Technology and Risk Considerations in Shaping Future Drone Legislation

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Abstract

The global aviation industry has decades-old and highly successful legislation enforcing safety in conventional manned aerospace. This framework has been evolved gradually around a set of mature technologies with particular goals and implementations, and legislators are now struggling to integrate the profoundly different implications of Unmanned Aerial Vehicle (UAV) technology into this regulatory environment.

This paper seeks to inform future UAV policy by highlighting its technological and distinctiveness from conventional aviation and making recommendations for future legislation, based on these observations.

1. Certification and Legislation of Aviation

Current aerospace legislation is based around the concept of *airworthiness certification*, applied throughout the entire lifetime of an aircraft. Under this model, aircraft are authorized to fly in a nation's airspace if "a certificate of airworthiness or similar documents are issued by competent authorities" [5]. Such documentation covers the design, manufacture, operation and maintenance of an aircraft, and therefore places obligations on a variety of organizations, from the Original Equipment Manufacturer (OEM) through to its contractors, its operator (for example an air force or airline), and its contractors (for example third party maintenance and pilot training), and even through to fare-paying passengers.

The global nature of the aviation industry has encouraged a unified approach, overseen by the International Civil Aviation Organization (ICAO). ICAO officially came into existence in 1947, and now has 180 "contracting states" abiding by its convention, which states that "the objective of international airworthiness standards is to define … the minimum level of airworthiness … thereby achieving, among other things, protection of other aircraft, third parties and property" [5].

Policing is devolved via a series of regional government organizations, either at a national level (for example the Federal Aviation Administration in the United States of America and Civil Aviation Authority in the United Kingdom), or more widely (for example the European Union Aviation Safety Agency across the European Union). In practice, due to the USA's dominance at an industrial level, evolution of standards is generally led by the FAA, closely harmonized with EASA.

The definition of *airworthiness* is based on the recognition that the acceptable risk of a system failure should be in proportion to the severity of its outcome in terms of damage to life and property. Thus, several categories of failure are defined: *Minor*, which does "not significantly reduce system safety", *Major*, which causes "significant reduction in safety margin", *Hazardous*, which causes "large reduction in safety margin", and *Catastrophic*, which "results in multiple fatalities and/or loss of the system" [15]. Acceptable failure rates (in terms of probability per flight hour) are explicitly assigned to these outcomes, as tabulated in Table 1.

Event Severity	**Adjectival failure rate**	**Numerical failure rate (per flight hour)**
Catastrophic	Extremely Improbable	10^{-9}
Hazardous	Extremely Remote	10^{-7}
Major	Remote	10^{-5}
Minor	Probable	10^{-3}

Table 1: Acceptable severity/probability rates

Thus the methodology recognizes the practical impossibility of complete elimination of risk, even for *catastrophic* outcomes, and allows appropriate engineering judgements to be made during allocation of resources to the reduction of the probability of a given outcome. For example, the risk of a catastrophic event due to the failure of a full-authority flight control system may be reduced by inclusion of redundant systems, justifying its attendant cost and weight penalties.

Despite the clearly stated numerical objectives, in practice there is a considerable element of qualitative moral value-judgement during the airworthiness assessment process during the event severity assignment phase. For example, differing levels of responsibility (and thus severity) are allocated to crew versus passengers, and fare-paying occupants versus owner occupants [12]. For example, under certain circumstances the loss of a freighter variant of a commercial aircraft is deemed of lower severity to the loss of a passenger variant, which can in turn manifest itself in reduced system redundancy being designed into the freighter variant [3].

In order to facilitate the design of certifiable aircraft by manufacturers, and the issuing of certification documentation by policing authorities, these concepts have been captured into hierarchical standards of "Aerospace Recommended Practice", headed by the ubiquitous ARP 4754

[30] and ARP 4761 [31], which recommend methods for system level analysis such as Functional Hazard Assessment (FHA), Fault Tree Analysis (FTA), and Failure Mode and Effects Analysis (FMEA) [10]. These high-level methods and processes may then be used in conjunction with component development standards, such as DO-178C [29] (software development) and DO-160G [28] (hardware environmental testing). Therefore, an aircraft designer may ease certification of a design by claiming adherence to an appropriate standard, rather than appealing to the more intangible requirements of a high-level convention.

Such practically-based legislation and conformance strategies extend to the explicit definition of discrete aircraft categories with particular requirements founded on assumptions on their properties and uses. For example, the Certification Specification categories defined by FAA/EASA regulations are shown in Table 2.

Category	**Description**
CS-22	Sailplanes and Powered Sailplanes
CS-23	Normal, Utility, Aerobatic and Commuter Aeroplanes
CS-25	Large Aeroplanes
CS-27	Small Rotorcraft
CS-29	Large Rotorcraft
CS-31GB	Gas Balloons
CS-31HB	Hot Air Balloons
CS-31TGB	Tethered Gas Balloons

Table 2: Certification specification categories

The complexities of incorporating UAV design and operation into this framework are well illustrated by the United Kingdom experience. There, safe operation of all aircraft is regulated by Civil Aviation Publication (CAP) 393, commonly referred to as “The Air Navigation Order” [6], and this document has recently attempted to clarify its applicability to UAVs by the inclusion of Article 94 in 2016, explicitly stating a variety of inclusions and exclusions with respect to conventional airspace. CAP 393 is supported by CAP 722 “Unmanned Aircraft System Operations in UK Airspace – Guidance” [7], which gives greater detail on the permissible classes of vehicle. This incremental approach has continued with the introduction of legislation in 2019 requiring the registration of UAVs over 250g Maximum Takeoff Weight (MTOW) against an operator ID, assigned on completion of a short competency test. The level of confusion and uncertainty triggered within the commercial and recreational UAV communities was acknowledged by the CAA’s release of the greatly simplified “Drone Code” clarification document [8], and the UK parliament initiating a broader response to future legislation [33].

2. Small Unmanned Aerial Vehicles

As stated, the rush to establish feasible sUAV legislation by the extension of existing law is largely a reaction to the clear distinctiveness of these vehicles in comparison to conventional aviation in weight, cost, complexity, and operational applications. Therefore, an understanding of the commercial and technological environment that has given rise to sUAVs is useful in order to understand how the technology is likely to evolve in the future and inform a proactive response. These issues are summarized and analyzed in this section.

Although the term Unmanned Air Vehicle (UAV) refers to remotely or autonomously piloted aircraft of any size, the most disruptive class, and hence that of most interest to legislators, is "Small" UAVs (sUAV), ranging up to a maximum take-off weight (MTOW) of 7kg. This upper threshold is highly significant, being the heaviest vehicle that may be flown by non-commercial operators without any formal training or qualification using guidance on Unmanned Aircraft System operations in public airspace [7]. In principle, sUAVs of MTOW lower than 250g should fall outside the scope of this analysis due to being exempt from registration and tracking. However, in practice the class is highly relevant as developments in this field profoundly influence those of larger vehicles, to the extent that the 250g limit is likely to be extended downward in the future. For example, "Micro" UAVs of less than 15g are widely available, and may be operated in such a manner as to cause injury to skin and eyes due to the presence of unguarded rotors [34]. The sUAV class of vehicles may also be considered as technologically distinct from larger UAVs typically deployed by armed forces, which employ technologies similar to manned military aircraft, and have similar cost and reliability rates (i.e. within the same order of magnitude). For example, the General Atomics MQ-1 Predator exemplifies this separate class, and defines public perception of the properties of large UAVs [32].

2.1. Summary of technology and business environment

The sUAV industry has followed the familiar economic trajectory of a nascent technology being initially exploited by small enterprises, followed by consolidation and backing from larger corporations. Despite the fragmented nature of the industry, many sUAV technologies are governed by a variety of emerging standards established collectively by the development community. For example, the MAVLink packet protocol, used to implement control and telemetry communications between UAVs and ground-based equipment, has been developed entirely by consensus by an internet forum-based development community, and has become the de facto standard for most flight control avionics, allowing inter-operability between otherwise independent open-source software systems [2]. Thus, to some extent sUAV technology may be regarded as following the same *unorganised* (or *self-organised*) model of previous knowledge-based technologies.

The partially matured nature of the industry is illustrated by the categories of product available in the sUAV market, and two overlapping classes are defined here: *Custom* and *Commercial-Off-The-Shelf* (*COTS*). *Custom* sUAVs are constructed by technically skilled amateurs and niche commercial manufacturers, using a variety of available components and sub-systems.

Conversely, *COTS* ("shrink-wrapped") sUAVs are produced by larger commercial enterprises, employing mass-production of airframes and using proprietary systems and software. An intersection of the *Custom* and *COTS* markets exists in the "*Ready To Fly*" (RTF) niche in which small commercial suppliers provide pre-assembled *Custom* equipment. The *Custom* approach offers greater flexibility and performance for a given price point. Conversely, the expertise and economies of scale offered by *COTS*- developed equipment offer greater sophistication, reliability, and ease of operation for unskilled operators: the proliferation of sUAVs has been almost entirely driven by this *COTS* segment [18]. The precise multi-axis control achievable by rotary-wing airframes solves many of the operational challenges of command and navigation, enabling many "deskilled" operations, during which the operator is freed from the task of controlling the attitude and position of the vehicle at a second-by-second rate, and is only required to navigate it through the operational environment. Thus, although rotary-wing vehicles are currently greatly limited in range and endurance relative to their fixed-wing counterparts, based on registration information available from the Federal Aviation Administration (FAA) [18], they dominate the market due to their simplicity of launch and operation.

The early industrial consolidation and the resulting technical sophistication of *COTS* UAVs is well illustrated by the products of the DJI company of Shenzhen, China. The success of DJI's products (particularly the *Phantom* and *Mavic* sUAVs) has established the company as the world's leading sUAV vendor and enabled the rapid expansion of the company from approximately 90 employees at its creation in 2006, to approximately 4000 when the Mavic was introduced in 2016 [16]. The proliferation of DJI products has served to define public perception of the capabilities (and limitations) of sUAVs in general.

The classes of technology that have arisen to enable sUAV proliferation are classified here by the functions that they contribute to the vehicle's operation: *Propulsion, Stabilisation and Control, Command and Navigation,* and *Communications*. *Propulsion* refers to the generation of thrust capable of being modulated with sufficient agility to allow controlled flight. *Stabilisation and Control* refers to sensing and control of vehicle stability. This category does not include accurate control of position, implying a need for a higher level of automatic or manual piloting to maintain and alter position, and *Command and Navigation* (distinct from *Stabilisation and Control*) relates to all functions necessary to move between selected positions and hold station to accomplish a mission. Automation of this category relegates a human controller to a supervisory or management role and enables fully autonomous flight if desired. *Communications* relates to provision of sufficient air-to-ground communication to allow such piloting or mission-management. For each of these categories, the current state of the art has been enabled by the convergence of several separate low-cost technologies developed for other consumer applications, particularly the smart-phone industry [23].

In the *Propulsion* domain, batteries using gel-polymer electrolytes ("Lithium Polymer" or "LiPo") offer high energy-densities and high power-delivery compared to conventional alkali batteries. These improvements in energy and power density are made accessible by electronically commutated motors via microprocessor-controlled switching equipment. The availability of LiPo technology has enabled the development of electrically powered thrust-borne vehicles with useful flight endurance (i.e. of the order of minutes). Ironically, applications and capabilities of sUAVs are now largely constrained by the limits of this same technology. In the *Stabilisation and Control* domain, automatic stabilisation avionics have been made possible by low-cost gyroscope and accelerometers, small format-factor microprocessors, and open-source stabilisation software [35]. Development has been accelerated by the availability of open-source software development tools. In the *Command and Navigation* domain, vehicle-mounted First-Person View (FPV) cameras, Global Position System (GPS) receivers, and open-source implementations of autonomous GPS navigation algorithms have provided high-level mission-management capabilities. Low-cost and low-weight sensing equipment and cameras have allowed mission tasks to be expanded. In the *Communications* domain, relatively short range (i.e. sub three kilometre) digital communication links with ground equipment include low-bandwidth command and instrumentation equipment operating in the unlicensed *Low Power Device* and *Industrial, Scientific, and Medical* spectra. The domain has been further enhanced by the availability of flat-screen monitors and goggle-mounted display equipment, enabling portable screens and Head-up Displays (HUD) to be integrated into command equipment appropriate for in-field use.

The consumer-market origins of these technologies imply several strengths and weaknesses in relation to conventional manned aircraft, which frequently run counter to intuitive expectations. For example, due to advances in the *Propulsion* domain, accelerations of up to 10g and maximum airspeeds beyond 100 mph are achievable by vehicles costing less than £1000. Conversely, accurate position control via inertial-based methods is highly problematic, necessitating a variety of complex compensation technologies to accurately maintain station under operator control.

2.2. sUAV reliability, threats and risk

Of all the comparisons between sUAVs and large UAVs, none is more distinct than reliability. As stated, larger UAVs employ technologies similar to manned military aircraft, and have similar cost and reliability rates. For example, the General Atomics MQ-1 Predator has a cost of approximately \$30M and a mean time between accidents (MTBA) of approximately 10,000 flight-hours, while the General Dynamics F-16 Fighting Falcon also has a cost of approximately \$30M and an MTBA of approximately 50,000 flight-hours [20] [22]. Conversely, sUAVs have both cost and reliability rates several orders of magnitude lower: reliable global statistics are not available, but the authors' experience in operation of both custom and commercial sUAVs has shown per-vehicle costs of approximately £1000 and accident rates of approximately $10^{1\ \text{per}}$ flight hour (i.e. 10 hours Mean Time Between Failure). This distinctiveness also extends to the causes of accidents, with large UAV accidents being dominated by human factors [19], in contrast to sUAV accidents being dominated by technical failures, which is to be expected given the shortcomings of the sUAV components and systems described in Section 2.1.

The use of consumer grade hardware and software and non-redundant architectures yield low sUAV reliabilities in both *availability* (assurance of commanded operation) and *integrity* (prevention of uncommanded operation). When proposing legislation such low technical reliability figures should be seen as placing an obligation on the operator to anticipate and contain such almost inevitable failures. Thus, three overlapping classes of threat are defined here, judged by the intentions of the human operator: *Accidental, Reckless,* and *Malicious*. These classes have been popularly described as "*The Clueless, The Careless, and The Criminal*" [1]. *Accidental* threat covers those due to reasonable operator error or (more frequently) technical failure. *Reckless* covers threats due to illegal controlled flight, and accidental excursions due to insufficient operator training or experience. *Malicious* covers threats due to deliberate action by the operator, often implying some level of mission-specific modification to the vehicle itself. As discussed, the boundaries of these classes of threat are not distinct, and each cover a range of activities and levels of sophistication. Example scenarios based on the author's experience, in escalating severity are cited here:

- Controlled privacy intrusion (Malicious): Targeted observation of members of the public. Motivations may include journalism, espionage, or abusive observation.
- Propulsion-loss in public space (Accidental): Loss of thrust causing a crash into a populated space. Typical causes may be switching device failure, computer hardware failures, battery depletion, and mechanical failure of wiring and connectors.
- Fly-away in public space (Accidental): Controlled but un-navigated "fly-away", causing a vehicle to impact in a remote public space. Typical causes may be software failure or loss of communications.
- Contraband smuggling (Malicious): Deliberate delivery of contraband by an operator. Typical applications may be smuggling into prisons and across national borders.
- Deliberate proximity flying (Reckless): A UAV being deliberately navigated close to a sensitive area, triggering an emergency response. Typical events may include unskilled observation missions near motorways and airports.
- Improvised weaponisation (Malicious): Deployment of improvised weapons developed from COTS or Custom airframes by skilled amateurs. Examples of this have been observed during conflicts in the Middle East [27].
- Military-sponsored weaponisation (Malicious): Deployment of nationally-funded but comparatively low-cost weapons developed from Custom airframes by experts. Examples of this are currently under development by a variety of nations [21].

Thus, sUAVs may be regarded as presenting a spectrum of threats, ranging from high-volume/low-exposure through to and low-volume/high-exposure. In common with common Risk Assessment methodology, the severity of a threat's outcome may be plotted against its probability of occurrence. Figure 1 shows such a qualitative plot for the example scenarios cited previously.

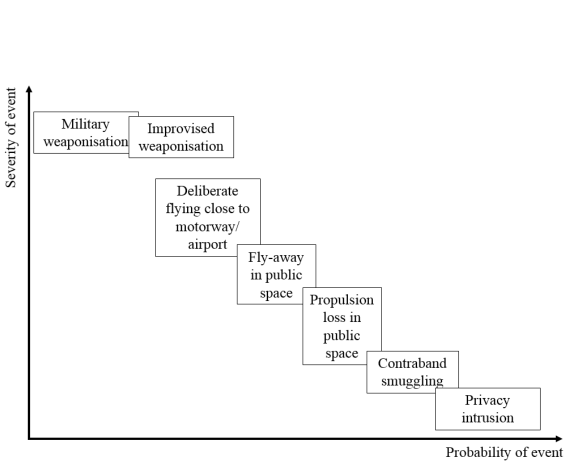

Figure 1: Event Severity/Probability

As implied by their position on the horizontal axis, actual incidents are dominated by accidental (occurring in public spaces on an almost daily basis but rarely reported), then reckless (with a few cases annually, and typically reported), and then malicious events (with no violent incidents reported in the UK).

3. Commentary

sUAV technology has key differentiators with respect to conventional aerospace: low MTOW (i.e. less than 10kg), low cost (i.e. less than £10,000), low reliability capability (i.e. less than 100 hours MTBF), and low reliability requirements (i.e. less than 1000 hours MTBF). These differentiators largely explain the unique nature of the threats due to sUAVs relative to conventional aerospace. Large commercial aircraft are designed and operated to achieve catastrophic failure rates of about one in a billion per flight hour, or nine zeroes, and even "General Aviation" light aircraft achieve catastrophic failure rates of about one in a 10 million, or seven zeroes. Conversely, Unmanned Air Vehicles (UAVs) performing commercial or recreational flying rarely avoid failure every 10 hours, or 1 zero: we call this approximately one million-fold divide the *"gap of six zeroes"*.

Both conventional and unmanned aviation share the common goal defined by the ICAO convention: protection of property and life by the assignment of responsibility to vehicle manufacturers and operators. However, conventional aerospace certification methodology is dominated by the inevitable need to protect the lives of a vehicle's occupants, and the fundamental lower limit on vehicle weight needed to implement manned aviation (recognized in American law by the FAA "Ultralight" category [14]). Thus UAV legislation has an identical fundamental philosophy to that of conventional aerospace, but potentially catastrophic outcomes are largely defined by mission and environmental factors, leading to profound differences in *implementation* philosophy. For example, a surface vehicle surveillance mission may be conducted over the Pacific Ocean or central Los Angeles by either a manned reconnaissance aircraft or UAV. In the case of the manned vehicle, the safety requirements would be almost identical in both environments, being dominated by protection of the crew, but for the UAV the safety requirements would vary greatly between the ocean and city environments, as the only safety imperative would be protection of persons on the ground. The absence of the occupant protection imperative has further implications: sUAV legislation can be regarded as being based on an assumption of very high rates of failure, requiring emphasis on *containment* of failure during operation, in contrast to conventional aerospace legislation being focused on *prevention* of failure during both design and operation.

Aircraft certification categories have been implicitly formed around implementations over the decades, as evidenced by the specifications listed in Table 2, and this approach has been viable due to the convergence of application-specific designs and the relatively slow pace of change in technology, with development times of the order of 10 years and in-service lifetimes of the order of 20 years. This approach to manned certification is currently being extended for manned electrically-powered Vertical Takeoff and Landing (eVTOL) with the introduction of the "SC-VTOL" category [24]. Categorization of conventional aircraft is further obscured by the use of MTOW as a differentiator. As with much legislation, aerospace is driven by the availability of practically discoverable metrics, and MTOW stands as a proxy for kinetic energy, which can in turn be regarded as a proxy for impact, and thence human injury [17]. For example, direct specification of Head Injury Criterion is entirely practical, and based on existing well-founded safety standards in other transport industries [26].

Such caution has largely been driven by expediency in reaction to rapidly evolving technology, but is a good example of application of the Precautionary Principle leading to likely emergence of unintended consequences [25], in which a policy of limited action in response to poorly understood conditions may yield unexpected effects. This concept is particularly true for UAV regulation, an example being the combined introduction of 250g MTOW limits and greater restriction of flying in unsegregated airspace in Europe and America, which has led to an explosion in development of sub-250g sUAVs suitable for operation in indoor environments, which has in turn increased opportunities for operators wishing to make illegal outdoor flights undetected.

The common public perception of sUAV-derived threats is of accidental and reckless incidents using commercial airframes, and much proposed legislation reacts to public concern based on multiple reported low-severity incidents. Low-impact legislation (such as registration) will help to greatly reduce accidental threats and partially reduce reckless threats by alerting cooperative operators to the possibility of accidental damage and the legal consequences of reckless operation. However, such application of the Precautionary Principle (by placing greater restrictions on cooperative operators) does nothing to address the low-frequency, high-severity cases of malicious behavior, and has unintended negative consequences by constraining development of cooperative, policing, and defensive technology. In keeping with the approach that has served conventional aerospace well over the decades, the limited sUAV regulation enacted so far has largely been a reaction to available COTS sUAVs, but overlooks the capabilities already available to skilled developers of custom equipment. Furthermore, attention should be paid to technology adaptation to circumvent over-proscriptive regulation, such as has occurred with the introduction of 250g MTOW limits for registration requirements.

Legislation should be, as much as is practical, “declarative” (i.e. specifying desired functional outcomes) rather than “imperative” (i.e. specifying desired outcomes rather than permissible engineering solutions) [13], otherwise legislation will trail innovation and potentially constrain it in undesirable and unexpected ways. Conversely, functionally defined legislation has the opportunity to shape innovation in useful ways, rather than encouraging innovation to circumvent proscriptive rules. This dilemma is demonstrated by the incremental introduction of European vehicle emissions standards since 1992, with a series of standards (“Euro 1-6”) being introduced in 1992, 1996, 2000, 2005, 2011, and 2014, each specifying maximum acceptable pollutant emissions per kilometer of travel [11]. This approach may be regarded as fundamentally declarative, with manufacturers free to adopt various technologies in order to achieve these clear limits. However, practical considerations of application and incumbent technology has resulted in the introduction of imperative elements, with varying limits for petrol and diesel engines within the regulation itself [11], and has been further obfuscated by monitoring legislation, such as a requirement for catalytic convertor solutions to be functional if installed at manufacture, regardless of whether emission limits are met without it [9]. This example also illustrates enforcement practicalities negatively shaping technological solutions, with experience of manufacturers developing systems capable of detecting test conditions and configuring the vehicle to only obey the standard under these circumstances [4].

These concepts are highly relevant to the emerging opportunities and threats presented by sUAVs, and recognition of the gulf between this novel form of aviation and its conventional forbears presents an opportunity to create more adaptive and change-resilient policy in the future.

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