. In addition, *perception controllers*

[3]http://feuerwehr.dortmund.de/

[4]The OCM approach was originally developed in the context of mechatronics and the nomenclature can be confusing for computer scientists. It was later adapted to mobile robots by us.

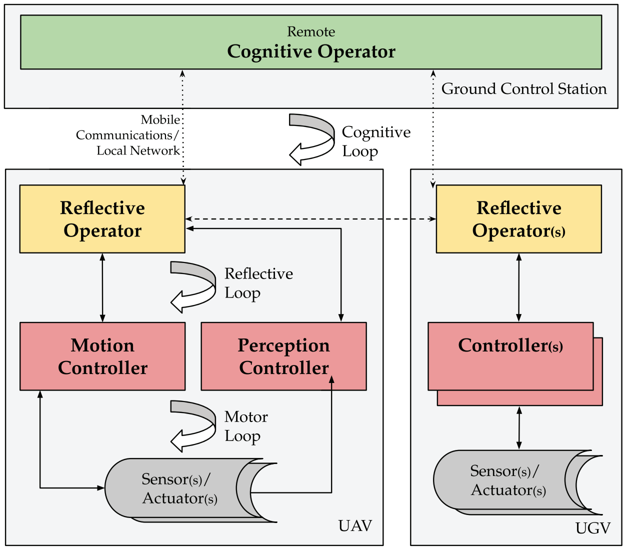

Figure 2. OCM-based system architecture.

are often used to sense more complex and advanced environment information, from battery status to visual sensors. Those *controllers* are connected through a real-time capable reflective loop interface to at least one *reflective operator* in the layer above. The *reflective operator(s)* collect(s) all necessary *controller* information and optimize the *controller*'s configurations for the current situation. For more advanced tasks, the *reflective operator(s)* are connected to a single *cognitive operator* (in our case, the Ground Control Station). The cognitive operator optimizes the system and coordinates the robots. Due to the hybrid deliberative/reactive robotic paradigm [9] this does not require real-time. In the presented scenario, the robots interact on different levels. Both communicate with the *cognitive operator*, but they are also connected on the *reflective operator* level to support time-critical tasks (e.g., cooperative localization).

B. Hardware

a) Platforms / locomotion: While multi- and helicopters, fixed-wing models, blimps and others each provide characteristic advantages, a multicopter is the obvious choice as the basic airframe for our UAV due to its high speed and agility, comparably low cost, and the ability to hover. In the long term, the relatively short flight time may be mitigated by employing multiple UAVs. The UGV shall be based on an established model (some examples were mentioned in section I). For typical use cases, it needs to be powerful enough to drag a fire hose behind it and overcome smaller obstacles.

b) Sensors: Cameras provide a lot of information for their low price and weight. While lidars measure distances more precisely, they can't detect colors and tend to be a lot heavier and more expensive. With RGB-D or stereo cameras, we obtain both color information (relevant for fire recognition) and depth information (for mapping). Additionally, RGB images can also improve situational awareness for the operators. However, cameras struggle in low-visibility conditions, e.g., in smoke-filled environments. For the time being, we find this limitation acceptable w.r.t. the targeted scenario and propose to use a stereo camera as the "main" environmental sensor of the UAV. An infrared camera could be a useful addition to improve fire detection. Other sensors (e.g., radar or ultrasonic) were ruled out on grounds of insufficient data quality for mapping and classification, weight, or cost. All named sensors are handled on a dedicated *perception controller* as they typically use a high amount of computing power. As it's standard for UAVs, it shall also feature an Inertial Measurement Unit (IMU) to control and stabilize the flight, and a GNSS receiver.

Based on the requirements, the UGV merely needs means of localization when driving towards the fire, for which a GNSS receiver and wheel odometry should suffice. But since it has fewer weight and power limitations, it is worthwhile to also add a stereo camera for localization w.r.t. to the 3D map—which would also enable navigation in GNSS-denied environments.

c) Computing hardware: The UAV requires a Flight Controller Unit (FCU) to keep it airborne and abstract from motor speeds to basic commands. In OCM terms (see fig. 2), this is the UAV's *motion controller*. Additionally, it requires an onboard computing platform connected to the FCU to serve as the *reflective operator* and enable medium-level autonomy. Due to the power and weight limitations a Single Board Computer (SBC) is preferable. A similar setup will also be used for the UGV. Commercially available models will already feature a *motion controller* to enable teleoperation, but additional computing units need to be added.

d) Communication: The robots need to communicate with each other and the Ground Control Station. While the interface with the *cognitive operator* could be realized with e.g. LTE or LoRA, the interaction on the *reflective operator* level needs a real-time capable connection like 5G to support time-critical tasks such as localization and collision avoidance.

C. Algorithms

This section examines major algorithmic components to enable a sufficient degree of autonomy in both robots.

a) SLAM: Even if a priori created map data of the mission site is available, an effective Simultaneous Localization and Mapping (SLAM) solution is needed to detect changes that occurred after the map's creation. In our use case, the SLAM component needs to handle environments that are 3D, possibly large and to some extent dynamic. It needs to be robust to disturbances (e.g., from smoke) and distributable, such that future iterations can have multiple robots mapping simultaneously. A review of Visual SLAM techniques (compatible to the proposed camera-based setup) was recently presented in [10]. The authors state: "Although the SLAM domain has been widely studied for years, there are still several open problems" [10], such as increasing the algorithm's robustness, optimize computational resources usage, and evolve the environment's understanding in the map representations [11]. To the best of our knowledge, there currently exists no solution which satisfies all aforementioned requirements to the SLAM component—underlying the need for an extensible system (NF2). A closer examination of [10] and other literature to select a suitable algorithm for a first system prototype is still pending.

b) Exploration: The SLAM problem is furthermore complicated by the question of *where* to gather more sensor data. This problem is also referred to as active SLAM (ASLAM), automatic SLAM, or autonomous SLAM. A review was recently presented in [12]. The authors state: "ASLAM is still far from being a solved problem that can be used effectively in nearly any environment. Although there are plenty of products [...], none of them offers the functionality of creating the map autonomously without human intervention" [12]. Open questions include the selection of termination criteria, the inclusion of semantic information and many more [12]. At the moment, receding horizon-based approaches seems to be the best choice for 3D data due to their low computational complexity (especially in large environments) compared to frontier-based solutions [12]. A drawback is the possibility to get stuck in local minima. Fortunately, a system prototype can be implemented without an exploration algorithm. As a substitute, the UAV can follow a fixed coverage path to map the area. This approach will produce comparably long flight paths and may fail to map obstructed areas accurately, but should work sufficiently well for a first proof-of-concept.

c) Path planning and collision avoidance: Our requirements regarding path planning and collision avoidance are relatively low. The UAV's main task is to gather sensor data, so it is unnecessary (possibly detrimental) to fly very high speeds. Second-order dynamics or other complex constraints do not need to be considered. Hence, we can rely on long-established, computationally simple approaches to solve path planning for the drone. A survey of common approaches was presented in [13]). Collision avoidance is mainly needed as a backup for potential errors in mapping and planning. We suspect a simple, reactive sense & avoid scheme to suffice. The situation is analogous for the UGV, but there are two complicating aspects to consider. Firstly, the UGV is typically dragging a fire hose behind it that may get caught on corners, slowing down or even stopping the vehicle. Secondly, the UGV should avoid hazardous materials (e.g., spilled chemicals) and prefer easy-to-traverse ground. This could be achieved by expanding the image processing module to classify the ground by traversability.

d) Fire detection: The system requires means to identify active fires. A review on machine learning-based approaches was recently presented in [14]. There are numerous challenges still under investigation, but the existing solutions already seem to provide satisfactory detection rates.

e) Mission management: A typical mission of our system follows a fairly linear progression and the robots' responsibilities are clearly separated. As a result, their respective tasks can follow a largely fixed script. For future system iterations employing additional robots, it may be necessary to investigate dynamic task allocation schemes.

IV. Conclusion

This work proposed a system consisting of a UAV teamed with an UGV, supported by a Ground Control Station, for firefighting. After presenting a scenario description we developed a first system concept, discussing possible design choices for the hard- and software. While many scientific and technical challenges need to be solved before such a system can be considered effective in real-life applications, we conclude that a proof-of-concept is achievable with today's technology. Open research questions that are specific to our scenario include path planning for a vehicle that drags a fire hose behind it, the usability of publicly available map data (such as DSMs) for robotic navigation, and selecting optimal firefighting strategies.

The work at hand constitutes the basis for our ongoing work in the field. We have already started the development of a prototype and plan to publish preliminary experimental results in the near future.

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