A Novel Real-Time Unmanned Aerial Vehicles-based Disaster Management Framework

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***Abstract*—The paper proposes a novel computing and networking framework that can be implemented for the realization of different disaster management applications or real-time surveillance. The framework is based on networks of unmanned aerial vehicles (UAVs) equipped with different sensors including cameras. The framework represents a holistic approach that exploits the distributed architecture of clusters of UAVs and cloud computing resources located on the ground. The proposed framework is characterized by the hierarchical organization among framework elements. In such a framework, each UAV is assumed to be fully autonomous and locally implements a state-of-the-art deep learning algorithms for real-time route planning, obstacle avoidance and object detection on aerial images. The main operating modules of the proposed framework have been presented, with the emphasis on the improvements which the proposed framework can bring in terms of event detection time and accuracy, energy consumption and reliability of application in disaster management systems. The proposed framework can serve as the foundation for the development of more reliable, faster in terms of disaster event detection and energy-efficient disaster management systems based on UAV networks.**

***Index Terms*—holistic framework, disaster sensing, UAV, deep learning, architecture, image processing, CNN, cloud, wireless**

I. Introduction

Global climate change and extreme weather have resulted in more frequent and severe disasters worldwide [1] [2]. The Balkan regions are especially prone to natural disasters, including floods, earthquakes, landslides and very frequent fires in the summer. As an example, on August 11th, 2021, Italy recorded the highest temperature ever in Europe as Sicily hit 48.8 degrees Celsius. It was the culmination of a very hot summer, which causes disastrous fires not only in Italy, but also in most of southern Europe.

Another example is that of Croatia [3], in which only during 2017, more than 6,200 separate open-space fires have been recorded, with burned areas spanning more than 100,700 hectares of land. To restrain such devastating fires, only in 2017, more than 17,000 flying hours of fire-fighting manned aerial vehicles were needed and more than 80,000 tons of water were used. Regional crisis management units, although equipped with state-of-the-art hardware, usually fail to respond adequately to such emergency situations, mainly because these events are detected very late, when they show unpredictable behavior and can't be controlled.

These are the reasons why the future massive implementation of real-time disaster observation and monitoring systems can reduce or even prevent such devastating destruction. It is shown that aircraft's (airliners) of commercial airlines can be exploited for remote lend observation [4], but their irregular flying schedules limits their implementation for reliable disaster monitoring. Also, traditional ground-based disaster observation and monitoring approaches have restricted area views, due to the presence of obstacles that diminish their detection precision. In order to minimize the impact of such disasters, early detection and monitoring system which enables detection from the sky and have capabilities of changing monitoring position are required. Therefore, small civilian unmanned aerial vehicles (UAVs) have attracted great interest for disaster sensing and management [5]. The main advantages of UAV systems are low costs, fast deployment and good coverage due to high-quality image sensing equipment. However, UAVs have significant battery power computation and processing capability constraints, which limits the usage of their full technological potential.

State-of-the-art small civilian UAVs can usually fly for 25-30 minutes without local processing and communication with the ground systems. Additional communication or computing load will further contribute to the faster battery consumption, which additionally reduce flying time and compromise the feasibility of UAV implementation in many practical applications. It is well known that the energy consumption of wireless devices is significantly impacted by wireless communication protocols [6]. Therefore, optimal real-time monitoring system architecture should force local processing when possible and tend to reduce communication with the ground [7]. The most promising architecture for achieving this goal is distributed architecture based on interconnected clusters of UAVs and cloud systems located on the ground. However, this architecture is often underestimated as a concept, due to the high computational demands of state-of-the-art algorithms, especially those that process images and video streams. Therefore, new disaster monitoring architecture that will enable efficient local processing in the distributed manner have to be envisioned.

Luo et al. [7] present a cloud-based disaster sensing framework, which aims to solve the limited computing resources and limited battery capacity as the most prevalent challenges when working with UAVs. Their proposal was based on establishing a client-server relationship between the UAVs and the cloud on the ground, where the most resource-intensive tasks are then offloaded to the cloud. The client only performs low-intensity tasks such as data pre-processing, which allows for efficient use of the limited resources. Lee et al. [8] propose a similar approach with the added goal of achieving real-time results. Their findings show that the Faster Region-based Convolutional Neural Network (R-CNN) algorithm achieves close to real-time speeds even when deployed in the cloud. Kyrkou et al. [9] offer detailed insight into the process of developing a CNN object detection algorithm and propose the network of UAVs (DroNet) as a solution for real-time UAV applications. The proposed algorithm achieves high accuracy even in environments where limited processing and battery resources are available. Additionally, through the implementation of a process called tiling, Plastiras et al. [10] introduce a new approach to processing large images with resolution-limited CNNs. By utilizing the proposed method, it is possible to achieve high accuracy, as well as the processing of high amounts of frames per second (FPS) in a central processing unit (CPU) of the processing platform.

Although stated references address partially some of the challenges related to the possible implementation of distributed UAV-based networks, there is still a lack of investigations that: *(i)* explore distributed or some hybrid distributed-like UAV network architecture that reduces UAV to ground communication; *(ii)* define the minimum requirements that one disaster monitoring system needs to have for the realisation of efficient UAV-based distributed architecture; *(iii)* explore state-of-the-art algorithms (especially those based on new machine learning techniques) for the UAV on-board execution. To overcome this gap and to entail a new distributed framework for disaster monitoring and management, in this paper a real-time UAV-based disaster management system exploiting deep learning algorithm and hierarchical organization of UAVs is proposed.

The rest of the paper is organized as follows: Section II gives an overview of the proposed framework architecture. In Section III, a detailed elaboration of the foreseen framework modules is presented. A conclusion is given in Section IV.

II. System Architecture

There are three different general architectures for the realisation of disaster monitoring and management systems based on UAVs. In Table I, the main requirements for the realisation of each architecture are overviewed. According to Table I, architectures can be classified as:

(i) Centralized, where data is collected on-board and after the collection phase, the data is processed on the ground. Most of the contemporary UAV-based systems follow this architecture. Its main drawback is that it is not adequate for applications that must operate in real-time (Table I).

(ii) Cloud-based, where on-board data collected have been immediately sent to the ground to be further processed by the cloud systems. This architecture requires high communication bandwidth, what consequently has an impact on high energy requirements (Table I).

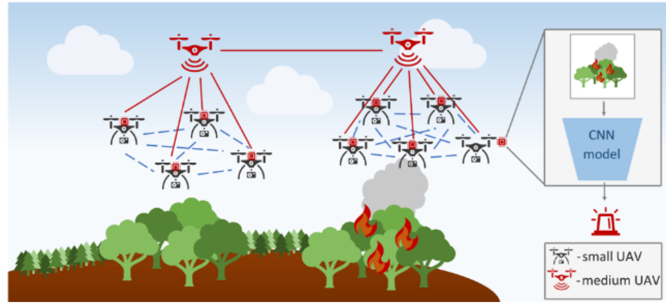

Fig. 1. Hierarchical architecture for UAV networks

(iii) Fully distributed, where each UAV performs data processing on-board. If the information extracted from data is important, it is immediately sent to the ground. Depending on the application, the on-board computation can range from medium to high, leading to medium energy requirements (high energy expenditure is noticed only when the processing task is very complex). Both cloud-based and distributed architectures are suitable for real-time applications, but their common drawback can be found in high energy requirements (Table I).

The architecture proposed in this paper is hierarchical and follows the very recent concept of pushing the data processing to the edge of the network. It is based on a hybrid approach encompassing both cloud-based architecture and fully distributed architecture. Similar architectures have been previously applied for realisations of smart homes and smart farming [13]–[16], where computing was divided among all participants in the system, i.e. devices, gateways and cloud. In the framework proposed in this paper, similar architecture is porpoised where UAVs (drones) represent the smart devices at the edge of the UAV networks, while UAV cluster-heads (UAV-CH) represent gateways or hubs of each UAV cluster (Fig. 1).

Therefore, the proposed framework is composed of different tiers. As shown in Fig. 1: a lowest (surveillance) tier consists of many small UAV networks and an upper (coordination) tier that consists of one medium UAV-CH as a representative of each UAV network cluster. The term medium UAV-CHs characterise UAVs that are more sophisticated and capable of communicating at longer distances than small UAVs.

Based on such hierarchical classification of UAVs, the two operation scenarios for disaster surveillance can be proposed (Fig. 2):

- Scenario 1: Each small UAV is able to collect data (images) and perform on-board processing using some of CNN algorithms. If an event of interest is detected (fire, flood, etc.), an alarm is sent to the UAV-CH, which is responsible for the transmission of the alarm to the cloud system on the ground.
- Scenario 2: Each small UAV collects images and performs on-board processing on resized images (with lower resolution) using some of CNN algorithms. If an event of interest is detected, the small UAV sends the original size

TABLE I
REQUIREMENTS FOR UAVS ARCHITECTURES

Type of architecture	On-board computation	Communication	Energy	Suitable for real-time applications
Centralized [11]	Low	Low	Low	No
Cloud-based [7] [8]	Low	High	High	Yes
Distributed [12] [9] [10]	Medium to High	Medium	Medium to High	Yes

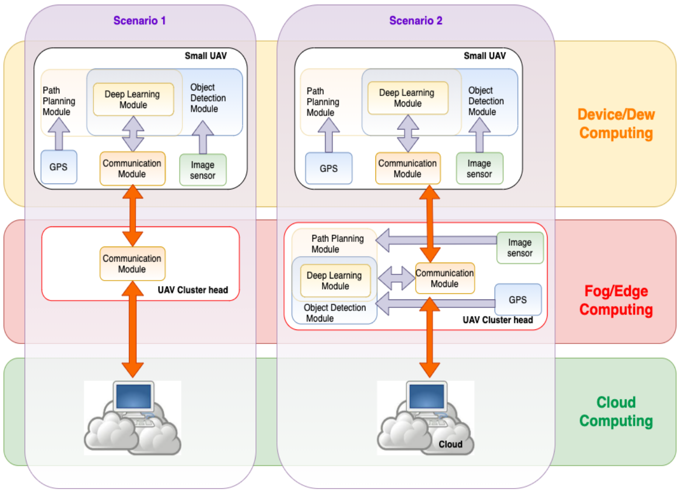

Fig. 2. Logic dependencies between the UAV modules for Scenario 1 and Scenario 2

image to the UAV-CH. The UAV-CH performs on-board processing on the image using the CNN algorithm and, if the event is again detected and therefore confirmed, sends the alarm to the ground.

According to Fig. 2, the proposed framework for disaster monitoring system is based on three-tier architecture. The lowest tier represented with a number of small UAVs, will perform light on-board processing. It is known as dew computing or the device/sensor computing tier. Considering the energy, memory and processing constraints of the devices, this tier should be as lightweight as possible. The communication at this tier is restricted to “UAV to UAV”, and never “UAV to ground” communication. The next tier, upper in the hierarchy (Fig. 2), is known as the fog/edge computing tier and it is responsible for “UAVs to ground” communication and occasionally some specialised processing. The last tier of the proposed framework presented in Fig. 2 is the cloud tier located at the ground. This tier applies very complex data processing in order to perform knowledge extraction for future analysis.

III. MODULES

To ensure networking and processing functionalities in the proposed three-tier architecture presented in Fig. 2, UAVs should contain the following modules: object detection module, cooperation/path planning module and communication module.

A. Object detection module

The main element which should be implemented in every small UAV for performing remote detection of interesting events is the object detection module (Fig. 2). Traditional techniques for object detection are being continuously replaced with new, more advanced techniques based on new artificial intelligence approaches, also known as deep learning techniques. Deep learning is a class of machine learning algorithms based on artificial neural networks (ANNs) which are capable of learning from data that is unstructured or unlabeled. These ANNs have been recently used for object detection in images and videos. Albeit costly in terms of energy consumption and computation complexity, they have generated very promising results, outperforming traditional approaches.

Hence, this module in the proposed framework takes images from image sensors and performs on-board object detection using deep learning models that had been previously trained offline (Fig. 2). This process should be fast (in real-time), accurate and also should be lightweight enough to meet the computational limitations of both small UAVs and UAV-CHs. To identify the most suitable model for such tasks, different algorithms should be developed and evaluated, including CNN, Faster R-CNN (Faster RCNN), “You Only Look Once” (YOLOv3 and Tiny YOLO), etc. This is important since choosing the most suitable algorithm is application-specific and can not be known in advance.

B. Cooperation module

In the proposed framework, solving an event-based risk-sensitive UAV coverage problem is important for each networked multi-agent system consisted of a large number of UAVs. The coverage problem is solved by finding paths for each UAV which will ensure proper monitoring of the interested region, such that the more interesting areas with larger information content should be given a higher priority [17]–[20]. The best choice to solve the coverage problem is by implementing a distributed architecture where each UAV computes its path on-board by taking into account the intentions of other UAVs in the cluster. Therefore, each UAV should have a cooperation module aiming to understand the positions of other UAVs in the cluster (Fig. 2). This enables maximization of both, the coverage efficiency of that cluster and the information passed to the related UAV-CH. Consequently, the risk-sensitive adaptation will help to increase the reliability of information passed to the related UAV-CH. This can significantly increase the efficiency of the system in terms of its capability to detect a risky event at its early stage.

C. Communication module

The main functionality of the communication module is to ensure the communication capabilities of each small UAV with other UAVs and UAV-CH (Fig. 2). Also, the communication module of UAV-CH must ensure a bidirectional relay between UAV cluster and ground stations. To accomplish this, the functionality of the communication module for each UAV will be based on a Flying Ad-Hoc NETworks (FANETs) concept. While static ad-hoc networks have predictable routing and throughput demand's [21], a connecting cluster of UAVs in FANET is a challenging task, due to distance and position variations of UAVs. In order to establish robust and reliable communication, appropriate routing protocols that can properly function in the proposed framework characterized with a dynamic communication environment among UAVs must be implemented. Also, to enable different communication scenarios between UAV-CH and the ground station, the communication modules of UAV-CHs should support single or multiple communication technologies such as wireless local area network - WLAN (based on IEEE 802.11 standards), Worldwide Interoperability for Microwave Access network - WiMAX (based on IEEE 802.16 standards), satellite network and mobile cellular networks of fourth-generation (4G), fifth-generation (5G) and future sixth-generation (6G).

D. Implementation challenges of the proposed framework

The main drawbacks of the proposed framework are reflected in the increased cost of realisation when compared with disaster monitoring systems based on a single UAV. Also, the existence of one UAV-CH represents a single point of failure for a cluster which functionality can be completely lost in cases of malfunction or failure of UAV-CH. A significant challenge in the practical realisation of the proposed framework will be in the harmonisation of energy consumption among UAVs belonging to the seam cluster, since the performance of the cluster will be limited with UAV which battery depletion will be fastest.

IV. Conclusion

In this paper, a novel three-tier networking and computing framework for disaster sensing based on the utilization of clusters of hierarchically organised UAVs is proposed. The functionality of the object detection, cooperation and communication modules as main modules of UAVs needed for practical realisation of the proposed framework has been presented. The proposed framework is based on exploiting deep learning approaches for information processing at UAVs, which operate as device and edge computing nodes. This enables offloading of only the most relevant processing tasks to the cloud, while simultaneously decreasing response time by performing data pre-processing at the UAVs. The introduced framework can serve as the foundation for the practical realization of a new generation of disaster monitoring systems which will be based on the exploitation of clusters of UAVs for remote sensing of events that are of particular interest.

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