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REVIEW

Collision-free cooperative Unmanned Aerial Vehicle protocols for sustainable aerial services

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Abstract

Unmanned Aerial Vehicles (UAVs) are offering many global industry sectors the opportunity to adopt more sustainable business models. They offer innovative ways of managing resources and water and offer newer opportunities to address key challenges in many areas like border surveillance, precision agriculture and search and rescue missions. All these new applications areas tend to require the cooperation of groups, or "swarms" of UAVs to provide collaborative sensing and processing solutions. These new scenarios impose new requirements in terms of safety, coordination, and operation management. This paper provides an overview of some of the technical challenges that multirotor UAVs are still facing in terms of aerial coordination and interaction. In this regard, it focusses on recent developments available in the literature and presents some contributions realised during the past few years by the authors addressing UAV interaction to achieve collision-free flights and swarm-based missions. Based on the analysis provided in this work, the paper is able to provide insight into the challenges still open that need to be solved in order to enable effective UAV-based solutions to support sustainable aerial services.

KEYWORDS

aerial IoT, ardusim, flight coordination, swarm, UAV

1 | INTRODUCTION

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

Another benefit of using drones that can be applied to sustainability is their use in solar power plants and wind farms. With the help of drones, 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, thus avoiding to put in danger peoples' lives while saving fuel and time.

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 Figure 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 UAVs are leveraged to assist in the creation of a richer heterogeneous IoT ecosystem,

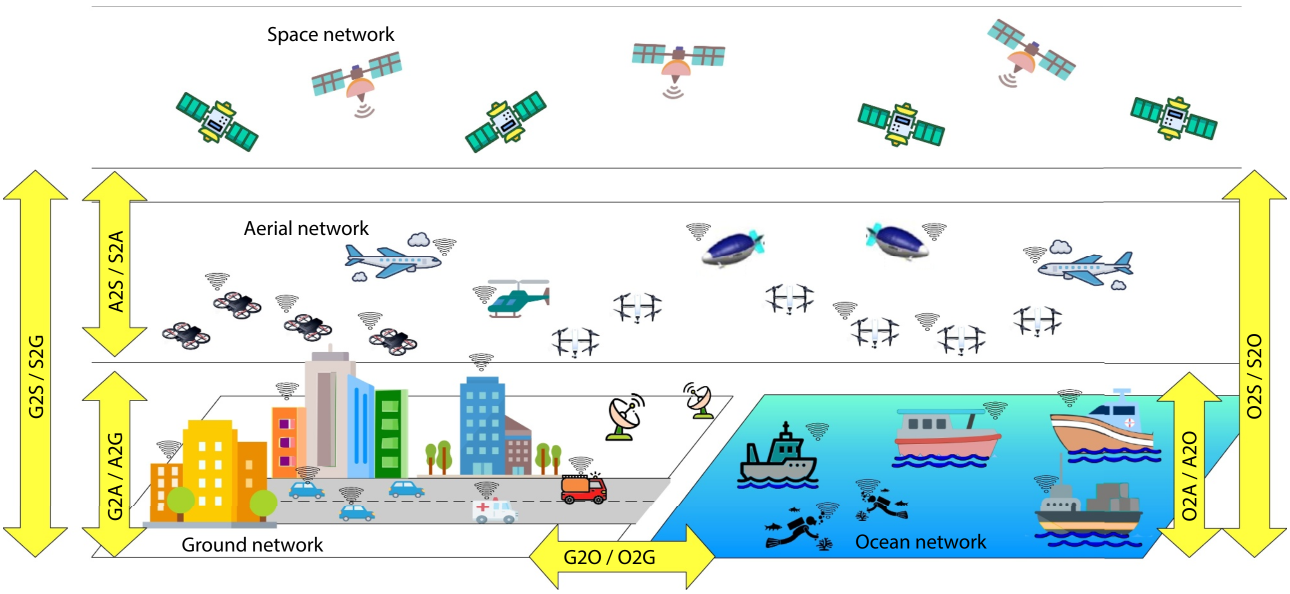

FIGURE 1 Schematic of ubiquitous IoT with integrated and overlapping ground, ocean, aerial and space networks. Legend: G2A/A2G (ground-to-aerial/aerial-to-ground), G2S/S2G (ground-to-space/space-to-ground), A2S/S2A (aerial-to-space/space-to-aerial), O2G/G2O (ocean-to-ground/ground-to-ocean), O2A/A2O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

which comprised of not only ground networks but also ocean, aerial and space networks.

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 is for these aircraft to act as relays through ground-to-aerial (G2A) wireless links for a rural IoT setting, where coverage issues require a UAV to be deployed so as 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.

Unmanned Aerial Vehicles can move in swarms and show a collaborative behaviour by leveraging communication facilities, with the aim of achieving a common goal [3]. 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.

Despite the many advantages, the use of drones involves a number of critical issues to be considered, such as privacy, security, and flight safety [4], 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 these issues, several efforts are taking place worldwide to make UAV flights safer. For instance, *U-space* is a 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 goal. The Single European Sky ATM Research Joint Undertaking [5] partnership was set up in order to manage this large scale effort, coordinating and concentrating all European research and development activities focussed on air traffic management. This way, a wide range of drone missions that are currently restricted will be possible in a near future thanks to a sustainable and robust European ecosystem that is globally interoperable.

The main contributions of this paper can be summarised as follows:

- The main challenges involved in sustainable aerial operations using UAVs are presented and discussed;
- Different cooperative solutions for collision-free flights are presented, including both sense and avoid techniques, and swarm management protocols. The performance of such solutions is presented briefly, and illustrative videos showing them in different scenarios are included;
- The main lessons learnt, based on the different experience of authors, are presented, highlighting which research areas remain open and significant for future contributions.

The rest of this paper is organised as follows. Section 2 presents an overview of the main challenges UAVs face when deployed for sustainability services. Section 3 describes some collaborative UAV solutions with particular emphasis on applications where UAVs swarms are mainly applied, and the respective solutions, along with UAV crash avoidance strategies to provide collision-free flights. Section 4 follows, dealing with some insights on the main gaps still existing with the current solutions, and sketching the main future research directions. Finally, conclusions are drawn at the end of the paper.

2 | UNMANNED AERIAL VEHICLE 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, such as dynamic and flexible geofencing to achieve flexible aerial operations in the context of U-Space [6], 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 drones 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 drones from entering no-fly zones, and keep them away from protected areas and critical infrastructures. Dynamic geofences can also be defined by a drone operator to create a temporary restricted airspace that avoids other drones 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 drones, it becomes possible that many drone operations take place in a same area (e.g. urban scenarios), and so a strict geofence per drone operation may become too restrictive, or severely affect the sustainability of operations.

An example is provided in Figure 2 where, in case A, UAV #2 had 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 case 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 was in fact operation away from the direct path followed by UAV #2 at the time it was approaching, meaning that the crossing of the geofenced area would not represent a problem for any of them.

To make such optimisation 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 minimisation.

The challenge described above can also be extended to the swarm case. For instance, if multiple drones from a same operator have to do a 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 drones fly sequentially in independent missions. Furthermore, in those cases, avoiding collisions with a swarm of drones instead of a single drone becomes much more complex. Inside the swarm itself, drones should also avoid collisions with their neighbouring drones. In this regard, planning optimal trajectories by avoiding collisions with other UAVs and obstacles remains a critical and open issue [7].

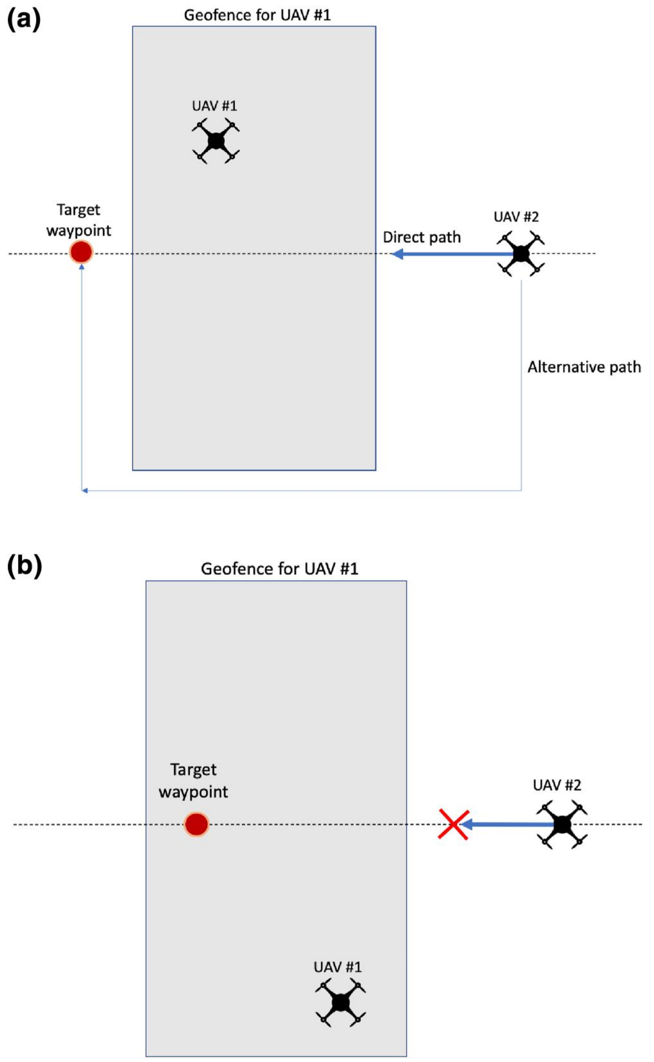

FIGURE 2 Examples of geofencing issues

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/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 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 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 [8]. Of course, network performance depend on the particular communication technology adopted. As an instance, in case of Free Space Optics data links, weather conditions and the atmospheric environment can cause fluctuations in amplitude and attenuation of the optical signal.

Energy Efficiency and Resource Management. Besides 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 characterised 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 optimised [9].

3 | 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, evidencing 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 other's paths; in addition, this section shows how to create and maintain UAV swarms undertaking both autonomous missions and manually guided swarm missions in order to minimise the flight UAV times, thereby reducing the impact of dynamic geofencing by releasing the airspace sooner.

In the following, the problem of dynamic geofencing based on sense and avoid techniques is addressed.

3.1 | 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 [4].

To address this challenge, which is formally known as Tactical Conflict Resolution, existing literature includes centralised approaches to solve this problem, as in Ref. [10]. In this approach, the computation time per UAV involved in a conflict grows exponentially with the total number of drones as solutions to conflicts are computed in a loop, being modified until no further conflicts are generated. In general, centralised approaches provide more control and monitoring about the air space but are computationally costly.

A distributed alternative to this problem known as Mission-Based Collision Avoidance Protocol (MBCAP) is presented in Ref. [11]. It provides 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.

Mission-Based Collision Avoidance Protocol has been implemented in real UAVs. Experimental results, along with large-scale simulation experiments, have validated the effectiveness of this protocol, evidencing the low overhead introduced both in terms of channel occupation and mission delays. Through practical validation, it was 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 km^2. Table 1 collects the performance of MBCAP, which shows an effective behaviour even when the number of UAVs reaches high values. In particular, it is found that the chances of collision remain in general very low, only surpassing the one crash per hour threshold for 100 UAVs. A video summarising these experiments is available online at https://youtu.be/bEdcsPX1hXY.

Further results of the MBCAP technique are reported in Figure 3, which depicts a Google Earth 3-D 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. It can be observed that the paths followed in simulation and in real experiments are quite similar and mostly overlap. A video showing these real experiments is also available online at https://youtu.be/xHnMuMOd9C0.

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

3.2 | Unmanned Aerial Vehicle swarm solutions

Although there are already some solutions for the automation of UAV swarm flights [12, 13], in certain situations the support for coordinated missions is required. Examples of such

TABLE 1 Number of Unmanned Aerial Vehicle (UAV) crashes and deadlocks avoided through the Mission-Based Collision Avoidance Protocol (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

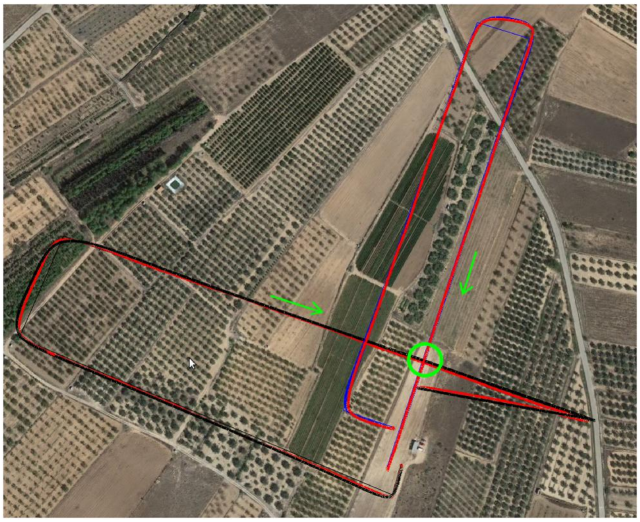

FIGURE 3 MBCAP simulation versus the real experiment in a perpendicular crossing

situations may include rescue operations and environmental monitoring as well as applications for large-scale agriculture 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 a 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 centralisation or decentralisation, (*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 drone 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 and rescue [14], fire tracking, or the monitoring of disaster areas. In 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 drones, which has the potential of minimising the usage of aerial space in order to release it as soon as possible for other operations in the same area. The next section addresses the swarm communication problem and then two proposals to create swarms efficiently are discussed.

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. In this context, studies such as Ref. [15] acknowledge the usefulness of wireless communications for UAV swarms. In particular, that study relies on measured Received Signal Strength Indicator values to coordinate the movement of multiple UAVs teams so as to avoid collisions. 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 neighbouring UAVs must also maintain consistency to avoid both collisions and interruption of communications, which hinders synchronisation, 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. [16] proposed an approach for the optimisation of the UAV swarm positions, in order to achieve a high multiplexing gain in multiple input, multiple output (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 [17] 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 optimise the capacity for the end-to-end link given that the source and the destination have uniform rectangular arrays.

2) *The MUSCOP protocol* [18]: 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 centralised approach where the master UAV synchronises all UAV slaves each time they reach an intermediate point in the mission. This 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 the ArduSim simulation framework, which allows to perform realistic experiments in two types of environments, that is ideal and lossy wireless channels, in order to validate the formations with different numbers of UAVs. An illustrative video (https://youtu.be/VLMsbL5B6tA) presents three experiments with different flight formations on the ArduSim simulator.

Figure 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 synchronisation among UAVs, thus becoming a critical problem. It is also worth mentioning that, for up to 300 m between contiguous UAVs, the time offset never exceeds the 1 s threshold, which is a significant achievement, and evidences the effectiveness of such solutions for addressing current challenges in this area.

3) *The FollowMe protocol* [19]: The other solution is the FollowMe protocol [19], which is 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 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 3-D 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. Figure 5 illustrates some of the concepts involved in the operation of this protocol, whose goal is to make sure that all UAVs follow as closely as possible its target coordinates $\overrightarrow{P_{k_{i+1}}}$, which are changing over time as the leader UAV is moving.

Concerning the performance of this protocol, Table 2 shows the different errors introduced by the protocol. Concerning the swarm formation coherence, the low error in the relative distances between slaves evidence that the swarm is maintained consistent, meaning that all slave UAVs move at a similar pace and maintain their relative distances. With regard to the leader, it can be seen that error values increase, meaning that the slaves experience some lag towards the leader, as expected. Nevertheless, such delay/distance lag is not critical in real applications, as it does not represent a problem for most types of missions.

Overall, 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 neighbouring UAVs are defined.

4 | 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. Based on the authors' 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 organise 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 characterised 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 Application Programming Interface. 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 min 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. In this regard, IEEE workgroup P1920.2 [20] is working on a new standard for Vehicle to Vehicle Communications for Unmanned Aircraft Systems.

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.

5 | CONCLUSIONS

Unmanned Aerial Vehicles 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 the COVID-19 pandemic.

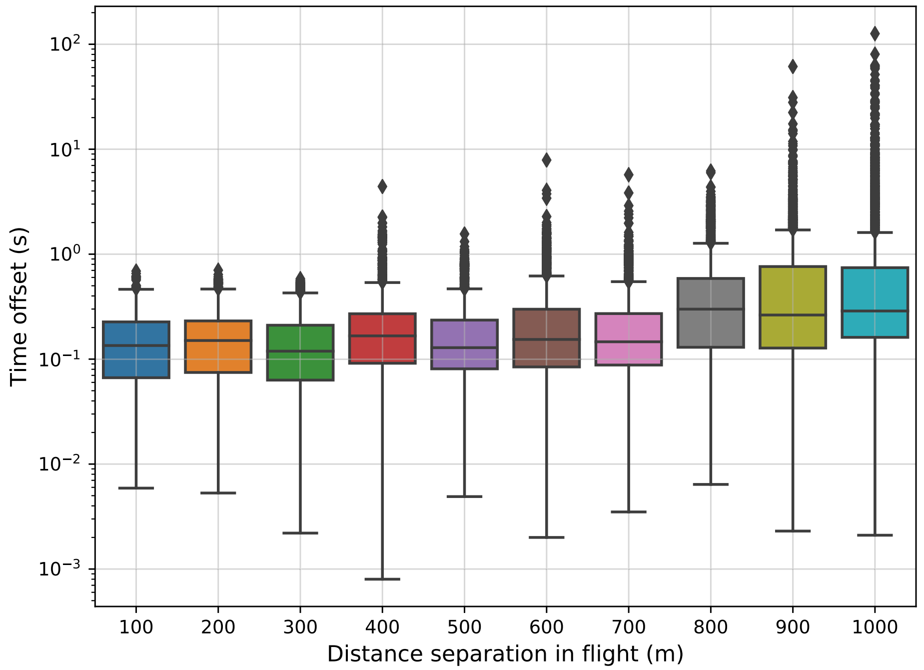

FIGURE 4 MUSCOP time offset when varying the inter-UAV distance, [18]

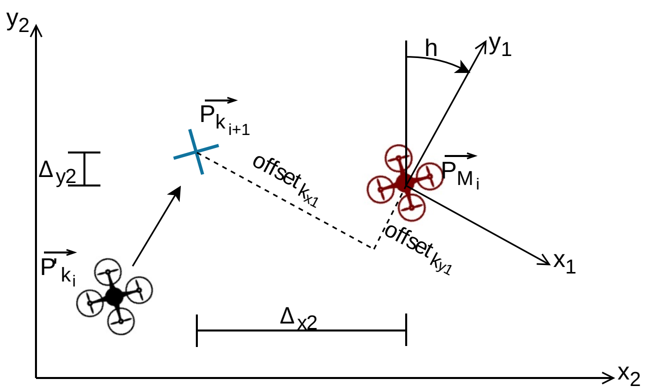

FIGURE 5 FollowMe protocol operation [19]: the target coordinates of the kth slave at instant $i+1$ (i.e. $\overrightarrow{P_{k_{i+1}}}$) is calculated considering the current location of the master Unmanned Aerial Vehicle (UAV) at instant i (i.e. $\overrightarrow{P_M}$) and the expected offset between the target location of the UAV and the master (i.e. offset$_k$)

TABLE 2 Errors values between slaves, and towards the leader, when using different flight formations (9-drone swarm)

	Error between slaves [m]			Error towards leader [m]		
Formation	**Mean**	**Max.**	**Std. Dev.**	**Mean**	**Max.**	**Std. Dev.**
Linear	2.48	4.42	1.18	21.76	24.96	1.90
Matrix	1.20	1.60	0.35	21.31	22.70	1.06
Circle	1.34	1.77	0.31	21.67	23.30	1.14

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, a sense and crash-avoidance solution is presented that has general applicability. Experimental results carried out directly on field as well as swarm management protocols are detailed, including some solutions that have been developed in the research group of authors. Experiments show it is feasible to achieve collision-less flights with a low communications overhead, and introducing minimal delay to the planned missions. Overall, the different contributions here presented will favour 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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CONFLICT OF INTEREST

None.

DATA AVAILABILITY STATEMENT

Data that support the findings of this study are available from the corresponding author upon reasonable request.

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