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Collision-free Cooperative UAV Protocols for Sustainable Aerial Services

Francisco Fabra*, Anna Maria Vegni[†], Valeria Loscri[‡], Carlos T. Calafate*, Juan Carlos Cano* and Pietro Manzoni*

*Department of Computer Engineering (DISCA)

Universitat Politècnica de València, Spain

Email: frafabco@cam.upv.es, calafate@disca.upv.es, jucano@disca.upv.es, pmanzoni@disca.upv.es

[†]Department of Engineering, Roma Tre University, Italy

E-mail: annamaria.vegni@uniroma3.it

[‡]FUN Team, Inria Lille - Nord Europe, France

E-mail: valeria.loscri@inria.fr

Abstract—UAVs are offering many global industry sectors the opportunity to adopt more sustainable business models. By offering innovative ways of managing resources, and newer opportunities to address key challenges in many areas, UAVs are expected to play a relevant role in the upcoming 6G networks scenario. As an example of their deployment, in smart-agriculture, UAVs are used to collect data such as weather and soil moisture, enabling more effective land management. They can also be applied to the inspection of infrastructure projects or equipment such as onshore and offshore wind turbines, reducing the need for potentially dangerous human inspection, or, finally, for the distribution businesses and services.

All these new applications tend to require the cooperation of groups, namely “swarms” of UAVs, in order to provide collaborative sensing and processing solutions. New requirements are then imposed in terms of safety, coordination, and operation management. In this paper, we provide an overview of some of the technical challenges that multirotor UAVs are still facing in terms of aerial coordination and interaction. In this regard, we focus on recent developments available in literature and present some contributions we realized during the past few years that address UAV interaction to achieve collision-free flights and swarm-based missions. Based on the analysis provided in this work, we eventually provide an insight on the challenges still open that need to be solved in order to enable effective UAV-based solutions to support sustainable aerial services.

I. INTRODUCTION

Recently, the concept of Internet of Things (IoT) is evolving to Internet of Everything, assuming a continuous increase of heterogeneous devices, from sensors for smart-agriculture and smart-farming to autonomous and unmanned ground vehicles, devices for smart home and smart cities, and also devices for health and wellness applications, including nanorobots for nanomedicine [1].

As depicted in Fig. 1, a general overview of IoT networks environment considers the coexistence, and also the coordination of a plethora of devices communicating with each other. In such a scenario, aerial IoT [2] is an emerging research area where the different benefits of Unmanned Aerial Vehicles (UAVs) are leveraged to assist in the creation of a richer heterogeneous IoT ecosystem, comprised of not only ground networks, but also ocean, aerial and space networks.

UAVs, popularly known as drones, are semi-autonomous or fully autonomous unmanned aircrafts that have embedded sensors, cameras, and communication equipment. UAVs have brought several benefits in the field of *sustainable development*. First of all, UAVs with cameras are a very useful tool when flying over large areas of land. They can quickly acquire images of cultivated areas, forest zones, areas with fire hazards, etc. with a minimal emission of pollutants and being able to reach the point of interest faster before the event becomes too serious.

Also, UAVs have been largely deployed in solar power plants and wind farm applications. With the support of UAVs, technicians can fly over solar power plants and wind turbines to check for technical failures, material leaks or malfunctions without having to relocate personnel to each element of the installation. In this way, it can be avoided to put in danger people life, while saving fuel and time. Finally, with the spread of the COVID-19 pandemic, UAVs have also been validated as a solution to counter this epidemic with specific tasks such as disinfection of large areas, thermal image collection, quarantine patient identification and monitoring, and contact detection [3].

Acting as supporting nodes for communications, UAVs can be deployed on demand, and can benefit from a wider communications range and better line-of-sight (LOS) features than ground network infrastructures. Communications among such heterogeneous devices should be guaranteed in order to enhance network performance and reduce connectivity issues, especially in harsh environments. A simple example relays on ground-to-aerial (G2A) wireless links for a rural IoT setting, where coverage issues require a UAV to be deployed in order to act as a mobile gateway for the different ground sensing devices. More complex deployments include those situations where UAVs are also acting as mobile sensors, gathering data and possibly processing and transmitting it in real time via aerial-to-ground (A2G) and aerial-to-space (A2S) links.

A detailed analysis on the impact of UAVs on CO2 emissions and cost has been provided in [4], where the authors demonstrate that using UAVs for last-mile logistics is not only

cost effective, but also environmentally friendly.

Finally, through swarm features, UAVs show a collaborative behavior by leveraging on communication facilities, with the aim of achieving a common goal [5]. When deployed as a swarm, UAVs can deliver multiple virtual/augmented reality immersive communication sessions to remote users, in order to assist more efficiently in these types of scenarios [6].

Despite the many advantages, the use of UAVs involves a number of critical issues to be considered, such as privacy, security, and flight safety [7], especially in urban environments where the consequences of any flight disruption are typically much more severe due to the risks of injuries for citizens. To address such issues, several efforts are taking place worldwide to make UAV flights safer. For instance, *U-space* is an European initiative that aims at making UAV traffic management safer and more secure. It attempts to provide an appropriate interface with manned aviation and air traffic control, to facilitate any kind of routine mission in all classes of airspace, thus achieving the ambitious Single European Sky (SES) goal. The SESAR Joint Undertaking [8] partnership was set up in order to manage this large scale effort, coordinating and concentrating all European research and development activities focused on air traffic management. This way, a wide range of UAV missions that are currently restricted will be possible in a near future thanks to a sustainable and robust European ecosystem that is globally interoperable.

In this paper, we will present an overview of main open challenges of UAVs, related to both their aerial coordination and interaction, as well as their communication capability, in the context of sustainable aerial applications.

This paper is organized as follows. Section II presents an overview of the main challenges UAVs face when deployed for sustainability services. In Section III, we describe some collaborative UAV solutions with particular emphasis to applications where UAV swarms are mainly applied, and the respective solutions, along with UAV crash avoidance strategies to provide collision-free flights. Section IV follows, dealing with some insights on the main gaps still existing with the current solutions, and we sketch the main future research directions. Finally, conclusions are drawn at the end of this paper.

II. UAV CHALLENGES FOR SUSTAINABLE AERIAL OPERATIONS

In the coming years, UAVs are expected to become ubiquitous, flying around in both indoor and outdoor environments. Such a massive number of UAVs raises new challenges that deserve scrutiny, like dynamic and flexible geofencing to achieve flexible aerial operations, energy efficiency and resource management, as well as security issues. In the following, a brief overview of the main UAV challenges is presented.

Dynamic geofencing for flexible aerial operations. Geofencing is essential to ensure that UAVs comply with airspace restrictions in order to efficiently use the low-altitude airspace, while keeping it safe for all. In particular, standard geofences are those that prevent UAVs from entering no-fly zones,

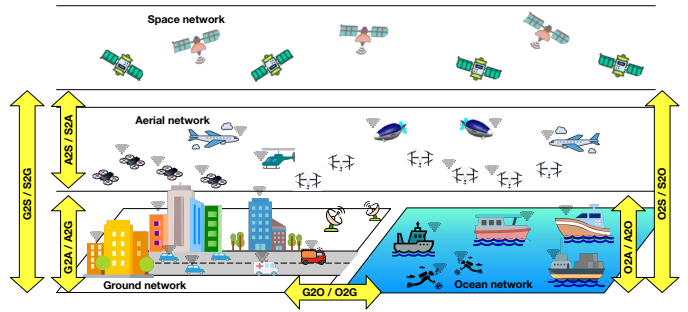


Fig. 1: Schematic of ubiquitous IoT with integrated and overlapping ground, ocean, aerial and space networks. Legend: G2A/A2G (ground-to-aerial/aerial-to-ground), G2S/S2G (ground-to-space/space-to-ground), A2S/S2A (aerial-to-space/space-to-aerial), O2G/G2O (ocean-to-ground/ground-to-ocean), O2A/A2O (ocean-to-aerial/aerial-to-ocean), G2O/O2G (ground-to-ocean/ocean-to-ground), and O2S/S2O (ocean-to-space/space-to-ocean).

and to keep them away from protected areas and critical infrastructures. Dynamic geofences can also be defined by a UAV operator to create a temporary restricted airspace that avoids other UAVs to enter that space during a mission. While the former type of fencing has little flexibility, it has the advantages that their number is reduced, and the locations of such fences are well known. On the contrary, with the proliferation of UAVs, it becomes possible that many UAV operations take place in a same area (*e.g.*, urban scenarios), and so a strict geofence per UAV operation may become too restrictive, or severely affect the sustainability of operations.

An example is provided in Fig. 2 (a) where UAV #2 has to take a long detour to avoid entering the geofenced area defined by UAV #1, which results in additional time and energy consumption. The problem is even more severe in Fig. 2 (b), where the target for UAV #2 is inside the area temporally reserved by UAV #1, meaning that UAV #2 cannot complete its mission until the reservation comes to an end. Yet, notice how, in both cases, UAV #1 is in fact operation away from the direct path followed by UAV #2 at the time it is approaching, meaning that the crossing of the geofenced area would not represent a problem for none of them.

To make such optimization possible, an automatic detection and avoidance of potential collisions between UAVs becomes quite relevant. Hence, the crash avoidance problem, and the computation of optimal paths, have to be jointly considered with the requirement of energy consumption minimization.

The challenge described above can also be extended to the swarm case. For instance, if multiple UAVs from a same operator have to do the same mission, it becomes much faster to make them fly together as a swarm, thereby being able to release the aerial space much sooner than having the UAVs fly sequentially in independent missions. Furthermore, in those cases, avoiding collisions with a swarm of UAVs instead

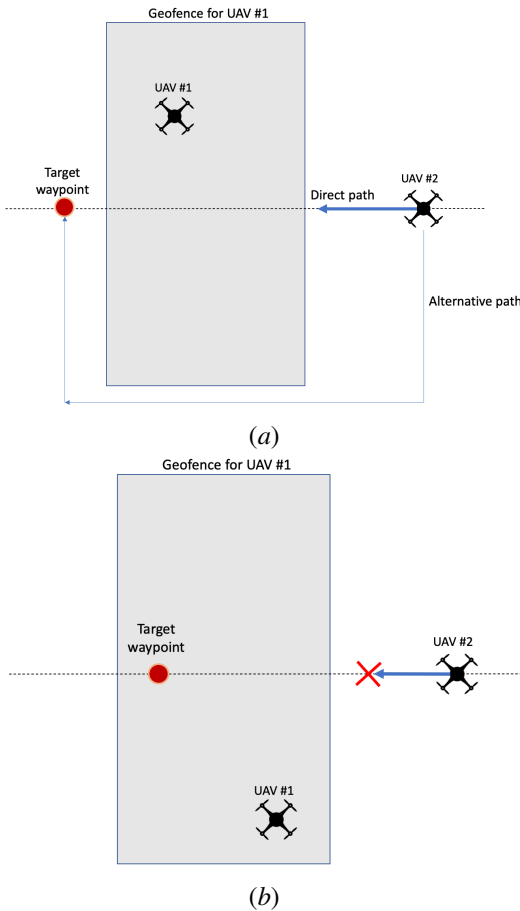


Fig. 2: Examples of geofencing issues.

of a single UAV becomes much more complex. Inside the swarm itself, UAVs should also avoid collisions with their neighbors. In this regard, planning optimal trajectories by avoiding collisions with other UAVs and obstacles remains a critical and open issue [9].

Aerial sensing and data relaying. The capabilities of UAVs enable the adoption of novel IoT applications. From the sensing perspective, they can lift sensors of low/moderate weight, and provide high-altitude measurements that prove to be priceless in many contexts, including fire detection, precision agriculture, wildlife monitoring, and every application benefiting from aerial cameras. Nowadays, these devices can also include embedded units with edge computing capabilities, allowing data to benefit from processing at the edge, on the UAV itself, effectively reducing communication requirements, and even enabling a faster response time in some contexts.

From the data relaying perspective, UAVs are shown to be highly beneficial in many aerial IoT contexts by acting as mobile sinks for sensors located in place with little – or also, no– wireless coverage, or merely as message relays towards the wireless infrastructure via multi-hopping, or by acting as data mules from a Delay Tolerant Networking (DTN) perspective.

Identification of Key Parameters and Performance Analysis of UAVs. In a complex IoT ecosystem with collaborative UAVs exchanging a high number of messages, including both data and coordination messages, the correct identification of the key parameters, and their inclusion in the system design, plays a fundamental role. In order to correctly evaluate the performance of a UAV-based aerial IoT system, Quality of Service (QoS) metrics should be considered, such as coverage, reliability, connectivity, etc. In most cases, trade-offs need to be considered related to the specific IoT scenarios/applications, by developing event-driven/mission-driven solutions [10]. Of course, network performance depend on the particular communication technology adopted. As an instance, in case of Free Space Optics (FSO) data links, weather conditions and the atmospheric environment can cause fluctuations in amplitude and attenuation of the optical signal.

Energy Efficiency and Resource Management. Beside evaluating the impact of the main parameters on the global system, important constraints such as the limited available energy should be considered for the implementation of effective IoT solutions. In particular, resource management for UAVs is characterized with specific challenges due to different factors such as (i) unique mobility characteristics, and (ii) stringent energy and flight limitations. An effective path plan has to consider all these features. However, such factors increase the complexity of these systems, requiring the resource allocation process to be optimized [11].

III. COOPERATIVE SOLUTIONS FOR COLLISION-FREE FLIGHTS

The previous section highlighted some challenges in different areas related to sustainable aerial flights. This section provides an overview of some contributions addressing the first challenge *i.e.*, *dynamic geofencing for flexible aerial operations*. We put evidence on how UAV coordination mechanisms enabled by wireless communications can effectively help at having flexible and dynamic geofencing that can avoid strict reservations of air space by detecting and avoiding possible crashes when UAVs cross each others paths. In addition, we also show how to create and maintain UAV swarms undertaking both autonomous missions and manually guided swarm missions in order to minimize the UAV flight times, thereby reducing the impact of dynamic geofencing by releasing the airspace sooner.

In the following, we start by addressing the problem of dynamic geofencing based on “sense and avoid” techniques.

A. Dynamic geofencing through sense and avoid techniques

Among the different areas where UAV flight safety is being considered, the development of sense and crash-avoidance mechanisms to enable dynamic and flexible geofencing has not yet been fully addressed. This problem is applicable to all types of contexts, and applies to both single UAVs performing a mission, or a group of UAVs acting as a single swarm, and often requires taking evasive actions to avoid crashes [7].

TABLE I: Number of UAV crashes and deadlocks avoided through MBCAP (mean value per hour of simulation).

Number of UAVs	25	50	75	100
Collisions expected	6.5	16.5	45.5	84.25
Risks detected	23.08	105.08	249.08	438
Crashes ($distance < 4$ m)	0.08	0.08	0.58	1.08
Deadlocks avoided	0	0.33	0.25	0.58

To address this challenge, we proposed the Mission Based Collision Avoidance Protocol (MBCAP) [12], *i.e.*, a collision avoidance solution that relies on wireless communications between nearby UAVs performing planned missions. In particular, MBCAP-enabled UAVs will constantly broadcast their future positions and, whenever two UAVs determine that their flight trajectories overlap in time and space, they will stop to quickly negotiate, and execute the process to safely go through the critical area, while giving higher priority to one of the UAVs according to any specified criteria.

MBCAP has been implemented in real UAVs. Experimental results, along with large-scale simulation experiments, have validated the effectiveness of our proposed protocol, and evidenced the low overhead introduced both in terms of channel occupation and mission delays. Through practical validation, we have observed that MBCAP is able to avoid UAV crashes, defined as having an inter-UAV distance lower than 4 m, when varying the total number of UAVs in an area sized 5×5 km². Table I collects the performance of MBCAP, which shows an effective behavior even when the number of UAVs reaches high values. In particular, we find that the chances of collision remain in general very low, only surpassing the 1 crash per hour threshold for 100 UAVs. A video summarizing our experiments is available online at: <https://youtu.be/bEdcsPX1hXY>.

Further results of the MBCAP technique are reported in Fig. 3, which depicts a Google Earth 3D view that shows (i) the path followed by the real multicopters with a *red* line, (ii) the path of the virtual high-priority UAV with a *blue* line, and (iii) the route of the virtual low-priority UAV with a *black* line. The green arrows indicate the direction the UAVs are moving towards before detecting the collision risk, also marked with a green circle. We can observe that the paths followed in simulation and in real experiments are quite similar and mostly overlap. A video showing our real experiments is also available online at: <https://youtu.be/xHnMuMOD9C0>.

Overall, we find that MBCAP technique can effectively allow multiple UAVs to operate without air space segregation, paving the way for more flexible and sustainable aerial operations, especially in environments characterized by a high volume of UAV activities.

B. UAV Swarm Solutions

Although there are already some solutions for the automation of UAV swarm flights, in certain situations the support for coordinated missions is required. Examples of such situations may include rescue operations and environmental monitoring, as well as applications for large-scale agriculture

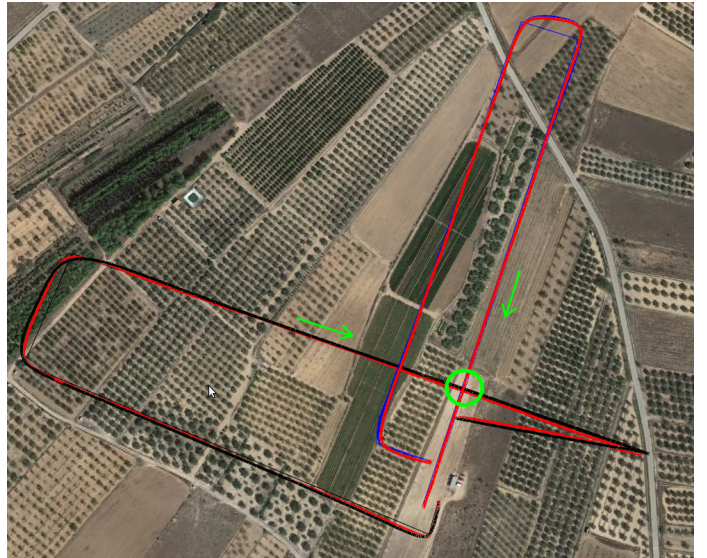


Fig. 3: MBCAP simulation vs. real experiment in a perpendicular crossing.

in search of pests or weeds, wild life recordings, or border surveillance, among others. In these cases, the coordination of all UAVs conforming the swarm is critical when carrying out the mission to avoid collisions and promote network stability. Such process typically relies on pre-planned missions where communications among UAVs are critical to enable near-real-time responsiveness so as to maintain the consistency of the swarm.

Mission planning for collaborative UAVs is a complex aspect that involves a compromise between (i) the necessary level of centralization or decentralization, (ii) the level of abstraction at which plans are generated, and (iii) the level to which such plans are distributed among participating units.

Regarding applications where UAV guidance must be manual and not following a pre-planned mission, UAVs that make up the swarm have to dynamically adjust their routes in order to follow the master UAV acting as the leader of the swarm. Such a solution may be required in scenarios such as search & rescue [13], fire tracking, or the monitoring of disaster areas. In all these cases, the pilot must respond to visual stimuli in real-time, and adapt the UAV course accordingly. Furthermore, there are situations where, in addition to manual guidance, there is the need to carry multiple items or sensors that go beyond the lifting capacity of a single UAV.

In terms of sustainability, having UAVs flying as a flock enables faster operations involving multiples UAVs, which has the potential of minimizing the usage of aerial space in order to release it as soon as possible for other operations in the same area. We now proceed to address the swarm communication problem, and then two proposals to create swarms efficiently.

1) *Swarm communications:* The reliability of wireless communications is one of the main problems in the creation and maintenance of swarms. Through direct wireless links, collaborative UAVs can build an infrastructure-less wireless

network. However, collaborative UAVs solutions present some limitations, mainly depending on the heterogeneous nature of devices. Developing applications for UAVs with heterogeneous devices, showing different energy levels, storage features, communication, sensing and processing capabilities, represents a complex task.

The distance separating neighboring UAVs must also maintain consistency to avoid both collisions and interruption of communications, which hinders synchronization, causing delays to the entire process, or even a reduction of the number of UAVs in the swarm.

Other of the key challenges in UAV-based communications is the backhaul throughput. Hanna *et al.* [14] proposed an approach for the optimization of the UAV swarm positions, in order to achieve a high multiplexing gain in MIMO backhaul with LOS. They developed two distributed algorithms to estimate UAV positions such that each UAV moves for a minimal distance to achieve the highest capacity in a LOS MIMO channel. Another work [15] considered the use of a UAV swarm as an amplify-and-forward MIMO relay to provide connectivity between an obstructed multi-antenna equipped source and destination. Authors also proposed a simple near-optimal approach to find the positions that optimize the capacity for the end-to-end link given that the source and the destination have uniform rectangular arrays.

2) *The MUSCOP protocol [16]*: The first approach is a solution able to provide UAV coordination to maintain the desired flight formation when carrying out planned missions. MUSCOP uses a centralized approach where the master UAV synchronizes all UAV slaves each time they reach an intermediate point in the mission. Our protocol allows different formations to be created around the leader (*e.g.*, matrix, linear and circular). In addition, the MUSCOP protocol has been validated using our ArduSim simulation framework, which allows to perform realistic experiments in two types of environments, *i.e.*, ideal and lossy wireless channel, in order to validate the formations with different numbers of UAVs. In an illustrative video (<https://youtu.be/VLMsbL5B6tA>) we run three experiments with different flight formations on the ArduSim simulator.

Fig. 4 shows the MUSCOP time offset when varying the distance among UAVs, which represents the relative delay swarm members have with regard to the reference, in this case provided by the master UAV. In general, it is observed that the mean time offset increases as the separation distance increases. This is expected since, in a lossy channel, large distances will impair or harm the synchronization among UAVs, thus becoming a critical problem. It is also worth mentioning that, for up to 300 m between contiguous UAVs, the time offset does never exceed 1 s threshold, which is a significant achievement.

3) *The FollowMe protocol [17]*: The other solution is the FollowMe protocol [17], able to define and maintain the formation of UAVs in a swarm. In particular, it is applicable to the specific case where a real pilot controls the swarm leader, and the other UAVs (*i.e.*, slaves) automatically follow it in real time. When all the slaves are detected by the master

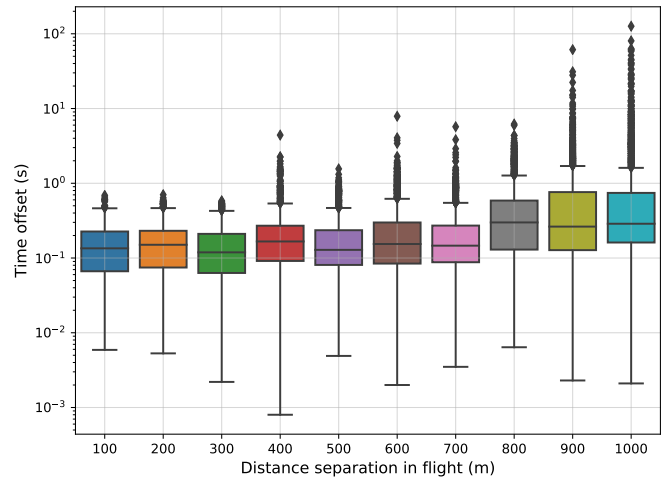


Fig. 4: MUSCOP time offset when varying the inter-UAV distance, [16].

UAV, and the user starts the setup step of the simulation, a message is issued by the master UAV, including its coordinates and their theoretical position in the flight formation. Once the master UAV reaches the same altitude as the rest of the UAVs in the swarm, it periodically broadcasts another message during its flight, which includes the current 3D location and heading of the master. Each time a slave receives this message, it calculates a new target location, and issues a command to the flight controller to move to the designated location in the formation. Finally, experimental results under different conditions show that the FollowMe protocol is able to adequately maintain the swarm formation and dynamically respond to the pilot's commands, with a lag of only a few seconds in the worst case, avoiding collision among UAVs as long as some minimal distances towards neighboring UAVs are defined.

IV. LESSONS LEARNT AND FUTURE RESEARCH DIRECTIONS

Bridging the research in the UAV field and the related IoT areas remains a challenge to be tackled due to the many issues that arise. From our experience, real UAV flights introduce several problems, including (*i*) deployment issues, (*ii*) flight restrictions, as well as (*iii*) development and communication issues.

In terms of deployment, carrying, assembling and preparing a high number of UAVs for a flight is quite time consuming, and can derive in crashes when attempting to take off a large number of UAVs. It follows that having more compact UAVs with minimal assembly time is important, as well as having self-arranging algorithms to automatically organize takeoff procedures. In fact, the latter is a complex problem when scaling up to hundreds of UAVs, and remains an open challenge. Similar considerations apply for the UAV development, as commercial UAVs are characterized in their majority by being closed platforms that are not easily amenable to

enhancements, hindering any development efforts in most cases, or merely offering a limited API. It becomes critical to promote open platforms that make UAV development possible and straightforward.

In terms of flight restrictions, many researchers disregard the current regulations regarding flight altitude (maximum of 400 feet in most countries), as well as the presence of physical obstacles, along with battery limitations, which limit flight times to a maximum of 30 minutes using current technology. Hence, in the context of aerial IoT and IoT-supporting UAVs, efficient path planning emerges as a critical issue.

Finally, regarding communication issues, it is worth pointing out that current commercial UAVs lack a technology that enables these UAVs to communicate with each other, a requirement that is critical to support any collaborative approaches such as the ones described earlier. In fact, there is currently no standard for UAV-to-UAV communications, meaning that experiments such as the ones performed are only made possible by relying on ad hoc wireless settings that are not generic enough to enable a seamless adoption. Additionally, commercial UAVs also lack the integration of wireless technologies that are more typical of IoT environments as only WiFi interfaces are usually available, and so additional interfaces must be equipped, a requirement that often can only be addressed via building custom UAVs.

V. CONCLUSIONS

UAVs and their associated applications represent nowadays some of the most exciting and promising research fields. In the upcoming years, with the advent of 6G networks, they are expected to provide several social benefits with a plethora of solutions for large-scale agriculture, environmental monitoring, or even contact monitoring and tracing in case of pandemics, such as COVID-19.

This paper presented the main challenges for sustainable and collision-free operations of UAVs, with an emphasis on those solutions where wireless communications are able to leverage collaborative UAV applications to improve the performance of different aerial scenarios. Specifically, we focused on a sense and crash-avoidance solution with general applicability, including experimental results carried out directly on field, as well as swarm management protocols, including some solutions that have been developed in our research group. Experiments have shown it is feasible to achieve collision-free flights with a low communications overhead, and introducing minimal delay to the planned missions. Overall, we believe such contributions will favor the deployment of autonomous UAV flights, which is a basic requirement for performing all sorts of tasks, and to promote a sustainable UAV ecosystem.

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