

BEYOND THE HARDWARE: REGULATION AND CERTIFICATION AS THE CRITICAL PATH TO ADF AUTONOMOUS CAPABILITY

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Abstract

The developmental trajectory of Uncrewed Aerial Systems (UAS) is currently undergoing a significant bifurcation. While small-scale, remotely piloted systems have achieved operational ubiquity in both commercial delivery and asymmetric warfare, the next generation of capability—large-scale Autonomous Collaborative Platforms (ACP) and heavy-lift supply drones—remains stalled in the 'trough of disillusionment'. This paper argues that the primary barrier to fielding these future capabilities is no longer aerodynamic or mechanical, but regulatory and institutional. By synthesising technology trend modelling and bibliometric analysis from both the combat and logistics domains, we demonstrate that the invisible barriers of regulation, certification, and reference architectures is lagging significantly behind technological innovation. Case studies and analysis of the evolution of large supply drones and Collaborative Combat Aircraft (CCA) reveal that while the physics of autonomous flight and hydrogen propulsion are solvable, the certification basis for these technologies does not exist. For the Australian Defence Force (ADF), this regulatory lag presents a critical strategic risk: without parallel investment in certification frameworks for autonomy, hydrogen propulsion, and advanced sensing, the industry cannot deliver compliant systems that can be introduced into service. To transition from a fast follower to a lead adopter, the ADF must treat regulation as a core capability, co-developing the airworthiness, digital and legal frameworks required to validate the autonomous systems of the 2030s.

Keywords: uncrewed aerial systems, autonomous drones, airspace regulation, drone certification

1. Introduction

Uncrewed Aerial Systems (UAS) have long been explored for combat and logistics missions [1, 2, 3, 4, 5, 6]. While remote-controlled, or remotely-piloted, systems like the MQ-9 Reaper have seen extensive operational use in recent history, they still require the pilot to be in the loop, and the full benefits of autonomy are yet to be realised [7, 3]. The trajectory of these systems has evolved from niche surveillance tools into central pillars of modern air power, most recently heralded as the 'heros' of Operation Epic Fury [8].

In the combat domain, Uncrewed Combat Air Vehicles (UCAV) have been in mature development for the last 30 years. The General Atomics family of systems, particularly the MQ-1 Predator and MQ-9 Reaper, saw prolific use during the Global War on Terror [9, 10]. More recently, combat drones have impacted the nature of warfare, both from non-state actors seeking asymmetric effects [11] and by major powers. The Ukraine-Russia war has seen combat drones employed to a limited extent in the early phase of the war, though reliable ground-based air defence has constrained more widespread use by denying them access to the air [12, 13]. Despite this investment, much of the potential of combat drones to be a potent autonomous military capability remains unrealised.

Simultaneously, the logistics domain has seen a parallel evolution. Supply drones have been in development for over six decades. The first uncrewed helicopter, the Gyrodyne QH-50, flew in 1960, demonstrating the potential for rescue and spare parts delivery [14]. In the commercial sector, small parcel delivery drones have achieved operational success. Companies like Wing, Amazon Prime Air,

and Zipline commenced initial operations between 2014 and 2016, having solved complex routing and battery optimisation problems to make autonomous delivery a reality [15, 16].

However, a 'hype gap' has emerged. Despite the success of these distinct categories, the promised revolution of large-scale, fully autonomous systems—whether they are Collaborative Combat Aircraft (CCA) flying alongside F-35s or heavy-lift supply drones replacing trucks—has not yet materialised. Our research into the technological readiness of these systems suggests that while the physics are solvable, the pathways to operational service are also blocked by non-technical barriers.

Specifically, the development of fully autonomous combat aircraft and large-scale supply drones relies on technologies that currently lack a certification basis. This lack of regulation spans hardware to software. There are no agreed standards for how a machine validates a lethal decision without a human in the loop. There are no finalised regulations for certifying hydrogen-electric powertrains for unmanned aviation [17]. There is no reference architecture for how an autonomous supply drone perceives a landing zone in unprepared terrain [18].

This paper provides research findings that identify some of these common, significant regulatory challenges. The study utilises technology bibliometric trend modelling and activity mapping methodologies to forecast the applicability of technologies that are currently identified as operational challenges. We argue that for the Australian Defence Force (ADF), leading the adoption of emerging UAS technology is not just a funding problem; it is a certification problem. To avoid acquiring fleets of experimental oddities that cannot be certified for safe flight, the ADF must invest as heavily in the regulatory 'airframe' as it does in the physical one.

2. Methodology

The technologies that led to the highly automated combat UAS and experimental platforms we see today are products of academic and community bodies of knowledge developed over several decades. These systems are hybrids of technology from 4th and 5th-generation fighter aircraft developments, and tactical and operational UAS developed primarily for intelligence, surveillance, and reconnaissance (ISR) [19].

To trace this evolution, we employed a comprehensive bibliometric literature review facilitated by the software tool Litmaps. Litmaps uses artificial intelligence algorithms to identify related and relevant articles based on topic, author, publication location, and citation chaining [20]. This allows for a bibliometric review that visualises the 'ancestry' of scientific citations.

Most of the development in combat drones has been undertaken predominantly by the military, with little recorded in open academic publications. Similarly, the rapid evolution of commercial supply drones has also outpaced academic literature. Therefore, to forecast and model the readiness of the technologies with recency, it is essential to track recent and contemporary developments by utilising open-source intelligence (OSINT) and industry intelligence. These intelligence artifacts were tracked and linked in the same Litmaps analysis databases, thereby extrapolating on documented research trends.

In Australia, where drone technology development and innovation are relatively advanced, industry engagement is also a valid tool for exploring and scrutinising industry claims. Notably, one of the most advanced Western CCA developments is the Boeing MQ-28A Ghost Bat, and the most utilised flight controller for experimental UAS, ArduPilot, is also Australian [21, 22]. Hence, we engaged with domestic industry to scrutinise and extrapolate key technologies.

Our mapping correlates with the maturity of a technology set. By displaying the Litmaps chronologically along the x-axis and citation count along the y-axis (where node size is proportional to citation count), we can visualise the impact and maturity of specific technical subsets [23, 24]. A dense web of high-impact citations indicates a mature technology ready for militarisation. A sparse map with low citation counts indicates a technology still in the research phase, or one where development is sequestered in proprietary silos.

The actual methodology

This methodology allows us to distinguish between 'hype' and 'breakthrough' research, providing a data-driven basis for our analysis of regulation as a 'lag'.

3. The Technical Trajectory: A Tale of Two Domains

To understand the magnitude of the regulatory challenge, one must first appreciate the scale of the

technical ambition. Both the combat and supply domains are moving toward systems that are larger, faster, and fundamentally more autonomous than current inventories. The engineering is advancing rapidly, creating a widening gap between what can be built and what can be allowed to fly.

3.1 The Combat Trajectory: From Pilot-in-the-Loop to ACP

The evolution of UCAVs has been characterised by a steady progression in airframe sophistication and a slower, more cautious evolution in autonomy. We can trace this through distinct eras of development.

3.1.1 The Era of Remote Control: General Atomics MQ-9A Reaper

The MQ-9 Reaper, also referred to as the 'Predator B', is a significant aircraft in the history of UAVs. It represents a substantial evolution from its predecessor, the MQ-1 Predator, transforming the role of drones from surveillance to a 'hunter-killer' capability [25]. Development began in the late 1990s as a company-funded project by General Atomics Aeronautical Systems, Inc. (GA-ASI), with the goal of creating a larger, more powerful, and heavily armed version of the Predator.

The key technology elements that enabled the success of the Predator were the maturing of fly-by-wire (FBW) flight control systems and high bandwidth satellite communications (SATCOM). These enabled the pilot to be removed from the aircraft and the cockpit to be located anywhere in the world. The MQ-9 achieved initial operational capability in October 2007, becoming the backbone of the USAF's remotely piloted aircraft fleet. Its ability to carry precision-guided bombs and Hellfire missiles, combined with long endurance, allowed it to provide persistent surveillance and strike capabilities against time-sensitive targets [9].

Over the years, the MQ-1/9 family has amassed over 9 million flight hours [26]. The incremental adoption, driven by tactical advantages and reduced risk to personnel, lays the groundwork for greater autonomy, but the system remains fundamentally 'remotely controlled'. The pilot is firmly 'in the loop'.

3.1.2 The Era of Stealth Demonstrators

In the 2000s and 2010s, a series of flying wing demonstrators proved that stealthy, autonomous flight was possible.

- **Northrop Grumman X-47:** The X-47 project evolved under the US Navy's Unmanned Combat Air System Demonstrator (UCAS-D) program. The goal was to demonstrate that a stealthy, fighter-sized uncrewed aircraft could operate seamlessly from an aircraft carrier. Key milestones included the first-ever arrested landing of an unmanned aircraft on a moving carrier (2013) and the first automated aerial refuelling in 2015. This program proved that complex, high-stakes maneuvers could be automated [27].

- **Dassault nEUROn:** A European experimental UCAV launched in 2003, nEUROn was designed to validate stealth (flying-wing design, composite materials), autonomous take-offs and landings, and internal weapons bay operations [28]. In 2014, it demonstrated formation flight with a crewed Rafale fighter, a crucial step in proving the concept of manned-unmanned teaming.

- **BAE Systems Taranis:** A UK effort to develop a long-range, stealthy, and highly autonomous UCAV. Taranis made its maiden flight in 2013 at the Woomera Test Range in South Australia. It demonstrated key technologies including stealth, automated navigation, and long-range control via satellite link [29].

3.1.3 The Era of Collaborative Combat and Attritability

Today, the focus has shifted to 'attritable' mass—low-cost aircraft designed to fight alongside crewed assets.

- **LCAAT and XQ-58A Valkyrie:** The Low-Cost Attritable Aircraft Technology (LCAAT) initiative aimed to break the cost curve of military aviation. The most significant output was the Kratos XQ-58A Valkyrie. Its rapid development (2.5 years) and low cost proved that attritable drones were feasible. It was designed for runway-independent operation and has demonstrated manned-unmanned teaming with fighter jets [30].

- **Skyborg and X-62A VISTA:** The AFRL Skyborg program sought to develop an autonomous 'brain' for these aircraft. In 2024, the X-62A VISTA (a modified F-16) flew fully under the control of an AI system, engaging in the first-ever human versus AI dogfight. This demonstrated that AI agents can perform complex air combat manoeuvres.

- **Collaborative Combat Aircraft (CCA):** These initiatives have culminated in the CCA program, which includes the Anduril FQ-44 Fury, the General Atomics XQ-67A, and the Australian Boeing MQ-28A Ghost Bat. The Ghost Bat, developed in partnership with the Royal Australian Air Force, is the first military combat aircraft designed and manufactured in Australia in 50 years [31] and has fired it's first air-to-air missile in test [32].

3.2 The Supply Trajectory: Scaling Up

Parallel to the combat evolution, the logistics domain is attempting to scale from small parcel delivery to heavy-lift supply.

3.2.1 Small Parcel Success

Small supply drones gained social license largely due to the global pandemic of 2020. However, their technical success was predicated on solving two key algorithmic challenges between 2014 and 2018:

- **The Battery-Charger Problem:** Research by Hong and Park optimised the location of recharging stations and battery assignment, turning theoretical math problems into 24-hour operations [33, 34].

- **The Vehicle Routing Problem:** Extensions of the 'Travelling Salesman Problem' allowed for the coordination of fleets of drones. Algorithms like the 'Flying Sidekick' model (tandem routing with trucks) and 'Cluster-First, Route-Second' strategies were critical [35].

With these solved, companies like Wing and Amazon Prime Air could scale.

3.2.2 Heavy Lift Stagnation

Scaling this to large supply drones (500kg+ payload) has stalled. Early attempts involved retrofitting helicopters, such as the Kaman K-MAX [7], which demonstrated autonomous cargo delivery in Afghanistan. More recently, Sikorsky has demonstrated an optionally piloted UH-60 Black Hawk [36]. However, these are retrofitted legacy platforms, not purpose-built autonomous supply systems.

3.2.3 AAM and advanced eVTOL demonstrators

The commercial Advanced Air Mobility (AAM) sector has emerged as a high-visibility testbed for scaling electric vertical takeoff and landing (eVTOL) platforms and advanced flight automation into controlled airspace. Industry leaders such as Joby Aviation and Wisk Aero illustrate two diverging architectural pathways to market, each exposing distinct certification hurdles. Joby has prioritised piloted operations using distributed electric propulsion (DEP) [37], pursuing type certification under airworthiness special conditions as an evolutionary bridge to commercial passenger services. In contrast, Wisk has pursued a self-flying, autonomous-first model underpinned by multi-layered detect-and-avoid (DAA), software-defined decision-making, and supervisory fleet management [38]. Both paradigms show that while power electronics, structural composites, and aerodynamic transition mechanisms have reached high Technology Readiness Levels (TRLs), operational entry remains bottlenecked by the lack of mature airworthiness and airspace-integration baselines.

For military stakeholders like the ADF, the progress of commercial AAM demonstrators highlights both an opportunity and a cautionary precedent. These platforms validate the feasibility of quiet, runway-independent logistics and intra-theatre mobility; however, they rely heavily on bespoke Means of Compliance (MoC) negotiated individually with civilian regulators. The resulting lack of standardised certification frameworks for high-voltage powertrain safety, autonomous contingency routing, and non-deterministic flight software directly mirrors the regulatory void facing heavy-lift uncrewed logistics and autonomous collaborative platforms. Without established dual-use certification baselines, military adaptations of emerging eVTOL and AAM technologies will remain confined to developmental flight test regimes, unable to transition into scalable, certified operational capability.

4. The Invisible Barrier: Regulation and Certification

The primary finding of our cross-domain analysis is that three specific regulatory voids are currently stalling progress: the Autonomy Deficit, the Sensing Gap, and the Propulsion Void. These non-technical barriers represent a challenge for advancing large UAS more profound than the hardware technologies themselves.

4.1 The Autonomy Deficit and Reference Architectures

One of the most profound challenges is the definitional and architectural ambiguity surrounding autonomy. There is currently no globally agreed standard for what constitutes ‘safe’ autonomy in a military context.

4.1.1 Defining the undefinable

Defining autonomy has proven inconsistent. The Australian Association for Uncrewed Systems (AAUS) has recommended a harmonised set of definitions to distinguish between 'automatic' and 'autonomous'.

- **Automation:** Describes a system's ability to perform actions based on predefined criteria without human intervention.
- **Autonomy:** Describes a system's independence and self-governance, including the ability to make decisions independently of an operator to achieve a desired goal [39].

The progression is viewed as a spectrum from Level 0 (No Automation) to Level 5 (Full Autonomy) [40]. Current UCAVs like the MQ-9 are at Level 1/2 (remotely controlled with some assistance). The goal for ACP is Level 4/5.

4.1.2 The Missing Architecture

The critical missing piece is a useable Government Reference Architecture for Autonomy (A-GRA). In the software-defined world of modern combat, the government must own the architecture to ensure interoperability and safety. Currently, no such reference architecture has been published. Without an A-GRA, research institutions and manufacturers are effectively ‘guesstimating’ design requirements. This creates a circular paralysis: industry cannot build to a standard that doesn't exist, and regulators cannot write the standard because they haven't seen the technology data.

4.1.3 The Human-Out-of-the-Loop Dilemma

This deficit is particularly acute for UCAVs involving lethal force. Moving to Level 5 Full Autonomy implies ‘human-out-of-the-loop’ operations. This raises profound ethical and legal dilemmas regarding the Laws of Armed Conflict (LOAC). The concept of meaningful human control is central to current debates, but certification bases for algorithms that make lethal decisions do not exist. As highlighted by Weiss and Patt, "it is irrational, irresponsible, and perhaps even unethical to contractually require more than a broad set of outcomes because we simply cannot know actual architectural requirements a priori in a software-defined world" [41].

4.2 The Sensing and Landing Gap

For large supply drones and tactical UCAVs, the ability to land without a runway and without GPS is essential. This requires landing zone autonomy—using onboard LIDAR, optics and other advanced sensors to profile the ground and make a safety decision. These have not yet been developed to a maturity level where they can be purchased off the shelf.

4.2.1 Inadequate Standards

Current regulations are insufficient. While standards like RTCA DO-365 and FAA TSO-C211 exist [42], they cover detect and avoid (DAA) for airborne traffic, supporting a technology sub-sector that has not yet matured a DAA that can be purchased off the shelf. While they have enabled a future air sensing capability, they do not prescribe performance standards for ground sensing or autonomous decision-making regarding terrain safety.

4.2.2 The Data Void

Our bibliometric analysis of this field using Litmaps reveals a scarcity of high-impact research on landing zone autonomy. The highest cited works achieve only ~230 citations, and none show a pattern indicating ‘breakthrough’ research [43]. This suggests that vital work is either immature or

sequestered in proprietary silos. Without open standards for how a drone 'sees' the ground, certification authorities cannot validate that a landing system is safe. This forces designers to keep pilots in the loop, negating the economic and tactical benefits of the system.

4.3 The Propulsion Void

The third barrier is specific to the heavy-lift/long-endurance requirements of future UAS: the certification of high-energy, cheaper powertrains.

4.3.1 Beyond Batteries

For a logistics drone to achieve useful ranges (e.g., >500km) with heavy payloads, UAS must move beyond lithium-ion batteries to hydrogen or hybrid-electric systems. Many e-VTOL and AAM efforts underway today rely entirely on this technology reaching maturity to be viable [44].

4.3.2 Regulatory Lag

The regulatory roadmap for these technologies, however, is arguably a decade away. The FAA and EASA only published initial roadmaps for hydrogen in 2024/2025, with policy readiness not expected until ~2030. Authorities must urgently codify standards for ground and airborne storage of these alternative fuels, cryogenic support, crashworthiness, and explosion prevention—considerations that are physically distinct from traditional aviation fuels.

4.3.3 Safety Cases

There are no mature standards for the crashworthiness of cryogenic tanks in composite airframes, nor for the thermal management of megawatt-class power electronics in flight [45]. For the ADF, this means that any hydrogen drone invested in or acquired today or in the near future is essentially uncertifiable for general airspace use, restricting it to restricted military ranges and severely limiting its logistics utility in real-world missions.

5. Implications for the Australian Defence Force

For the ADF, these regulatory gaps are not abstract academic problems; they are capability risks. Australia has positioned itself as a potential leader in this field, being home to the Ghost Bat and a vibrant commercial drone ecosystem, however, this sovereign advantage is fragile.

5.1 The 'Fight Tonight' vs. 'Fight Tomorrow' Risk

The lack of certification pathways creates a bifurcation. The ADF can buy 'Fight Tonight' capabilities—standard, remotely piloted systems like the MQ-9B SkyGuardian—which are mature, certified, and safe [46]. Or, it can invest in 'Fight Tomorrow' autonomous systems, which are currently being developed in a regulatory grey zone [47].

The risk is that without parallel investment in regulation, the 'Fight Tomorrow' fleet will struggle to graduate from the testing range. The ADF risks acquiring fleets of advanced prototypes—like the Ghost Bat—that cannot be deployed in coalition airspace or trusted with lethal autonomy because the digital paperwork (certification) was never developed.

5.2 The Commercial Disadvantage

The military no longer drives innovation in autonomy; the commercial sector does. Weiss and Patt [41] note that commercial markets consume trillions of chips and generate millions of lines of code, dwarfing military output.

If the ADF's regulatory processes remain glacial and misaligned with commercial standards, it will be unable to leverage this commercial mass. Commercial firms will not engage with military business if the certification barriers are too high or unique. The ADF needs to align its regulatory frameworks with civilian bodies (CASA, FAA, EASA) to ride the wave of commercial innovation rather than trying to build a bespoke military ecosystem.

5.3 The Cost of 'Guesstimating'

Without clear architectures (like A-GRA), industry is forcing design decisions that may ultimately be non-compliant. The cost of retrofitting an autonomous fleet because the initial safety architecture was rejected by a regulator is prohibitive. This leads to a 'Trough of Disillusionment', where promising technologies fail not because they don't work, but because they cannot be legally operated/realised into useful capability.

6. A Roadmap for Lead Adoption

To transition from a customer of hardware to a master of capability, the ADF must adopt a new approach to acquisition. It is not enough to buy the aircraft; the ADF must build an 'invisible airframe' in parallel that allows it to fly. We propose a three-pillar strategy for the ADF to navigate the regulatory trough.

6.1 Recommendation 1: Co-Develop Regulation with Industry

The ADF cannot wait for civilian regulators to solve the autonomy problem. It must actively sponsor the development of reference architectures and certification standards.

- **Action:** When the ADF funds a demonstration (like Ghost Bat or a sovereign supply drone), a deliverable must be the *draft certification basis* for that technology.
- **Mechanism:** Establish 'Regulatory Sandboxes' where industry and regulators co-develop standards in a safe, instrumented environment. This allows the regulator to see the data required to write the rule.

6.2 Recommendation 2: Master the 'Digital Triad'

Excellence in autonomy requires collaboration across the 'digital triad' of software, data, and AI/ML models. The ADF needs to invest in the infrastructure to validate these models.

- **Action:** Invest in Simulation-Assisted Machine Learning and tools that allow for the training of robot policies in simulation.
- **Validation:** Physics-Informed Neural Networks (PINNs) are indicating their utility to reduce the data required for validation. The ADF must build the capability to certify a system based on its performance in a validated simulation, as traditional flight hours are insufficient to test non-deterministic AI across all possible edge cases [48].

6.3 Recommendation 3: Harmonise with Allies

The challenges of certifying hydrogen propulsion, landing autonomy and lethal autonomy are too large for Australia to solve alone.

- **Action:** Prioritise regulatory harmonisation with AUKUS partners. Just as we share nuclear propulsion technology, we must share the certification bases for AI and autonomous control.
- **Goal:** A shared safety case for AI piloted aircraft that is recognised by the US Air Force, the Royal Air Force, and the RAAF. This prevents the duplication of effort and ensures interoperability in coalition operations.

7. Conclusion

The future of air power and military logistics will heavily leverage autonomy, but that future is not guaranteed by physics alone. Our analysis of the UCAV and supply drone sectors reveals that while the engineering is advancing—evidenced by the technical feasibility and flight testing of the Ghost Bat—the regulatory frameworks required to certify these systems are dangerously immature.

The hype of immediate autonomy masks a deep fragility in the certification ecosystem. Our analysis illustrates that while we can design a hydrogen-powered, heavy-lift drone that solves the logistics problem, we cannot yet certify the fuel that powers it or the brain that lands it. Similarly, the evolution of UCAVs from the MQ-9 to the Ghost Bat has outpaced the legal definitions of command and control.

The ADF stands at a precipice. It can continue to procure 'safe' remotely piloted systems while waiting for the world to solve the autonomy problem, or it can lean in. By treating regulation as a capability to be developed in parallel, investing in the 'digital triad', and co-developing standards with industry, the ADF can build the 'invisible airframe' required to support the fleets of tomorrow.

A drone that can fly but cannot be certified is not a capability; it is a liability. To be a lead adopter in the age of autonomy, the ADF must direct its resources not just into the metal and carbon fibre of the aircraft, but into the intellectual and legal infrastructure that defines how they operate. Only by building this regulatory bedrock can we ensure that the autonomous fleets of the 2030s can actually

be cleared for takeoff.

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