Chapter

Defining and Implementing Autonomy in Multi-Drone Systems

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Abstract

Defining autonomy or autonomous capability from the context of a single drone is often the default position. However, future drone applications will deploy as multi-drone systems comprising multiple drones. Such systems will carry out specific and complex tasks cooperatively in various use scenarios. It is imperative to understand how autonomy for these multi-drone systems could be better defined for design, regulatory and operational purposes. The chapter proposes a framework for defining and evaluating autonomy for multi-drone systems by segregating the system into hierarchies and layers. In the work, a typical multi-drone system is segregated into three (3) layers consisting of; Single Vehicle Control (Layer 1), Multi-Vehicle Control (Layer 2) and Global Mission Control (Layer 3). This framework could be beneficial to designers, regulators and standardisation efforts. Currently, some progress is in motion to find a consensus on the definition and ramifications of autonomy levels and human-autonomy interactions. This chapter contributes to the ongoing efforts by proposing a framework that addresses autonomy or autonomous capability for multi-drone systems.

Keywords: drone, UAV, autonomy, autonomous drones, multi-drone, UAS operations

1. Introduction

A drone which is also known as an Unmanned Aerial Vehicle (UAV) is a powered aerial platform or vehicle that does not have a human pilot physically on board. It can be designed to fly autonomously or remotely piloted hence also called a remotely piloted aircraft (RPA). According to the UK Civil Aviation Authority (CAA) and the European Union Aviation Safety Agency (EASA), an Unmanned Aircraft (UA) is ‘any aircraft operating or designed to be operated autonomously or to be piloted remotely without a pilot on board’ [1, 2]. The UK CAA & EASA also distinguish between autonomous and automatic operations. In automatic or automated operations, the drone follows pre-programmed instructions with the Remote Pilot (RP) still able to intervene in the flight [1, 2]. The term unmanned aircraft system (UAS) [2] is used when all other aspects of the system are considered including those on the ground. A typical UAS will include the UAV, ground control station (GCS), payload, control and data link and all other supporting equipment [3]. It is essential to lay out these key definitions to enhance our understanding and considerations for autonomy or autonomous capabilities in drones. Drones as shown in **Figures 1** and **2**, are mainly multirotor or fixed-wing (or some form of hybrid) with consequential technical and operational differences.

UAV autonomy is often defined from the context of a single drone and its capabilities to make decisions with minimal or no human input. The use of single remotely piloted drones within visual line of sight (VLOS) is commonplace and implemented across several use cases. However, the application of fully autonomous multi-drone systems is still futuristic. Multi-drone systems in the context of this chapter refer to the use of multiple drone (multi-drone) platforms in a coordinated fashion to carry out a specific or diverse array of tasks. It is important to distinguish the context and definition of autonomous multi-drone systems from swarming or drone swarms and the implications of the concept of systems.

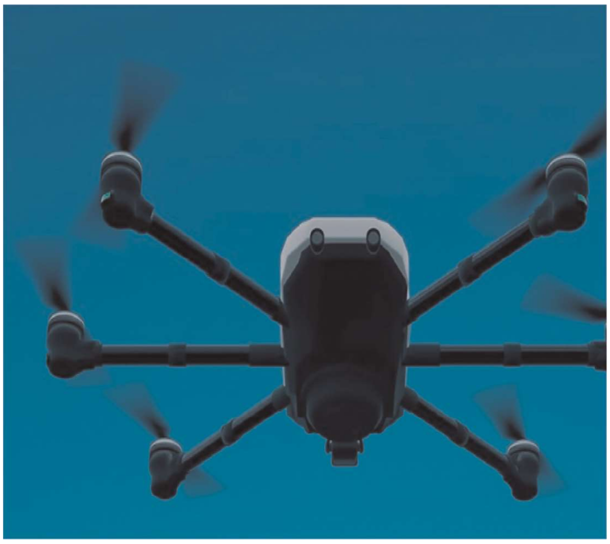


Figure 1.
Multirotor drone [1].

Figure 2.
Fixed-wing drone [4].

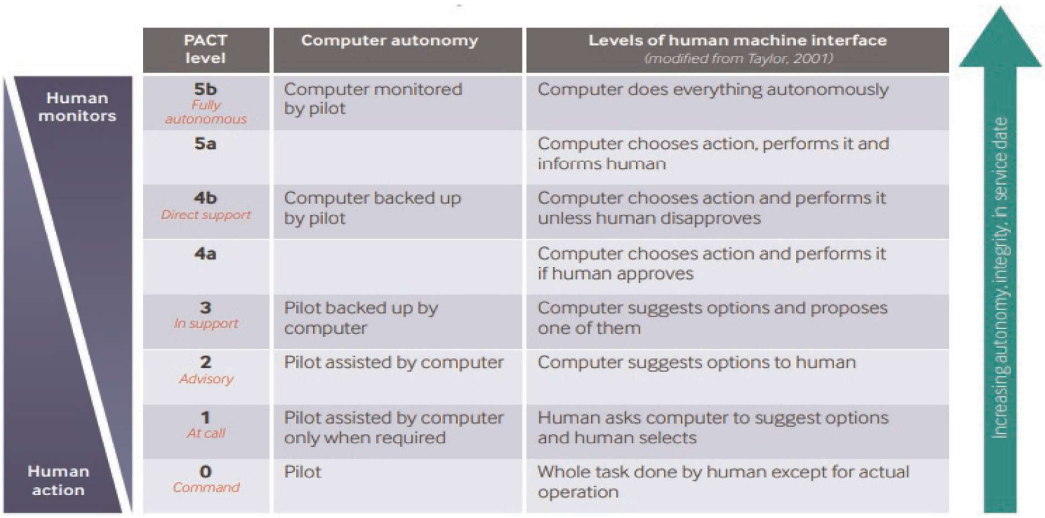
Drones are fast becoming mainstream and increasingly deployed within our industrial, social and digital domains to solve various challenges, for example, Agriculture, traffic management, logistics & last-mile delivery, power line inspection, connectivity and a host of other areas [4, 5]. According to GSMA, it is estimated that drones can boost Gross Domestic Product (GDP) by 1.6% in the UK alone by 2030 [6]. Globally, this trend is also noticeable and growing across industries and applications. Drone startups and technology companies are driving innovation and solutions with drones globally. On the regulatory front, efforts are ongoing to provide adequate oversight and support to find the right balance between safety and security on one hand and innovation on the other. The regulatory aspect of the drone business will be crucial in determining its short- and long-term viability, especially from a commercial standpoint. One of the key challenges is safely integrating them with the rest of the manned airspace. Currently, most drones operate outside controlled or restricted airspace minimising incidences with other airspace users [5]. This is in addition to the significant challenge of regulating growing drone traffic with aeroplanes, helicopters and other aerial systems.

The main contribution of this paper is to propose a framework or model to define the autonomy of multi-drone systems which are still in development or futuristic at this time. This framework will help understand the challenges of designing, implementing and regulating the operations of such autonomous multi-drone use cases. Regulators have been cautious in approving the use of fully autonomous drone operations and have constantly requested input from stakeholders. This chapter is expected to contribute some ideas to the ongoing conversation on the parameters for implementing safe and autonomous drone systems. Section 1, introduces some key definitions and context of the chapter. In Section 2, the concept of drone autonomy/autonomous operations is evaluated. BVLOS operations and the concept of autonomy were addressed in Section 4. In Section 5, the proposed framework detailing hierarchy and layers of autonomy for both single and multi-drone systems was introduced. Finally, the conclusions drawn by the author are captured in Section 6.

2. Defining autonomy or autonomous operations for drones

Generally, autonomy or autonomous capability is defined within the context of decision-making or self-governance in a system. According to the Aerospace Technology Institute (ATI), autonomous systems fundamentally can decide by themselves how to achieve the objectives of a mission without any human intervention [7]. These systems are also capable of learning and adapting to the changing state of the operating environment. Autonomy, however, is defined in levels and may depend on the design, functions and specifics of the mission or system [8]. Autonomy more broadly can be viewed as a spectrum of capabilities ranging from zero autonomy to full autonomy. The Pilot Authority and Control of Tasks (PACT) assigns levels of authority, from level 0 (full human pilot authority) to level 5 (full system autonomy), also applied to the automotive industry for autonomous vehicles (see **Figure 3**) [7]. Another general but useful model for describing levels of autonomy in unmanned systems is the Autonomous Levels For Unmanned Systems (ALFUS) [9].

The EASA in one of its technical reports provided some insight on autonomy levels and guidelines for human-autonomy interactions. According to the EASA, the concept of autonomy, its levels and human-autonomous system interactions are not settled and remain actively discussed in different domains (including aviation) as no



PACT level	Computer autonomy	Levels of human machine interface (modified from Taylor, 2001)
5b *Fully autonomous*	Computer monitored by pilot	Computer does everything autonomously
5a		Computer chooses action, performs it and informs human
4b *Direct support*	Computer backed up by pilot	Computer chooses action and performs it unless human disapproves
4a		Computer chooses action and performs it if human approves
3 *In support*	Pilot backed up by computer	Computer suggests options and proposes one of them
2 *Advisory*	Pilot assisted by computer	Computer suggests options to human
1 *At call*	Pilot assisted by computer only when required	Human asks computer to suggest options and human selects
0 *Command*	Pilot	Whole task done by human except for actual operation

Figure 3.
Pilot authority and control of tasks (PACT) [7].

common understanding of these terms currently exists [2]. Since these concepts are still fluid in a sense, it becomes a huge challenge for the UAS regulatory environment as these concepts remain largely unsettled. This chapter attempts to provide a framework that may address some of the current challenges around a common understanding of concepts across jurisdictions. A framework that will have universal appeal must be uncomplicated and effective in addressing the concerns of regulators across jurisdictions.

3. Autonomy in multi-drone systems

Multi-Drone Systems in the context of this chapter refer to systems or implementations where multiple drones work together to complete a specific task. In these implementations, a single drone cannot deploy singularly regardless of sophistication. It is also technically not a swarm since a swarm by definition constitutes simple entities or agents interacting locally with their environments and jointly achieving an emergent advanced global behaviour [10] which far outweighs what any agent could have achieved as a single entity. The fascinating murmuration of a flock of starlings is a good example of how simple local actions can have an incredible global output. However, in multi-drone systems, individual drones are not expected to be simple and oblivious to the global mission. The design of multi-drone systems requires individual drones to have elevated levels of autonomous capabilities. Some of the tasks or areas where multiple drones can be implemented are;

- Search and Rescue Missions

- Network Area Coverage and Connectivity

- Space Specific Explorations

- Exploration and Extraction in Hostile Environments

- Sensitive Material Handling and Transportation

- Coordinated Wildfire Containment

Some of the use cases cited above are currently being resourced by single drones working solo. For instance, the NASA ingenuity helicopter deployed for Mars exploration is a single drone (see **Figure 4**) [11]. Upgrading this single drone to a fully autonomous multi-drone system will entail having about 2 or more of these helicopters working in a coordinated and autonomous mode on the surface of Mars. This is also the case with the firefighting support drone (see **Figure 5**), used by the Spanish Emergency Military Unit (UME) in emergencies like wildfires and natural disaster responses [12]. These firefighting drones at the moment contribute mainly towards providing timely information to commanders on the ground about the progress of the

Figure 4.
Ingenuity - NASA's Mars helicopter [11].

Figure 5.
Spanish UME firefighting drone [12].

fires whilst reducing the risks to those on the ground. However, in a fully autonomous multi-drone firefighting system, drones can coordinate and contain or extinguish fires with minimal or no human intervention using artificial intelligence and machine learning-based capabilities. This is the desired trajectory for multi-drone systems, however, this has to be done with the highest safety case.

Whilst the autonomous capabilities for single drones can be technically easier to define and evaluate, the question is can these same considerations be extended to a multiple drone system? As shown in **Figures 6** and 7, most operational or commercial drone applications are mainly single drone operational models. For example, Zipline uses single drone operations to deliver its autonomous aerial logistics business. It provides on-demand blood delivery, vaccines and many essential medical products using its fixed-wing drones [13]. The key consideration here is that the logistics use case being delivered by Zipline does not meet the definition of a multi-drone system.

Figure 6.
Zipline's drone logistics use case [13].

Figure 7.
Alphabet's drone delivery use case [14].

The same applies to Aplhabet's drone subsidiary which employs a single drone operational mode for its drone delivery business.

4. Beyond visual line of sight (BVLOS) and autonomy

Aviation authorities are careful to ensure that safety is of the highest consideration in the operations of any manned or unmanned flight. This becomes even more critical as the weight of the vehicle increases or flies over populated areas. In the civil UAV domain, the mode of operation mostly supported by regulation is one in which the UAV is within the pilot's visual line of sight (VLOS), (between 500 m and 2 km) [15]. The International Civil Aviation Organisation (ICAO) insists that VLOS means a straight line along which the remote pilot or UA observer has a clear view of the UA [16]. This mode of operation is cautiously considered to minimise safety and security hazards that may result from flying beyond visual sight. However, this approach imposes significant challenges on innovation and prevents and imposes limitations on scaling the operations. The conservative and cautious regulatory position on keeping VLOS as the default mode is understandable but stifles innovation in the civil UAV domain. Another option for UAS operations is the extended visual line of sight (EVLOS), where the pilot's view is extended by using other human observers positioned within the visual line of sight of the drone. The EASA guidance document defines BVLOS operations broadly as any UAS operations that are not conducted under VLOS conditions which specifically require the remote pilot to maintain continuous unaided visual contact with the unmanned aircraft [2] (see **Figure 8**).

BVLOS, which involves the UAV being able to continue operations beyond the pilot's field of view or observation, is highly restricted for civil UAS operations in most jurisdictions globally [15]. To operate safely and fly autonomously, drones will need to be BVLOS certified with reliable and secure methods for control [4]. BVLOS operations, however, have been in use by advanced military and defence establishments for a long time now. In essence, the issue is not just about the technological capabilities required for BVLOS but its management, integration and operational impact on the

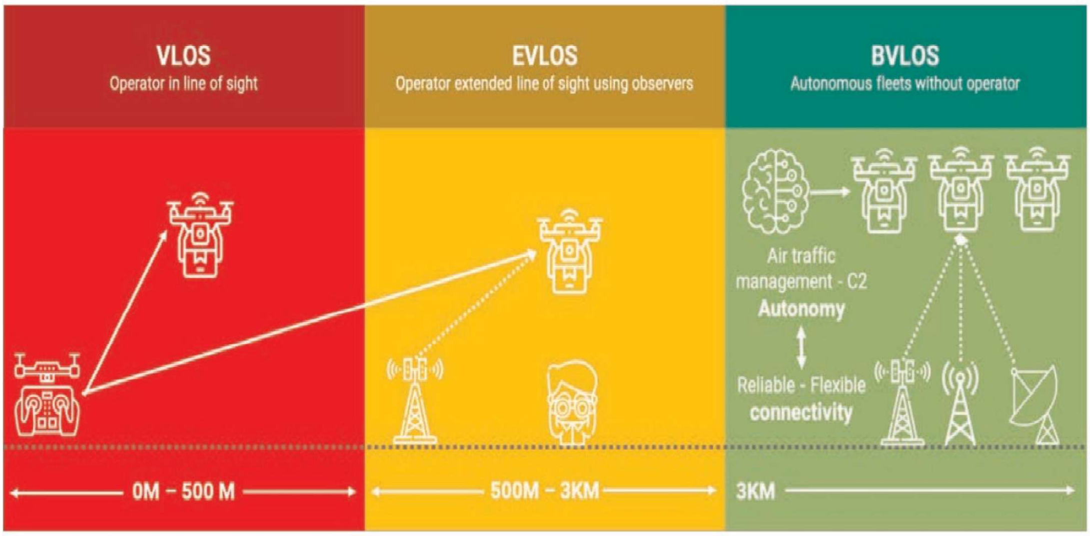


Figure 8.
Illustrating VLOS, EVLOS & BVLOS [17].

safety and security of the civil aviation environment. That is why this chapter is more focused on the autonomy models or frameworks that will aid the management, operations and regulation of UAS within the civil aviation domain.

Currently, a jurisdiction's BVLOS approval framework can be used to gauge appetite and readiness for increased levels of autonomous UAS operations. The current Federal Aviation Authority (FAA) Part 107 rules for commercial drone operations prohibit flying BVLOS [18], though special waivers and approvals are granted on a case-by-case basis to companies testing or trialling use cases. BVLOS operations can unlock the potential of the drone industry and specifically the multi-drone use cases. It will enable the capability to use connectivity, cloud infrastructure and other enabling technologies to scale multi-drone applications. However, one crucial requirement for BVLOS operations is a highly reliable C2 link which is imperative to fulfilling the BVLOS safety case. In terms of defining autonomy especially in multi-drone operations, is BVLOS capability the ultimate expression of autonomy? These questions are important to guide and inform regulatory oversight of multi-drone implementations and use cases.

5. Defining and segregating autonomy into hierarchies/layers

One approach to addressing the autonomy challenge is to segregate autonomy in drones and multi-drone systems into hierarchies/layers. These layers will have standard definitions and protocols to guide technology development and regulatory oversight. The author proposes two distinct layers for single drone autonomy models which will consist of Vehicle/Platform Control (Layer 1) and Mission Control (Layer 2), see **Figure 9**. As shown in **Figure 9**, multi-drone systems on the other hand will have three (3) layers consisting of Single Vehicle/Platform Control (Layer 1), Multi-Vehicle/Platform Control (Layer 2) and Mission Control (Layer 3). These layers or hierarchies are not necessarily physical but logical to provide both conceptual and functional ways to manage the complexities in design, technology standards, regulation and operations. It is important to ensure that all aspects of the framework and supported protocols are open which will drive innovation and lower barriers to entry.

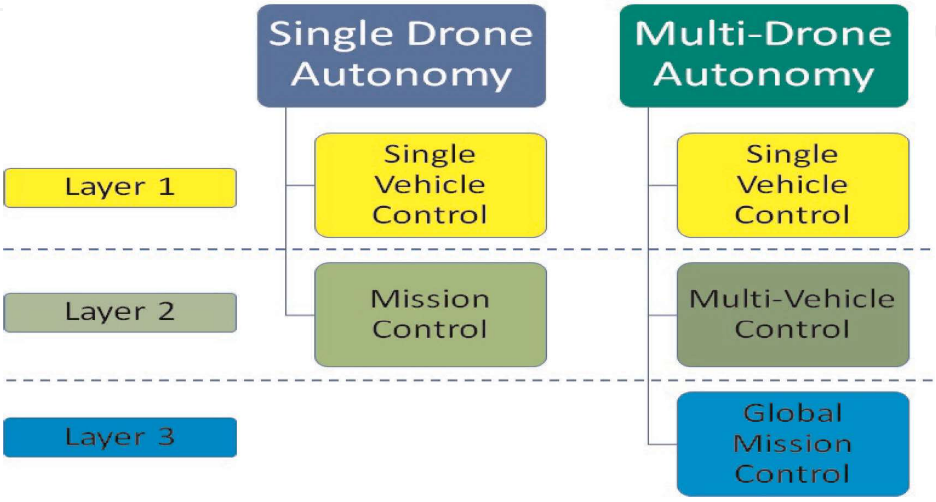


Figure 9.
Autonomy hierarchies/layers for multi-drone systems.

5.1 Hierarchy and layers for single drone autonomy

The autonomy hierarchy and layers for a single drone are outlined below and capture a conceptual model that is consistent with current implementations.

- **Single Vehicle Control - Layer 1:** This layer occupies the highest position in the single drone autonomy hierarchy or model. In practical terms, this layer ensures that the drone remains airborne operating safely and able to return/land safely even in the event of operational challenges without human pilot intervention. In a typical single drone setup, this layer includes the Flight Control System (FCS) and any other hardware/software needed to ensure the vehicle can fly safely and securely without collision or stalling from one set point to another.

- **Mission Control - Layer 2:** In a single drone system, the mission control layer is tasked with making decisions and fulfilling the objective of the mission as defined. It is the mission managing layer and ensures that the drone can autonomously handle the mission. In a typical single drone setup, the mission control layer will largely need some sort of additional computing hardware to process mission control tasks (e.g., signals from different sensors). It is currently common to find companion computers supporting the mission control tasks added as extra hardware separate from the FCS. In more advanced systems, integrated units can handle both vehicle and mission control tasks, however, the hierarchy (as shown in **Figure 9**) should prioritise the vehicle control layer with the authority to override mission control in critical scenarios. It is therefore necessary for designers of autonomous drones to ensure that this hierarchy model is clearly defined at the fundamental level of the drone design philosophy. There is also the design consideration to be made in terms of the level of autonomy each layer should be tuned to. It is also possible to experiment with different permutations of autonomy levels (PACT levels) to find the optimal combination. However, the ideal goal or objective is to have both the vehicle and mission control layers operating at full autonomy levels. Notably, the single vehicle autonomy model does not have a third layer.

5.2 Hierarchy and layers for multi-drone drone autonomy

The multi-drone autonomy model has 3 layers, unlike the single drone case which has only 2. It is important to emphasise that multi-drone systems are not just multiple drones flying autonomously. Multi-drones in this context are fully autonomous drones flying in a coordinated fashion to achieve a specific goal which cannot be done by any single one of them. In such a scenario, the operational environment is more complex than the single drone scenario. In these types of multi-drone systems, the layers of autonomy are explained further below;

- **Single Vehicle Control - Layer 1:** A multi-drone system is made up of single drones with autonomous capabilities. In a multi-drone setup, the single vehicle control layer occupies the same hierarchy and serves the same functions outlined in the single drone model. It is important to establish that the autonomy model proposed in this work elevates the hierarchy of the single drones that make up the autonomous multi-drone system. These single drones are expected to have elevated levels of intelligence and decision-making capabilities for the multi-drone system to fulfil its mission, which is somewhat contrary to the philosophy of swarming or swarm intelligence-based models. In essence, the vehicle control layer is the same for both single and multi-drone systems. As a practical matter, a single drone should have sufficient autonomy to make decisions that may override the global mission objective if prevailing conditions threaten its safety or security. Indeed, it is due to issues of this nature that the author proposes a model of evaluating autonomy for multi-drone systems.

- **Multi-Vehicle Control - Layer 2:** In the multi-drone system autonomy framework, the second layer is the multi-vehicle control layer tasked with coordinating the multi-vehicle decision process. This layer introduces the complexity inherent in multi-drone systems. For the first time, the issue of coordination and information exchange comes into focus. In some sense, this layer is difficult to simulate or conceptualise. Centralised control is not supported as it defeats the concept of autonomy. Participating drones retain a subset of the overall control structure. It is challenging to define autonomy at this layer as a cumulative concept. The author would rather define autonomy at this layer as a distributed and dynamic concept or capability that fluctuates based on what happens in Layer 1. The structure of this layer must be robust and flexible to adapt as local states in Layer 1 keep evolving. The ability of the entire system to manage and learn from these changes is key to survival and fulfilling mission goals. Depending on the use case or mission, the constituent drones in the system have to make decisions relevant to their local environments whilst tracking impact on the entire stability and posture of the fleet. How to functionally define and implement the autonomy existing at this layer makes the multi-drone system autonomy a challenging concept for design and regulation. This layer could be viewed as a bridge linking the single vehicle control layer to the global mission control layer.

- **Global Mission Control - Layer 3:** This is the layer that handles the actual mission or the objective of the multi-drone system. It ensures that the global mission i.e. the overall objective of the multi-drone application is achieved. For instance, an autonomous multi-drone system that is tasked with identifying and extracting a toxic or radioactive piece of material must be able to autonomously coordinate all the drones in the mission to identify and transport the mission to the designated site. It is interesting when the decision-making process and the autonomy requirements are analysed against the framework proposed. Each drone in the fleet must be equipped with sensors that will enable it to identify the target material, fly in formation, and position appropriately to lift and extract the material. The mult-drone system in this scenario must be able to understand the mission and coordinate with other drones to fulfil it. However, this layer is the lowest in the hierarchy and can be overridden by the layers 1 or 2.

6. Conclusions

The future of drones lies in the maturity and application of autonomous multi-drone systems capable of fulfilling different use cases. However, the definition of autonomy or autonomous capability is not settled for the multi-drone operational scenario. Whilst the push for the standardisation and approval for beyond visual line of sight (BVLOS) operations is important, it is equally necessary to have a common model or framework to guide BVLOS for multi-drone use in the civil aviation space. Multi-drone systems are very different from single drone uses although a significant aspect of current regulation is predicated or informed by single drone operational concepts. This chapter lays out a framework that may be of interest to regulators, UAV companies and the majority of other stakeholders. The framework defines autonomy in both single and multi-drone implementations in hierarchies and layers. The proposed multi-drone systems were segregated into 3 main layers and hierarchies of autonomy namely single vehicle control (Layer 1), multi-vehicle control (Layer 2) and global mission control (Layer 3). In this framework, Layer 1, which is single vehicle control, occupies the highest hierarchy and hosts functions performed by the flight control system (FCS) for instance. By developing and segregating these autonomy hierarchies, the design, implementation and regulation of autonomous multi-drone systems can be approached and managed efficiently across jurisdictions.

6.1 Future work

This is still a very dynamic area of research with multidisciplinary implications. As regulators request for input over the next few years, it is important to develop prototypes and demonstrations of the framework and ideas shared in this chapter. It is also important to look into how the physical forms of the drones may affect its operational environment/specific use cases and how that may impact autonomy considerations. Whilst the proposed framework is inherently designed to be agnostic to technology, it will be helpful to see how much technological developments will impact current thinking and by extension the extant regulatory regime.

Abbreviations

UA	Unmanned Aircraft
UAV	Unmanned Aerial Vehicle
UAS	Unmanned Aircraft System
VLOS	Visual Line of Sight
EVLOS	Extended Visual Line of Sight
BVLOS	Beyond Visual Line of Sight
PACT	Pilot Authority and Control of Tasks
ALFUS	Autonomous Levels For Unmanned Systems
EASA	European Union Aviation Safety Agency
FAA	Federal Aviation Authority
CAA	UK Civil Aviation Authority
ICAO	International Civil Aviation Organisation

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