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On unmanned aircraft systems issues, challenges and operational restrictions preventing integration into the National Airspace System

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ABSTRACT

Commercial interest for unmanned aircraft systems (UASs) has seen a steady increase over the last decade. Nevertheless, UAS operations have remained almost exclusively military. This is mainly due to the lack of a regulatory framework that allows only limited public and civil UAS operations with usually crippling restrictions. Although efforts from the Federal Aviation Administration (FAA) and its partners are already underway to integrate UAS in the National Airspace System (NAS), the appropriate regulation will not be ready for several more years. In the meantime UAS developers need to be aware of the current operational restrictions, as well as make informed decisions on their research and development efforts so that their designs will be airworthy when the regulatory framework is in place. This paper aims to present an overview of current aviation regulation followed by an investigation of issues and factors that will affect future regulation.

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1. Introduction

The need to regulate civil aviation ensuring safety and healthy competition dates back to the 1920s, with several relevant conventions addressing related issues and concerns. The most significant such convention took place in Chicago in 1944, right after the end of the Second World War with more than 50 states attending. The accomplishments of that conference set the groundwork for aviation safety and international cooperation on regulations, standards and procedures development, all relevant even to this day.

Aviation agencies around the world are currently faced with a new type of aircraft that needs to share the skies with manned aviation. Unmanned aircraft systems (UASs) are becoming ever more popular, although the enabling technologies are considered far less mature when compared to that of manned aviation, raising safety concerns to the general public as well as other airspace users.

UAS operations were very limited before the 1944 Chicago Convention and only picked up during the last two decades with increasing use of such systems in military operations. Currently, UAS applications are still almost exclusively military in nature, with several systems being in service and more under active development.

Over the last decade, benefits of UAS use in civil application domains have been realized by the public sector and several organizations/agencies (including the US Coast Guard, Customs and Border Protection, Department of Homeland Security, Department of Agriculture as well as local law enforcement agencies) are launching initiatives to introduce UAS in their infrastructure [1]. The potential for commercial applications has not been left unnoticed either, with several million dollars of investments predicted over the coming years [2].

However, despite significant interest for commercial applications, efforts in that area are limited, mainly because of the lack of appropriate regulation that allows only limited, non-commercial operations, mainly for flight testing purposes. Moreover, because of lack of regulations, current UAS operations may be based on the wrong interpretation of FAA policies as admitted by the FAA in [3]. These operations, besides being illegal, may also compromise public safety. Up to now the FAA has grounded several UAS operators that did not have appropriate authorization to fly, but has refrained from fining or seeking legal action against them. Nevertheless as the regulations take shape this policy is subject to change.

The FAA's philosophy on UAS integration in the NAS, as stated by Mr. N.A. Sabatini, Associate Administrator for Aviation Safety, is best reflected by the "First, do no harm" principle of medicine's Hippocratic Oath [4]. Based on this principle it is safe to assume that the basis of any future UAS regulation, will be to ensure the

safety of the public, to a level at least equivalent to that of manned aviation. Nevertheless what constitutes an equivalent level of safety (ELOS) is still open to discussion.

The goal of this paper is to review the current regulatory status and existing airworthiness certification avenues available, but also examine possible future developments, based on the ELOS principle. This serves two purposes; inform current UAS developers of the procedures required to fly lawfully as well as safely in the NAS and provide some insight on where to focus R&D efforts, in order to streamline compliance with future regulation. Current aviation users also stand to benefit since within a decade they will have to share the same airspace with an increasing number of unmanned aircraft.

This work begins with a short overview of current manned aviation regulation, which in all likelihood will be the basis for the development of UAS regulation. The status of relevant regulation in the US is followed by an international overview. Then an ELOS for UAS is derived and appropriate system requirements are calculated. The rest of the paper is involved with possible UAS regulatory elements, using manned aviation regulation and public safety as a basis.

1.1. Background definitions for clarification purposes

Although the term unmanned aerial vehicle (UAV) has been very popular for several years, lately there has been a drive to use the term unmanned aircraft system (UAS) instead. The latter has already been adopted by the US DoD and FAA [5] as well as EASA [6]. The main difference is the use of the term "aircraft" that implies the need for airworthiness certification. In addition to that, a UAS is now a "system" that includes both the aircraft as well as the launch and retrieval system, the ground control station and the communication link.

UAS encompass all the diversity of current manned aviation and more. They range from a few grams to several tons in maximum take-off weight (MTOW), fixed or rotary-wing, conventional, short or vertical take-off and landing configurations. Fig. 1 presents an overview of the spectrum of UAS currently available or in development.

Before proceeding, the terms *damage*, *hazard*, *risk* and *accident* also need to be clarified, since there is some ambiguity in their meaning and they have been used interchangeably or in the wrong context in the literature. The definition of each of these terms, based on [7], is provided below.

1.1.1. Damage

An undesired outcome that may include injury, fatality as well as physical, functional and/or monetary loss.

economic and safety regulation of the aviation industry as well as the safety of both civil and military operations in the NAS. More specifically they are given the authority to *conduct investigations, prescribe regulations, standards, and procedures, and issue orders* [49 USC §40113(a)]. Of particular importance is safety which is assigned the highest priority in air commerce operations [49 USC §40101(d)]. The statutory mandate of the FAA also includes regarding safety:

...before authorizing new air transportation services, evaluating the safety implications of those services; and preventing deterioration in established safety procedures [49 USC §40101(a)]

2.2. Regulation overview

Currently US aviation is regulated based on the CFR, Title 14, Chapter 1, also known as Federal Aviation Regulation (FAR). This code comprises several parts related to airworthiness certification (21–39), maintenance (43), aircraft registration and marking (45–49), pilot certification (61–67), airspace classes (71–77), operating rules (91–99) and special classes of vehicles (101–105). Responsible to oversee access to the NAS (both civilian and military) is the FAA, a federal agency belonging to the Department of Transportation.

The provisions of the CFR notwithstanding, the FAA issues supplementary material like handbooks, orders, ACs and TSOs that clearly define appropriate procedures, standards and practices required to comply with current regulations. This material helps ensure that aircraft manufacturers and operators are able to establish the minimum level of safety and reliability required for civil operations [8]. Several of these documents adopt established standards prepared by government agencies like the US Department of Defence, standards development organizations and similar bodies (AIAA, ASTM, SAE, RTCA, ANSI, ARINC and IEC) as well as other organizations, national or international (NASA, ICAO, EUROCAE).

Traditionally aviation regulation has been based on sufficiently mature technologies for which standards had been developed and possibly implemented. In this case, the regulatory body undertakes the task of assessing the technology and standards available and develops appropriate regulations. Because of the aforementioned requirements, this process is slow, costly and in some cases counter-productive since developed technology and standards are not necessarily adopted.

In March of 1996, the US congress recognizing the need to advance cooperation between industry and the federal government, signed Public Law 104-113, also known as the National Technology Transfer and Advancement Act of 1995. Section 12(d)(1) reads:

Except as provided in paragraph (3) of this subsection, all Federal agencies and departments shall use technical standards that are developed or adopted by voluntary consensus standards bodies, using such technical standards as a means to carry out policy objectives or activities determined by the agencies and departments.

This “industry consensus model” was recently used for the regulation of the light-sport aircraft (LSA) category. In this case the FAA participated actively in the development of standards and as a result these standards were immediately incorporated into the regulatory framework upon publication. This approach is faster and more cost-effective, since the burden of drafting the standards is mostly with the industry.

2.3. Airworthiness certification

In order for any aircraft to fly legally in the US, it must carry an airworthiness certificate issued by the FAA. According to the FAA, there are two conditions that need be met in order for an aircraft to be considered airworthy; it must conform to its type certificate including any supplemental certificates, and it must be in a condition that ensures safe operation [9]. For aircraft that are not type certified, compliance with the second condition is adequate. Besides standard certification, special airworthiness certificates are also available, usually for experimental or special purpose aircraft.

Although as already mentioned all aircraft need either a standard or a special airworthiness certificate to fly, there is a category of aircraft (classified as vehicles in the FAR) for which this requirement is waived. Finally, although not mentioned in the FAR, R/C model aircraft may also operate under few restrictions and without any certification requirements, but only for recreational purposes [3,10].

2.3.1. Standard certificates

Standard airworthiness certificates are given to aircraft that comply with their type certificate in any of the categories defined in FAR Part 21, including:

- Normal, utility, acrobatic and commuter aircraft (FAR Part 23).
- Transport aircraft (FAR Part 25).
- Normal rotorcraft (FAR Part 27).
- Transport rotorcraft (FAR Part 29).
- Manned free balloons (FAR Part 31).

In addition to the above categories, type certification is available for primary, restricted, US Army surplus and imported aircraft, as well.

2.3.2. Special certificates

For aircraft that do not meet requirements for a standard certificate but are still capable of safe flight, special airworthiness certificates are available [9]. There are six types of such special certificates:

- *Primary*: Aircraft type-certificated under the primary category (airplanes that are unpowered or single-engine, with MTOW of at most 1500 kg and an unpressurized cabin with a maximum capacity of four people).
- *Restricted*: Aircraft type-certificated under the restricted category. The restricted type is for aircraft that have special purpose applications (agricultural, forest and wildlife conservation, weather control, aerial surveying, etc.).
- *Limited*: Aircraft type-certificated under the limited category. This category is for aircraft that are required to operate under certain restrictions.
- *LSA*: This category is for aircraft other than helicopters that do not exceed 600–650 kg, have a maximum speed of not more than 120 knots and a capacity of not more than two persons. Additional requirements are made on the presence of certain equipment. The certification process includes FAA inspection of the documentation accompanying the aircraft as well as the aircraft itself. Upon successful completion of these inspections the FAA issues a special airworthiness certificate that may include operational restrictions.
- *Experimental*: This category is for research and development, to show aircraft compliance with a type certificate, to demonstrate functional and reliability requirements, to train flight-crews or perform market surveys. Kit-built aircraft may also

qualify for an experimental certificate under certain conditions. Several operational requirements exist for experimental aircraft depending on their characteristics.

- *Special flight permits*: These permits are given to aircraft that would not qualify for other airworthiness certificates, usually for flight testing purposes.

2.3.3. Vehicles

This category of aircraft includes moored balloons, unmanned balloons, unmanned rockets and ultralights. Many of the requirements regarding pilot certification, operating and flight rules, vehicle registration and marking, maintenance certification, including the requirement to carry an airworthiness certificate that are normally applicable to aircraft, are waived for this category [11]. Nevertheless, operational restrictions are in place. For example, the following pertain to the operation of ultralight vehicles (FAR Part 103):

- Single occupant.
- Daylight operations.
- Recreation or sport purposes only.
- No flight over congested areas in cities, towns or open areas when crowds are present.

2.3.4. R/C models

Model airplanes are regulated on a voluntary basis, based on AC91-57 with few operational restrictions. In addition to that an independent organization, the AMA issues normal or restricted flight permits after inspection of the model, provides insurance for its members and organizes areas to safely practice aeromodeling. It is noteworthy that the AMA poses additional restrictions to the ones in FAA AC91-57, both in design (e.g. the weight of the models and their propulsion methods) as well as in operation [12].

Despite the fact that R/C model airplanes have been suggested to present a mid-air collision risk to other aircraft [13], there is only a small number of incidents reported in the ASRS database, all occurred between 1993 and 1998. Furthermore, incident occurrence was either due to model operators violating restrictions or because the pilot of the manned aircraft was unaware of authorized R/C model activity. As such, current regulation for this category of vehicles can be considered adequate to ensure appropriate levels of safety for people and property.

2.4. Pilot certification

According to FAR Part 61, no one may assume the role of pilot in command or required flight crew member without either a pilot certificate (student, sport, private, commercial, recreational, airline transport) or special pilot authorization. Besides pilot certificates, flight instructor and ground instructor certificates are also available. Each pilot certificate comes with ratings for aircraft categories, classes and types the holder may operate as well as the instrument rating for private and commercial pilots. Some operators are also required to possess a current medical certificate.

Part 61 also includes the level of knowledge, training, operations proficiency and experience a pilot must possess before being issued a certificate. Part 63 is involved with certification of crew members other than pilots and Part 65 with airmen certification.

2.5. Operation rules

Operational rules for manned aircraft are prescribed in FAR Part 91, which applies to all aircraft except ultralights (FAR Part 101 and 103). According to FAR the person ultimately responsible

for the operation of the aircraft is the pilot in command. The pilot is also responsible for evaluating the condition of the aircraft and determining if it is safe to fly.

With the exception of water operations, normally the aircraft with less maneuverability has the right-of-way. This rule is superseded when an aircraft is in distress, at which time it has the right-of-way with respect to all other air traffic. In emergencies pilots are allowed to deviate from the requirements of Part 91, even contrary to ATC instruction, provided that ATC is notified of this deviation as soon as possible.

Similarly when the FAA administrator determines that the ability for safe aircraft operations is comprised due to an emergency condition, then Part 91 allows the issuance of an immediately effective traffic rule or regulation and the use of NOTAMs to notify aircraft operators.

Part 91 defines two types of flight rules, visual flight rules (VFR) and instrument flight rules (IFR). In order to fly using VFR, there are specific requirements on the amount of on-board available fuel, the operational altitude as well as the weather conditions. Moreover the pilot is expected to control the aircraft's trajectory and avoid other aircraft based on visual cues.

Flight under IFR is subject to similar restrictions in terms of fuel availability, but in addition to that the presence of an operational and properly maintained VHF omnidirectional range (VOR) radio navigation system is also required. In order to operate IFR in controlled airspace, the pilot must first submit an IFR flight plan and receive appropriate ATC clearance. Once in controlled airspace, the pilot is required to report to ATC when he/she reaches predetermined points, encounters unforecast weather conditions or other problems that may affect flight safety.

To prevent potential collisions, Part 91 stipulates that no one is allowed to operate an aircraft close to another. In addition to that, it requires that aircraft operators be alert to "see and avoid other aircraft", regardless of whether they are operating in VFR or IFR conditions. Nevertheless when operating in IFR, appropriate separation should be ensured with ATC instruction.

With respect to maintenance, Part 91 states a "continued airworthiness" requirement. This requirement entails keeping a current maintenance schedule and incorporating design changes and revisions to maintenance instructions. Responsible for keeping the aircraft airworthy is either the operator or the owner. Unless an aircraft had an annual inspection in which it was found fit to return to service, it is not allowed to fly.

In addition to the normal operations described above, part 91 includes special operations like aerobatics, towing and parachuting. Furthermore it covers issues like equipment and instrument certification and operation, operational noise limits and foreign aircraft operations among others.

2.6. Airspace classes

Depending on the altitude and proximity to airports, the NAS is segregated into several classes as shown in Fig. 2. For each airspace class, different operating rules may be in effect, based on the stipulations of Part 91. Classes A–E correspond to controlled airspace. Airspace between 18,000 ft above mean sea level (MSL) to about 60,000 ft, belongs to the Class A airspace which is reserved for IFR traffic. Classes B, C and D include the airspace above and around airports of different sizes. They are designed to include traffic from/to the airport and ensure appropriate separation. Finally Class E corresponds to the rest of the controlled airspace and includes major airways and the space above airports with no control tower.

The last class is Class G airspace, which normally includes the space up to 1200 ft above the ground. Although Class G airspace is

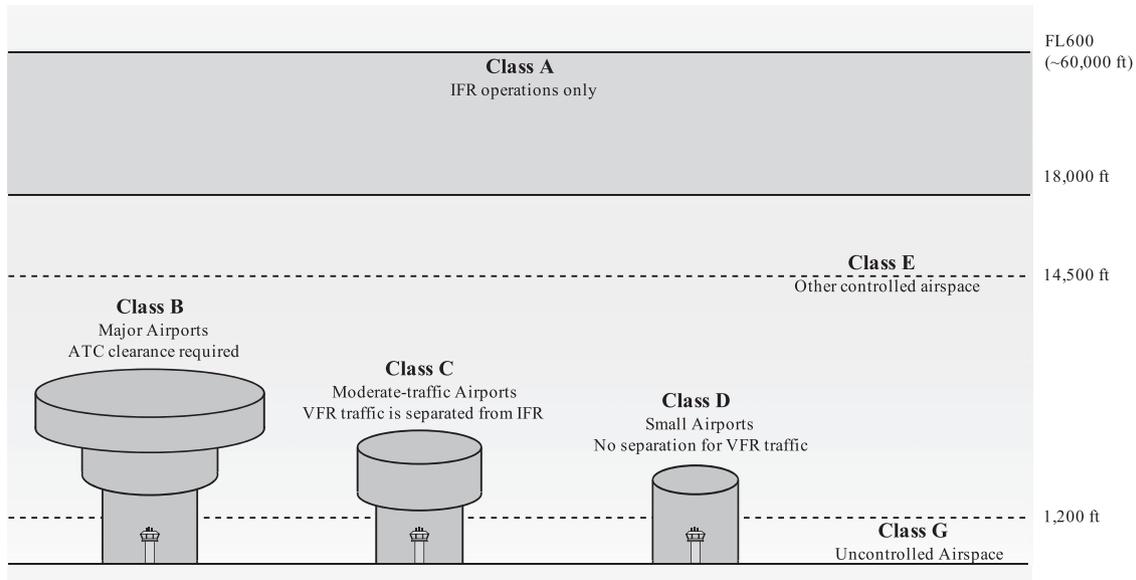


Fig. 2. Overview of the NAS classes. This figure depicts only a general view of the airspace classes. For the accurate limits of each airspace class the reader is referred to the FAR.

also known as uncontrolled airspace, operating rules do apply. Helicopters and aircraft should typically operate clear of clouds and at speeds that allow the pilot to see and avoid other traffic as well as any obstructions on the ground. Other restrictions may also be in effect depending on the type of the aircraft, such as avoiding crowded areas, noise limits, etc.

3. UAS regulation in the US

3.1. Background

The first efforts towards UAV regulation were taken as early as 1991, when the FAA issued a notice for proposed rule making and formed an industry support group [14]. Over the following years work progressed mostly with development of ACs regarding design, maintenance, pilot qualification and equipment requirements, among other topics.

The University of New Mexico published in 2001 the first version of the high altitude long endurance (HALE) UAV Certification and Regulatory Roadmap [14], which was sponsored by the NASA Erast Project. Since then, newer versions have been published with feedback from other stakeholders. The goal of that document was to be a basis of discussion between the FAA, the industry and other stakeholders for establishing regulation for aircraft airworthiness, flight standards and air traffic that will allow safe operation of HALE UAS in the NAS. This effort was continued with the Access 5/UNITE program also sponsored and funded by NASA with participation of FAA, DOD and other stakeholders. The aim of this project was to integrate HALE UAS in the NAS [15] but it was terminated early in February of 2006 due to budgetary reasons [15].

The LSA model for regulation development was successful in enabling accelerated NAS access and reducing costs without compromising public safety [2]. Nevertheless, UAS technology is still under development and the FAA seems to adopt a more cautious approach to UAS regulation. According to Mr. N.A. Sabatini, Associate Administrator for Aviation Safety, the process of UAS airworthiness certification is riddled with technical challenges such as the sense and avoid (SAA) system and the communication issues between ground station, ATC and aircraft [4].

To assist with the aforementioned technical issues the FAA contacted RTCA which, in October of 2004, formed committee SC-203 with participation from government and industry representatives from several countries. The first task was to develop “Guidance Material and Considerations for UAS”, a document that was issued in March of 2007. In addition to that, the committee has been working on MASPS for:

- UAS;
- Command, Control and Communication Systems for UAS; and
- SAA Systems for UAS.

These standards are not expected to be completed before 2011 [16].

Another organization that has been particularly active with the development of standards for UAS is the ASTM that has also formed a specialized committee for this reason. The goal of the ASTM F38 committee is to build technical standards that will support the MASPS developed by the RTCA [17]. So far ASTM has produced more than 10 such standards, one of the most known being the F2411-07 Standard Specification for Design and Performance of an Airborne SAA System, which according to ASTM has been adopted by the US DOD [18]. Others include “Standard Practices for UAS Airworthiness”, “Standard Practice for Quality Assurance in the Manufacture of Light UAS” and “Standard Practice for UAS Visual Range Flight Operations”.

The ASTM through its standard practice document [19], proposes two certification pathways; type certification leading to a standard airworthiness certificate for large UAS and a “Light UAS” special airworthiness certificate similar to that for LSA. The special airworthiness certificate for the LSA category is issued by the FAA if the aircraft complies with all eligibility requirements in [9] and after the manufacturer of the aircraft provides all the necessary documents that certify compliance with industry consensus standards [11]. The only requirement mentioned by the ASTM for eligibility in the “Light UAS” category is an MTOW of at most 600 kg. In addition to that, the ASTM is currently working on a standard guide document for mini UAS airworthiness, as well as a review of requirements for unmanned rotorcrafts.

In March of 2006 the FAA established the Unmanned Aircraft Program Office to facilitate the UAS regulation process [4]. A few months later, in September, it contracted Lockheed Martin to begin development of a five year roadmap for integration of UAS in the NAS [16,20]. Although the first version of the roadmap was supposed to be published in March of 2007 [16], publication is still delayed pending review and approval. For 2008, FAA has declared an initiative to “Develop policies, procedures, and approval processes to enable operation of UASs” [21].

3.2. Current status

Currently, flight of public UAS is authorized on a per-case basis after a COA application. The COA is meant to establish an ELOS to that of manned aviation [4] and is issued after submission of required documentation and an analysis performed by the FAA Air Traffic Division to determine that an ELOS is indeed achieved. It is noteworthy that the airworthiness basis is the responsibility of the public agency operating the UAS. A COA is normally effective for up to one year and may contain operational restrictions, usually in the form of a prohibition of operations over populated areas and a requirement that the UAS be constantly observed. Towards that end, in March of 2008, the FAA issued an updated guidance document, titled “Interim Operational Approval Guidance 08-01”, that replaces the older AFS-400 policy [23] that was used as the basis for the evaluation of applications for COA. This document contain operational guidelines for both public and civil UAS operations.

Despite the regulatory problems, a significant interest for the use of UAS was demonstrated with the number of COA applications. In 2005 the FAA issued 50 COA and more than 100 were issued in 2006 [24,25].

It should be noted though that according to that policy the FAA accepts COA applications only for public UAS. Civil UAS can get a special certificate under the experimental category with the limitations imposed for that category in FAR Part 21 [26] and possibly additional provisions set by the FAA, specifying other operational requirements [5]. The procedures and requirements for issuing such a certificate were recently provided by the FAA in “Order 8130.34 Airworthiness Certification of UASs”. By early 2008, 28 special airworthiness certificates were already issued [27] and several are in queue [28]. Besides these two avenues, the FAA is considering an additional category of unmanned vehicles, for smaller systems, that can be regulated based on an instrument like AC91-57 [3,16].

It should be noted though that the FAA considers both the COA and special airworthiness certificate processes as interim measures [4].

4. International UAS regulatory efforts

The large number of stakeholders in many different countries and the need for international operations and interoperability lead to the involvement of many different organizations with the regulatory efforts. In many cases the progress has been shared among different groups and there have been also joint efforts like the first EUROCAE/RTCA joined meeting in Florida, in January of 2007. This section provides a brief overview of related efforts.

Several states like Australia, Canada, Finland, Italy, Malaysia, Sweden, UK and the US, are currently implementing procedures to issue special operating authorizations for UAS [29]. Furthermore, many states foresee international civil UAS operations in the near future [29], a fact that has motivated the ICAO to explore UAS regulations.

ICAO involvement with UAS dates back to April 2005, when it decided to consult some of its member states regarding current

and future UAS activities in their NAS, and the need for ICAO guidance material [29]. An informal, exploratory meeting followed in May 2006 in Montreal, Canada, where attending delegates of 15 states and 7 international organizations agreed that ICAO was not the appropriate body to lead the regulatory effort and that although it could guide and coordinate to some extent the regulatory efforts, the latter should be based on the work of RTCA, EUROCAE and other bodies [29]. In a second ICAO meeting during January 2007 in Florida, a UAS study group was established with the goal of supporting the regulation and guidance development within ICAO [30]. Furthermore in a working paper presented by the US in the 36th ICAO Assembly in September of 2007 the need to amend the accident definition with occurrences involving UAS and appropriate investigation of such accidents was put forth [31].

In Europe, the JAA/Eurocontrol UAV Task force issued a report in 2004 [32] for regulations on civil UAS. A year later EASA issued an A-NPA based on that report, titled “Policy for Unmanned Aerial Vehicle (UAV) certification” [33]. Currently EASA has published a Comment Response Document (CRD) based on the comments received for the A-NPA and plans to publish a new policy. Nevertheless this new policy will not cover SAA and communications security requirements as well as light UAS [6]. Nevertheless EASA believes in the necessity of complete UAS regulations that cover airworthiness, environmental protection, operations, crew licensing, ATM and airport [34]. Currently EUROCAE has taken the lead to develop UAS standards and guidance based on the recommendations of the JAA/Eurocontrol and EASA reports [35]. Nevertheless UAS type certification is not expected before 2010 and 2012 for state and civil applications, respectively [36].

The French Flight Test Center adopted CSs for normal, utility, aerobatic and commuter manned airplanes to UAS [33]. CAA and CASA also had similar programs to regulate UAS operations in their respective airspace [37,38]. In Australia the ARCAA research center was also founded with a mission to facilitate UAS research and certification by providing simulation, development and testing facilities for all aspects of UAS operations [39].

Japan started using unmanned helicopters for agricultural applications (mostly pesticide spraying) almost 20 years ago [40]. More than 2000 Yamaha Rmax models were in service by 2002 and several are added each year [1]. At the moment the fleet of unmanned helicopters has surpassed the number of manned ones used for agriculture and they are expanding into new applications [40]. Recently UAS certification procedures became available that allow systems with weights up to 50 kg, to fly over unpopulated areas [40]. Two such systems have been already certified; the Yamaha Rmax and the Fuji RPH2 [40].

In the military domain, the JCGUAV of the NATO Naval Armaments Group approved the first draft of STANAG 4671 on Unmanned Aerial Vehicles Systems Airworthiness Requirements in March of 2007 [41]. STANAG 4671 is currently in the process of national ratification. This will allow UAS to fly over different countries, something that is not currently allowed by the ICAO without permission from the countries whose airspace the UAS will enter [42].

For safety reasons UAS flight in the US and worldwide is currently segregated from the rest of the air traffic with the use of NOTAMs [43].

Most of the documents previously mentioned concern civil UAS with MTOW above 150 kg [33,41]. In Europe, airworthiness certification for lighter vehicles as well as public UAS remains with national authorities [33]. Although national authorities retain control for certification of vehicles lighter than 150 kg, there is currently little or no information available on general certification requirements for this category of UAS; the only

exception being a recommendation from the UK CAA that was also adopted by the JAA/Eurocontrol UAS task force [32].

In the UK, the CAA realizing that small UAS would have problems complying with regulations, published a “Policy for light UAS systems” [44]. Eligible UAS under that policy are those that do not exhibit a maximum kinetic energy on impact over 95 kJ. UAS also need be operated within 500 m of the pilot and at altitudes not exceeding 400 ft [44]. In order for such vehicles to be certified, a positive recommendation is required from an accredited organization that has inspected the design and manufacture of the vehicle followed by successful completion of a reliability flight test program [44]. Furthermore, the CAA waives COA requirements for UAS with weight less than 20 kg, provided that they operate within a specified safety distance from airports, congested areas, third party vehicles, structures, etc. Finally for vehicles less than 7 kg, most of the requirements are waived.

In Australia, CASA exempts only ultra light UAS (less than 0.1 kg) and requires from the rest of the light UAS to operate away from populated areas at a maximum altitude of 400 ft [43].

It is clarified that there is a difference in using the term “light” in the airworthiness certification literature of manned aircraft versus that used for UAS. In the former category, light aircraft are those that do not exceed an MTOW of 600–650 kg depending on their use. On the other hand, the aforementioned weight requirements for light UAS (less than 150 kg) correspond better to the ultra light category as defined in the FAR Part 103.

5. Equivalent level of safety

According to the JAA/Eurocontrol UAS Task Force as well as the EASA, one of the guiding principles for UAS regulation should be *equivalence*, and based on that they assert the following [32,33].

Regulatory airworthiness standards should be set to be no less demanding than those currently applied to comparable manned aircraft nor should they penalize UAS systems by requiring compliance with higher standards simply because technology permits.

Therefore, the problem is how to define an ELOS. Manned aviation is currently regulated mostly through a code of requirements, usually in the forms of standards for various aircraft subsystems and for all stages of design, manufacture and operation the final system must adhere to [42]. Nevertheless, there are also provisions that define safety levels used to evaluate new technologies or designs, not covered by existing code [32]. These requirements may be found in *paragraph 1309* of current CS or the corresponding AMC sections. *Table 1* presents the risk system proposed in the 1309 AMC section of EASA CS 25, where an event that includes injuries and/or fatalities, is categorized as hazardous and as such it should be extremely remote ($<10^{-7}$ events per flight hour) [22]. On the other hand, multiple fatalities are considered to be of catastrophic severity with a likelihood requirement of 10^{-9} or less [22].

Such requirements pertain to the frequency of accidents that result in fatalities. Due to the wide range of UAS sizes and characteristics as well as the fact that they are unmanned, the outcome of an accident can range from minor injuries to a large number of fatalities and accident frequency could be misleading. Therefore this approach is not readily applicable to define an ELOS for UAS and as a result the ELOS need be exclusively based on the *fatality rate*. When the ELOS has been defined, the target level of safety (TLS) can be determined as the maximum acceptable frequency of an accident_i ($f_{\text{accident}_i, \text{max}}$) from (1) based on the expected number of fatalities:

$$f_{\text{accident}_i, \text{max}} = E(\text{fatalities}|\text{accident}_i)^{-1} \cdot f_{F, \text{max}} \tag{1}$$

UAS operations are subject to various hazards that can lead to three primary accidents: unintended or abnormal system mobility operation [45], mid-air collision, and early flight termination [46], either controlled or uncontrolled. A secondary accident is ground impact of debris following a mid-air collision. Potential damages resulting from these accidents include injury or fatality of people on the ground or on-board another aircraft, damage or loss of the vehicle, damage to property, environmental damage (fire, pollution, etc.) as well as societal rejection or outrage. The latter can be due to a high accident rate (even if no injuries occur) or if the accident involves cultural/societal sensitive areas like national parks or monuments, schools and churches. *Fig. 3* summarizes possible accidents and corresponding damages stemming from the operation of UAS in the NAS.

In safety engineering, the procedure for defining safety constraints for a specific hazard is normally based on the desired likelihood of the worst possible outcome [47], which in this case is

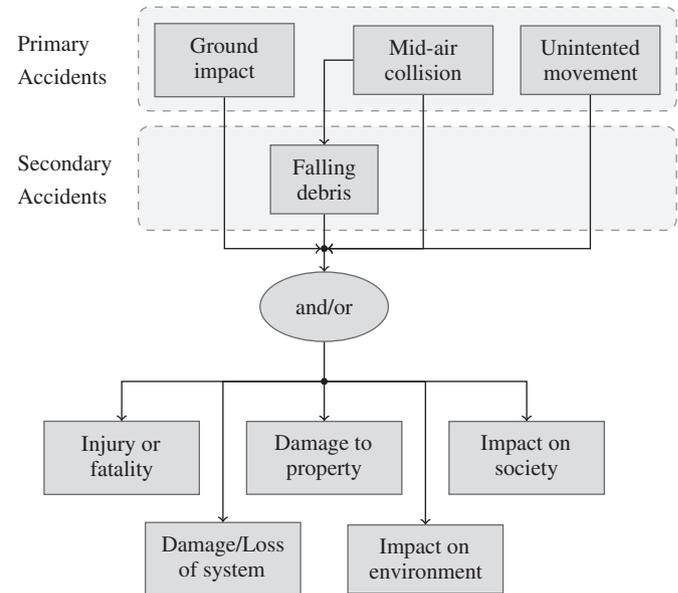


Fig. 3. Primary and secondary accidents that can result from the operation of UAS.

Table 1
Risk reference system for large manned aircraft (the grayed areas signify unacceptable risk)

		Catastrophic	Hazardous	Major	Minor	No safety effect
Probable	$> 10^{-5}/hr$					
Remote	$< 10^{-5}/hr$					
Extremely Remote	$< 10^{-7}/hr$					
Extremely Improbable	$< 10^{-9}/hr$					

Source: [22].

the occurrence of a fatality either on the ground after an impact or on another aircraft due to a mid-air collision. This can then be used to define the TLS for the accident. If the latter is known, the UAS can be designed in such a way that the rate of occurrence of the hazards does not cause the accident rate to increase above the set level. In the following sections appropriate TLS will be derived based on the ELOS requirement, for the two main accident types; ground impacts and mid-air collisions.

5.1. Ground impact

Although current manned aviation regulation does not impose limits on fatality rates, a statistical analysis of historical data can provide valuable insight on the fatality rates of manned aviation and be the basis for defining the ELOS for UAS. It should be noted that because UAS are unmanned, only the number of fatalities on the ground are to be taken into account when deriving the ELOS for ground impact. An analysis of NTSB accident data from 1983 to 2006, presented in Table 2, shows that ground fatalities in manned aviation, are only a very small percentage of the total fatalities and occur at a rate of about 1 per 10 million hours of flight. It should be noted that the exact number may vary depending on the type of aviation (general, regional/commuter, large) and the period over which the data are averaged [48]. This is also evident from the analysis in [47] that presents a survey conducted by the US Navy for ground casualties. Based on 10 million flight hours an average of 18, 7 and 4.7 fatalities is reported for US Navy, Commercial and General Aviation, respectively. The survey included data from 1980 to 1998 for US Navy flights and from 1982 to 1998 for civil aviation.

Considering the above, under ELOS requirements a fatality rate of $f_F = 10^{-7} \text{ h}^{-1}$ or less is proposed for UAS that is consistent with that of manned aircraft.

However, lower or higher likelihoods have also been proposed. In [49] a limit of 10^{-8} was proposed to account for the fact that the benefits of UAS operations are not evident to the general public and as a result the tolerance for fatalities will be lower. In [46] analysis is based on multiple acceptable likelihoods ranging from 10^{-6} to 10^{-9} . The Range Safety Criteria for UAS proposed a fatality rate of 10^{-6} or less based on the US Navy survey discussed previously [47], but their requirements are for military operations that allow higher fatality rates. Finally the NATO USAR also adopted the 10^{-6} rate [41].

Although stricter requirements may be attractive, they can seriously impede commercialization of UAS as well as their integration in the NAS. Therefore, a conservative evaluation of the risk from emerging hazards is preferable, since it can be later accommodated as flight hours accumulate and confidence in risk estimates improves.

5.2. Mid-air collision

To derive an ELOS for mid-air collision accidents, the total number of fatalities should be taken into account, since such accidents may occur between a UAS and a manned aircraft. Nevertheless, because in this case accidents may involve manned

aviation aircraft, a conservative TLS based on accident frequency is preferable. As a result, under ELOS requirements, a mid-air collision rate of $f_{\text{MaC}} = 10^{-7} \text{ h}^{-1}$ or less is hereby proposed.

6. Translating the TLS into system requirements

Although a TLS for the fatality rate cannot be directly used as a design specification, it is possible to determine the appropriate system reliability under various conditions to achieve it. A minimum system reliability requirement can then be readily converted to design requirements for the UAS components.

It should be noted that the derived reliability requirements will depend to a certain degree on the environment. For example, higher reliability is required for overflying high population density areas. Nevertheless for regulatory purposes these environmental parameters can be given “standard” values that will provide adequate safety under all scenarios.

6.1. Ground impact

The expected number of fatalities after an aircraft ground impact can be determined using (2), where N_{exp} is the number of people exposed to impact:

$$E(\text{fatalities}|\text{ground impact}) = N_{\text{exp}}P(\text{fatality}|\text{exposure}) \quad (2)$$

Assuming a uniform population density, N_{exp} can be calculated by (3) as the product of that area (A_{exp}) by the population density (ρ):

$$N_{\text{exp}} = A_{\text{exp}} \cdot \rho \quad (3)$$

There are several ways to determine the A_{exp} based on impact characteristics. For a vertical crash, this area may be approximated by the frontal area of the aircraft augmented by a small buffer to account for the width of an average human [50], whereas for a gliding descent it can be approximated by (4), where the wingspan and the length of the aircraft have been increased by the radius of an average person [48]:

$$A_{\text{exp}} = W_{\text{aircraft}} \left[L_{\text{aircraft}} + \frac{H_{\text{person}}}{\sin(\text{glide angle})} \right] \quad (4)$$

The minimum required time between ground impacts ($T_{\text{Gl,min}}$) can be calculated after combining (1), (2) and (5), obtaining:

$$T_{\text{Gl,min}} = f_{\text{Gl,max}}^{-1} = \frac{A_{\text{exp}} \rho}{P(\text{fatality}|\text{exposure})} \cdot f_F \quad (5)$$

As a result, when the number of people exposed to the crash is known, the fatality probability given the exposure needs be calculated. The probability of fatality can be estimated as a function of the kinetic energy on impact, although other parameters may also influence it. Unfortunately, there is no agreement or consensus in the literature on how this relationship/function is best defined, as demonstrated in Fig. 4. According to study results presented in RCC323 [47], an 11b object with kinetic energy of 50 J has a probability of causing a fatality of 10%, while for more than 200 J that probability rises to above 90%. According to study results presented in RCC321 [51], the corresponding kinetic energy estimates for an impact of a 1000 lb object to the torso are approximately 40 and 115 kJ, respectively, a difference of three orders of magnitude from the previous model. These differences can be attributed to the fact that kinetic energy does not correlate well with accident data [51] and, as a result, objects of different mass can have different effect even if the kinetic energy imparted at impact is the same. Even though this is the case, a logistic curve based on the kinetic energy impact is considered a good model for fatality rate estimation [51].

Table 2

Fatality rates in h^{-1} from analysis of NTSB accident data between 1983 and 2006

Accident type	All accidents	Mid-air collisions
Accident rate	8.05×10^{-5}	3.74×10^{-7}
Fatalities aboard	2.77×10^{-5}	6.82×10^{-7}
Ground fatalities	6.54×10^{-7}	1.87×10^{-8}

It is also stated that the existing models are based on direct impact of an object to a person without taking into account that during an impact, some of the impact energy may be absorbed by buildings, trees, vehicles or other obstacles. In [49] the probability of fatality is given as a penetration factor that depends on the characteristics of the UAS and takes into account sheltering. But observing the four example penetration factors given by Weibel [49] as illustrated in Fig. 4 for comparison purposes, it can be argued that Weibel's estimate for smaller vehicles is over conservative, since a fatality probability of 5% is assigned to a vehicle that weighs less than 100g, while, at the same time, the model underestimates the lethality of larger vehicles. No method is provided to consistently estimate the penetration factor (parameter) for other UAS.

Considering all previous justifications and observations, and based on the form of the fatality curves derived in [47,51], a variation of the logistic growth model has been proposed [53] to estimate $P(\text{fatality}|\text{exposure})$ as a function of kinetic energy at impact (E_{imp}) that also takes into account the mass of the aircraft as well as sheltering. The model is presented in (6) and depends

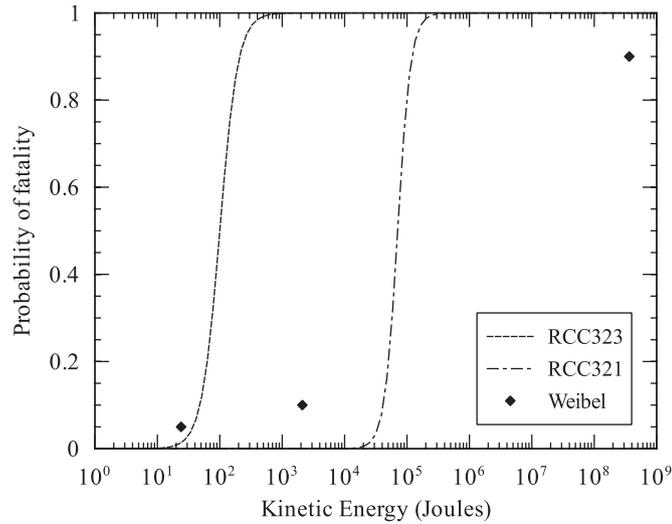


Fig. 4. The probability of fatality as a function of kinetic energy impact as estimated by Weibel [49] and models derived in RCC321 [51] and RCC323 [47].

on three parameters (α , β and p_s):

$$P(\text{fatality}|\text{exposure}) = \frac{1}{1 + \sqrt{\frac{\alpha}{\beta}} \left[\frac{\beta}{E_{\text{imp}}} \right]^{1/4 p_s}} \quad (6)$$

The sheltering parameter $p_s \in (0, 1]$ determines how exposed is the population to an impact. It takes an average value of 0.5, with higher values meaning better sheltering and a lower probability of fatality for the same kinetic energy. The α parameter is the impact energy required for a fatality probability of 50% with $p_s = 0.5$ and the β parameter is the impact energy threshold required to cause a fatality as p_s goes to zero. For small values of p_s and appropriately chosen β , (6) approximates accurately the curves in [47,51]. Fig. 5 presents the curves generated from the proposed model for various values of the p_s parameter.

The kinetic energy at impact is a function of impact speed that may vary depending on the UAS and the descent characteristics. At terminal velocity it can be calculated from (7), where m is the vehicle mass, g is the acceleration of gravity, ρ_x is the air density, A is the cross-sectional area of the vehicle and C_d is its drag coefficient. The latter two parameters are not always available, since they vary with the orientation of the aircraft during a descent:

$$E_{\text{imp}} = \frac{m^2 g}{\rho_x A C_d} \quad (7)$$

In [32,33,42], instead of the terminal velocity, the use of the maximum operating velocity (v_{op}) increased by 40% is proposed, resulting in:

$$E_{\text{imp}} = m v_{\text{op}}^2 \quad (8)$$

Using the above methodology it is possible to derive the reliability requirements for various types of UAS overflying different parts of the US. The results for six UAS using a sheltering factor of 0.5 are presented in Fig. 6. The UAS chosen span both fixed and rotary wing aircraft and all sizes and their characteristics are presented in Table 3.

6.2. Mid-air collision

In [49] the mid-air collision risk assessment was based on the use of a gas model of aircraft collisions, to estimate the number of expected collisions per hour of flight (f_c) from (9), where A_{exp} is

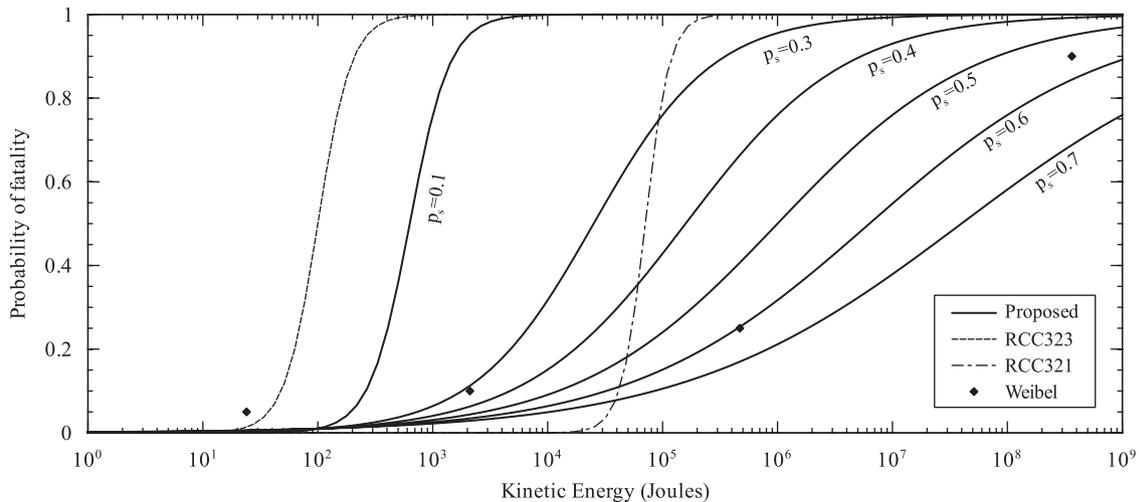


Fig. 5. The probability of fatality as a function of kinetic energy impact for the proposed model with $\alpha = 10^6$ J, $\beta = 100$ J and for several values of p_s . For comparison purposes the estimates of Weibel [49] as well as the models of RCC321 [51] and RCC323 [47] are given.

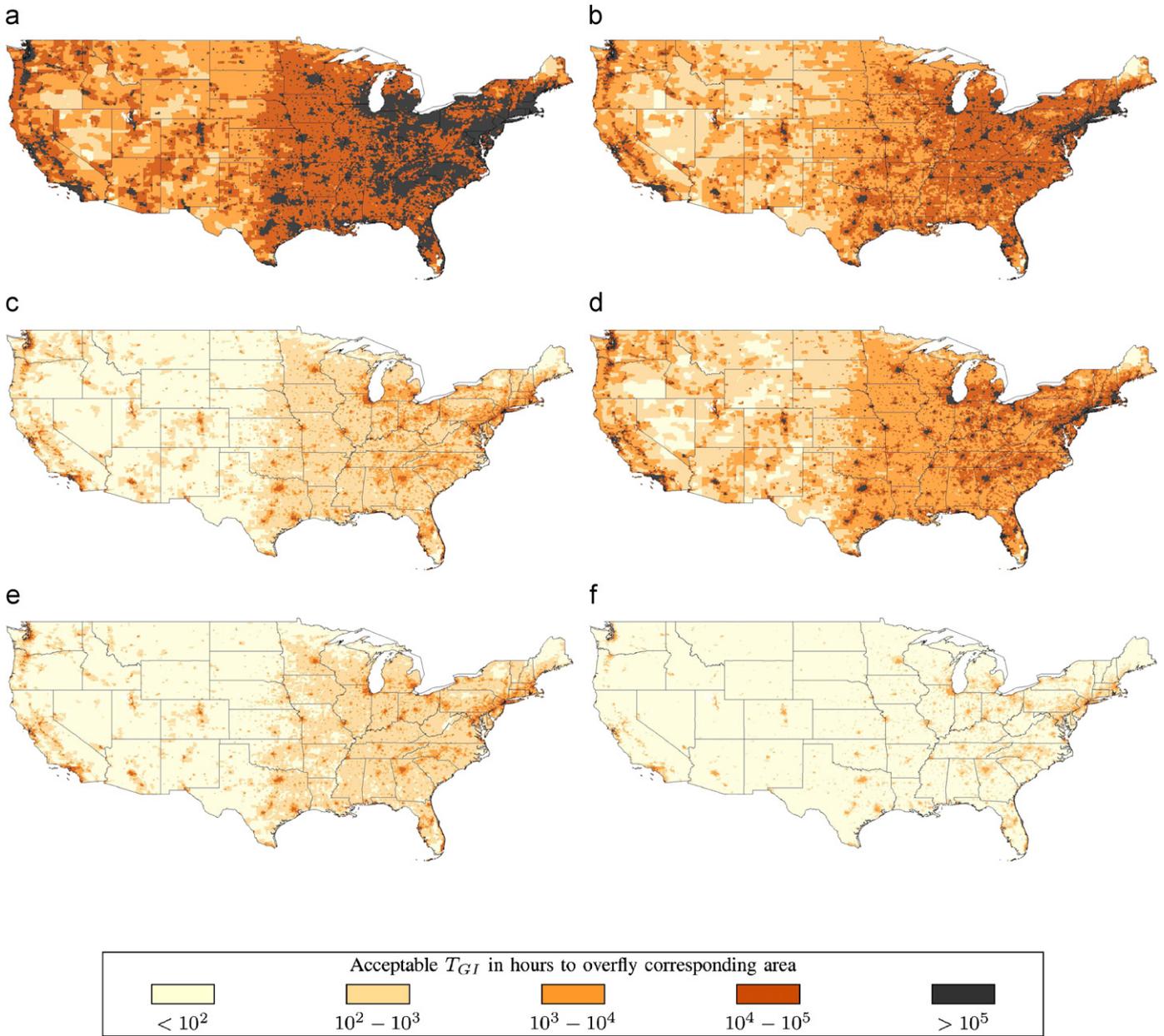


Fig. 6. The areas of the US, UAS are allowed to overfly based on their reliability with respect to ground impact occurrence frequency (a) RQ-4A Global Hawk; (b) MQ-1 Predator; (c) Neptune; (d) RQ-6 Five Scout; (e) Rmax IIG; (f) Maxi Joker 2.

Table 3
 Characteristics of three fixed wing and two rotorcraft UAS of various sizes, as well as two R/C helicopters, used for the case analysis

	Class	Weight (kg)	Dimensions (m)	Oper. speed (m/s)	Oper. altitude (ft)
RQ-4A Global Hawk	HALE	11,612	35.4 (wingspan)	177	65,000
MQ1 Predator	MRE	1021	14.8 (wingspan)	70	20,000
Neptune	CRE	36	2.1 (wingspan)	43	8000
RQ-6 Fire Scout	MRE	1157	8.4 (rotor diameter)	65	20,000
Rmax IIG	CRE	94	3.12 (rotor diameter)	5.6	500
Maxi Joker 2	Mini	8	1.8 (rotor diameter)	20	400

Source: [43,52].

the exposed area of the threatened aircraft, d is the distance traveled, V is the airspace volume and t is the time required to travel the distance d :

$$f_c = \frac{A_{exp}d}{V \cdot t} \tag{9}$$

It should be noted that this model estimates the number of mid-air collision hazards due to insufficient spatiotemporal separation given predetermined flight paths or simply the number of *potential* collisions. This is important because in the analysis presented in [49] an unstated assumption is made that all possible collisions are treated as expected collisions for getting the expected level of safety.

An additional term is required to take into account the fact that one or both of the aircraft in a collision course may attempt maneuvers to avoid each other. As a result, the expected number of collisions should be calculated from (10), where CT denotes a conflicting trajectory:

$$f_c = \frac{A_{\text{exp}} d}{V \cdot t} \cdot P(\text{collision}|\text{CT}) \quad (10)$$

$\underbrace{\hspace{10em}}_{E(\text{CT})}$

The use of the model in (10) to assess $E(\text{CT})$ presents significant difficulties since it requires the exact trajectories (both in space and time) of all air traffic, in the area where UAS operations will take place. This requirement is almost impossible to meet, because air traffic is dynamic and never identical from day to day and because not all traffic is monitored by ATC (aircraft at low altitudes or aircraft that fly in uncontrolled airspace and are not required to file a flight plan). In addition to that, in the event of a deviation from the predefined trajectory, the number of collision hazards following that event may change. Thus, a worst-case $E(\text{CT})$ may be assumed, instead. Based on the analysis in [49] high $E(\text{CT})$ is found in proximity of major airways with the highest at FL370, where it is approximately 4×10^{-5} CT/h. Since the results were obtained by averaging data over a 24 h period, a process that can hide higher peaks, a worst-case $E(\text{CT}) = 10^{-4}$ or even higher can be chosen to also account for future traffic growth.

Given the maximum acceptable collision frequency the maximum acceptable $P_{\text{max}}(\text{collision}|\text{CT})$ using (11), which substituting for the values proposed above gives:

$$P_{\text{max}}(\text{collision}|\text{CT}) = E(\text{CT})^{-1} \cdot f_{c,\text{max}} = 10^{-3} \quad (11)$$

This probability depends on the collision avoidance capabilities of all the aircraft involved and as such can be used to determine minimum performance requirements of such systems.

7. Adaptation of existing regulation

Although the FAR does not specifically mention UAS, current aviation regulations can be assumed to apply equally to all aircraft categories, including UAS [2]. Unfortunately applying current aviation regulation to UAS is not without problems. Traditionally safety levels have been considered under the assumption that the vast majority of manned aircraft fly in point-to-point operations and a significant portion of their flight time is spent over less densely populated areas [33]. This same assumption does not hold for UAS, since especially for surveillance/patrolling applications they are required to loiter over specific areas. It is obvious that if such areas under consideration have very low population (borders, forests, etc.), then, the safety level requirement obtained for manned aviation would be over conservative; on the contrary, if the UAS is required to loiter over a metropolitan area, this safety level would be inadequate.

Other important differences between manned and unmanned aircraft also need be considered. For example, UAS are sacrificable, that is allowing the UAS to crash in order to minimize damages to people and property may not only be acceptable but also desirable. This is in contrast with manned aviation regulation which strives to reduce the probability of any type of abnormal flight termination.

The FAA CGAR has conducted research into UAS regulation to determine how applicable current regulation is to UAS. In 2007, a regulatory review was presented at the CGAR Annual Meeting where it was found that only 30% of current manned aviation regulation applies as is to UAS; 54% may apply or may require revisions and 16% does not apply. The study concluded that there are significant gaps in the regulation that remain to be addressed.

A significant question that was posed in the same study was whether UAS have substantially different characteristics that warrant new regulation rather than adaptation of the existing one. Nevertheless, it would be inefficient and costly in terms of money and time not to use the experience and expert knowledge already contained in current regulation. This is reflected also in the literature where there seems to be a consensus on basing UAS regulation on that of manned aircraft of the same category, the latter defined primarily by their MTOW [32,33,42,53]. This is achieved by removing the non-applicable paragraphs and adding any additional requirements where needed, just like other special aircraft categories.

8. UAS classification

Let it be stated that the UAS take-off weight range extends down to a few grams and as a result the whole spectrum of UAS cannot fit in the manned aviation classes. Therefore, a need arises to determine appropriate UAS classes for regulatory purposes.

As mentioned earlier, the primary measure proposed for aircraft classification is the MTOW. This is because the MTOW correlates well with the expected kinetic energy imparted at impact, which in turn is considered to be the primary factor affecting the probability of fatalities [32,33,42,47,49,51]. Other factors include:

- *Sheltering*: Buildings, trees, vehicles and other obstacles can shelter a person from the impact, thus, reducing the probability for a serious injury or fatality.
- *Population density*: It is needed to determine the number of people exposed.
- *Aircraft frontal area*: It is used to determine the area affected by a crash.
- *Percentage of voluntary versus involuntary exposure*: Voluntary exposure relates to people involved in the operation of the UAS who are more aware of the risks and can take steps to avoid them. Higher fatality rates may be acceptable for voluntary exposure [48].

Based on the analysis carried out in Section 6.1, the T_{GI} for 43 UAS of various types and sizes was calculated to maintain an expected number of fatalities of less than 10^{-7} h^{-1} . The kinetic energy at impact was calculated using the maximum estimate from (7) and (8). The other parameters of the fatality probability model were assigned average values ($\alpha = 10^6$, $\beta = 10^2$ and $p_s = 0.5$). A standard population density of 200 people per km^2 has been assumed, which corresponds to the average scenario used to evaluate manned aircraft [33]. The T_{GI} requirement for each UAS is plotted against its MTOW and presented in Fig. 7. The existence of an approximately linear relationship between the MTOW and the T_{GI} is evident.

Using Fig. 7 a natural classification of UAS may be based on the order of magnitude of their MTOW, where each subsequent class will require an accident rate an order of magnitude smaller than the previous. Such a classification is presented in Table 4 where the MTOW-based classes were derived using the linear interpolation mentioned earlier, including a 300% safety margin to ensure a conservative estimate.

Although the actual classes may vary depending on the model parameters used, such a classification is important because of the significant differences in risk presented by aircraft of different classes. For example the micro and mini class UAS, as defined in Table 4, are so light that it is almost impossible for a fatality or serious injury to occur after a ground impact. They are also unlikely to cause problems to other aviation, provided that they

operate with sufficient clearance from airports, due to their usually low operating altitudes.

Although MTOW provides a good basis to classify aircraft based on the risk they present to people and property after a ground impact, UAS classes based on altitude are also of interest since they will dictate to a degree collision avoidance requirements. A simple classification is proposed below:

- (1) Very low altitude: This class of UAS will operate in uncontrolled airspace, typically at altitudes less than 400–500 ft. Due to the low altitude, these systems will need to avoid collision with terrain and other uncooperative flight. There is already a significant interest for small UAS flying at these altitudes which is considered the entry point for commercial applications in the future [39].
- (2) Medium altitude: This class will operate in controlled airspace up to FL600. In this case the UAS will most likely require a cooperative collision avoidance system, to avoid other VFR and IFR traffic.
- (3) High altitude: This class is for UAS operating at very high altitudes, like the RQ-4A Global Hawk. Although traffic at these altitudes is scarce, since they will need to transverse other controlled airspace, sophisticated collision avoidance systems will still be required.

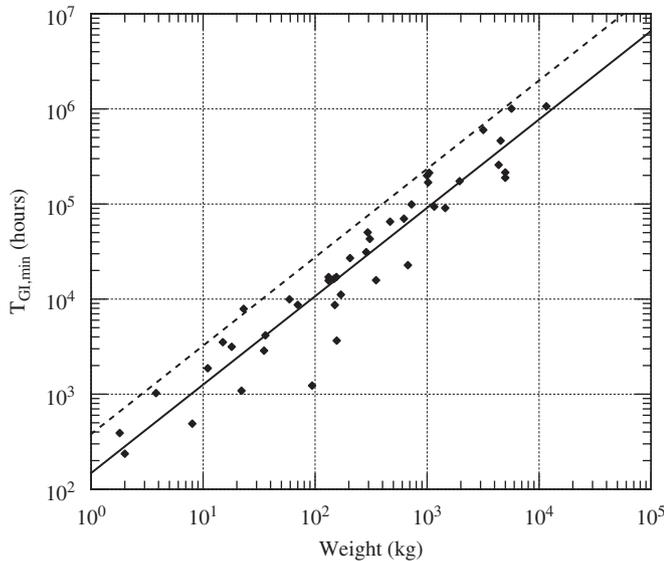


Fig. 7. The calculated T_{GI} requirement versus the corresponding MTOW for 43 UAS of different types and sizes. The calculations are done for a population density of 200 people per km^2 , $\alpha = 10^6$, $\beta = 10^2$ and $p_s = 0.5$. The relationship is approximately linear with respect to their logarithms. The dotted line corresponds to the requirement derived with a 300% safety margin added.

Another way to categorize UAS that is also of interest for certification purposes is based on their level of autonomy, as follows:

- Remotely piloted: A certified pilot remotely controls the system.
- Remotely operated: The UAS is given high-level commands (waypoints, objects to track, etc.) and its performance is monitored by a trained operator.
- Fully autonomous: The system is given general tasks and is capable of determining how to accomplish them. It can monitor its health and take remedial action after the occurrence of faults.

Regardless of the level of autonomy, UAS airworthiness requirements are likely to also include provisions for human override capabilities, compliance with ATC instructions, satisfactory system failure handling and collision avoidance among other things [33].

Finally UAS—like other aircraft—can be categorized based on their ownership as *public* or *state* when they are owned and operated by public entities like federal agencies or local law enforcement and *civil* when they are owned by industry or private parties [5].

9. Collision avoidance

As already mentioned, for UAS to achieve an ELOS to that of manned aircraft, two areas need be investigated. The frequency of ground impacts need be reduced, as well as the probability of mid-air collisions. The first can be achieved through increased system reliability for which well-known techniques, such as redundancy and fault-tolerance, are available and have been applied extensively in the past. On the other hand collision avoidance has been a major topic of debate since most of the available technology relies primarily on pilots and secondarily on ATC instruction.

Mid-air collision avoidance can be divided into two parts. The first part is involved with ensuring appropriate separation of aircraft, which is achieved via procedural rules and ATC instruction [2], but does not apply to all aircraft and airspace classes. The second part is involved with actually avoiding a collision in the case of inadequate separation. This entails systems like the TCAS-II and ADS-B as well as the FAR-mandated “see and avoid” requirement.

Collision avoidance in manned aviation is achieved through various mechanisms that build additional layers of security to minimize the probability of collision, shown in Fig. 8. The first layer, cooperative collision avoidance, is currently realized through the ADS-B system. This system operates by broadcasting the current location and vector of the aircraft to other aircraft in

Table 4
Proposed UAS classification for certification purposes

Number	T_{GI}	MTOW	Name	Notes
0	10^2	Up to 200 g	Micro	Most countries do not regulate this category since these vehicles pose minimal threat to human life or property
1	10^3	Up to 2.4 kg	Mini	These two categories correspond to converted R/C model aircraft. The operation of the latter is based on AC91-57 which the FAA has decided is not applicable for UAS
2	10^4	Up to 28 kg	Small	
3	10^5	Up to 336 kg	Light/ultralight	Airworthiness certification for this category may be based either on ultralights (FAR Part 103), LSA (Order 8130) or normal aircraft (FAR Part 23)
4	10^6	Up to 4000 kg	Normal	Based on MTOW these vehicles correspond to normal aircraft (FAR Part 23)
5	10^7	Up to 47,580 kg	Large	These vehicles best correspond to the transport category (FAR Part 25)

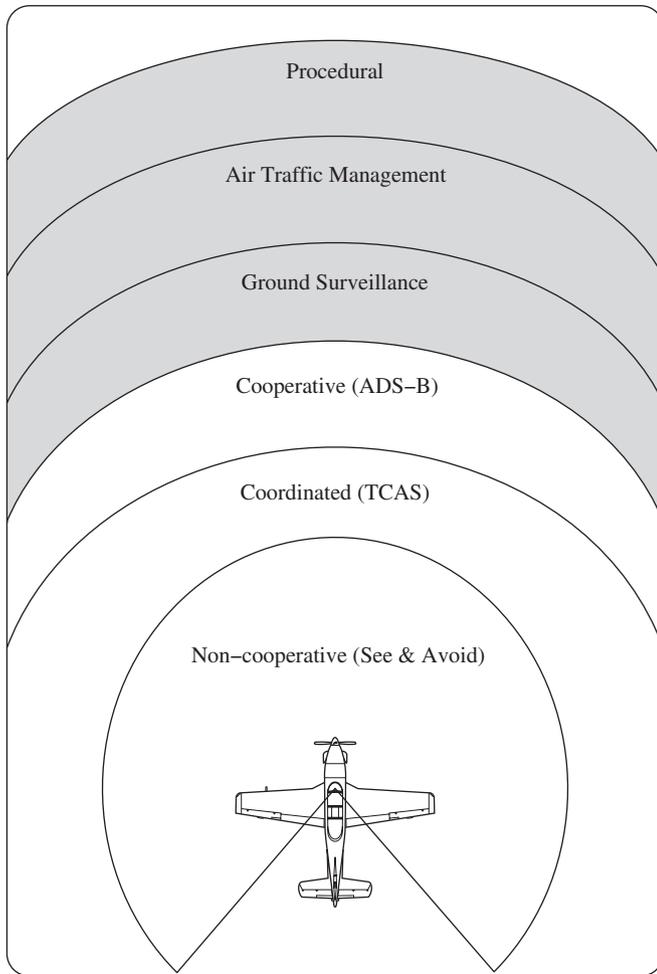


Fig. 8. Collision avoidance mechanisms available to civil aviation. In gray are the techniques to ensure separation. Adapted from [54].

the area. Although this system offers superior deconfliction, it may fail even if one aircraft in the area is not equipped with it. Since it is currently in the very early stages of adoption [2], its effectiveness is greatly reduced.

TCAS is an older collision avoidance system that has been already mandated for certain classes of passenger aircraft [2]. It operates by requesting information on a specific communications frequency and receiving replies from other aircraft equipped with TCAS. Using that information it is capable of evaluating the positions of all the TCAS-capable aircraft in the area and giving simple, auditory advice to alert the pilot of a possible collision as well as suggest a vertical maneuver to resolve the problem [55]. A new version of the system TCAS III is also going to include horizontal as well as vertical deconfliction. Significant modifications would be required to successfully use the system in UAS due to the differences in aircraft characteristics and the nature of possible collisions [55,56].

Based on current regulations, it can be expected that for the foreseeable future UAS collision avoidance cannot depend exclusively on either the ADS-B or the TCAS. This is because there will be airspace users that will not be equipped with any of these systems. A change in current regulation is also unlikely, since UAS integration in the NAS should be possible with current ATM systems and not incur any cost to current airspace users [39]. Furthermore, these systems are not capable of terrain and other obstacle, like birds and powerline, avoidance [56]. Thus, the requirement for see and avoid capabilities becomes apparent.

See and avoid or sense and avoid (SAA) as is the most common use of the term for UAS is currently required from all aircraft operating in the NAS. A SAA system installed on a UAS should be capable of operating under various weather conditions and situations [56] and, as autonomy increases, with limited operator involvement. This entails information fusion from multiple sensors. SAA sensor research has investigated electro-optical, acoustic and microwave sensors [2]. When combined, these sensors offer unique characteristics that enable a UAS to detect and in some cases track one or more targets in difficult conditions like fog, glare or darkness. In technology demonstrations SAA systems were able to surpass human pilots in detecting approaching aircraft from greater distances [2].

Although successful demonstrations of various SAA systems have been made, extensive simulations and field testing are required to evaluate their performance under various conditions and collision scenarios, before they can be used in civilian applications. On the other hand testing without access to the NAS is problematic and as a result specialized test centers are needed that will have permission for airborne tests.

10. Technology testing and evaluation

In parallel with standards and regulations development, other efforts are required to streamline the integration process of UAS in the NAS. Of foremost importance is to build test centers to evaluate UAS and their subsystems for both R&D as well as certification purposes. Recently the UAS CoE of the University of North Dakota demonstrated an interest for building such a test center [57]. Similar centers are planned or have already been built in France, Canada, Australia and New Zealand. Such centers can then be used to certify UAS hardware and software components as well as provide UAS crew training, as is the goal for the ARCAA in Australia [39].

Equally important is the development of a database like the ASRS [58] to store flight logs and all incidents and accidents from UAS operations. This database will provide invaluable information for UAS developers and operators as well as insight for standardization and regulation efforts. Furthermore the UAS reliability data are also useful for insurance providers, since companies operating civil UAS will be liable for damages incurred due to UAS operations and will require indemnification [59].

11. Operator training and certification

Currently a significant percentage of UAS accidents have been attributed to human errors; errors which in several cases can be attributed to inexperience [60]. As a result operator training is a major concern for UAS and already some research centers are working on procedures and requirements for UAS operator and crew training. There are two significant differences between UAS and manned aviation that need to be taken into account in this case. The first is that the operator, being physically removed from the cockpit, has limited perception of surroundings. This is because one relies only on data sent back from the UAS, which may not provide some information like smell, vibration, controller feel [2,61]. For remotely operated UAS, this separation has the added side-effect that there will be some lag between the UAS sensing something and executing a correction, since information must travel to the ground control station and back. In addition to that, it has been suggested that because the pilot is in a safe environment and serious consequences from a failure are not expected, pilot errors may be more frequent and maintenance personnel may become complacent [62].

The second difference is that the authority of controlling the UAS may reside with the on-board control system and the operator is limited to observing and providing only high-level commands. More specifically depending on the level of autonomy, the operator may need little to no training to operate the UAS and may in fact operate more than one at the same time [61]. Operating more than one vehicle at the same time will require new types of training, so that operators are fully aware of the situation of each controlled UAS, applying the correct action for each one.

Regardless of the level of autonomy, if the UAS fail-safe system relies on manual pilot override, then a fully qualified pilot will be required at all times.

12. Certification paths

As mentioned in Section 3.2, currently there are only two avenues for UAS certification, either by applying for a COA in the case of public UAS or by applying for a special certificate in the experimental category for civil UAS. The latter presents prohibitive problems for the industry because it takes time and there are no clearly defined procedures for UAS. In addition to that, experimental certificates are quite restrictive and do not permit commercial applications.

Current certification paths are counter-productive for the FAA as well, because they force FAA to allocate resources for thoroughly investigating each application instead of producing the required regulation [2].

Although the FAA is under pressure to present a UAS airworthiness certification roadmap, the document is still in development and not currently available. Nevertheless it can be expected that because UAS technology is new and untested, FAA will take a cautionary approach to regulation development and as a result the process of UAS integration in the NAS may take several years. During this time the required technology will first be developed, tested and verified and then standards will be drafted before the FAA produces the required regulations.

To speed-up this process, a step-by-step integration of UAS in the NAS is proposed, starting with the small and simple designs and progress towards the larger and more complicated ones. This process has the advantage of allowing fast integration of the smaller and “safer” classes of UAS and aiding in developing technology, expertise and standards that can be used to regulate the larger classes. In addition to that integration can be achieved incrementally, at first UAS will be restricted to low population/low air traffic areas but gradually this restriction will be relaxed [63] as technology matures. As a consequence the micro/mini and ultra light categories should be the main focus of current regulatory efforts.

13. Discussion

Current manned aircraft have a T_{GI} of 10^5 h or better depending on the vehicle type [43,48,52], whereas contemporary operational UAS have been reported to have mishap rates of 1–2 orders of magnitude larger¹ [65]. Nevertheless it should be noted that different vehicles exhibit very different safety performances. Fig. 9 shows that the number of accidents of the Global Hawk UAS dropped below that of the manned F-16 fighter jet after accumulating a total of 1000h of flight. At the same time other UAS like the Shadow and Pioneer exhibit significant accident rates even after 100,000 h of accumulated flight.

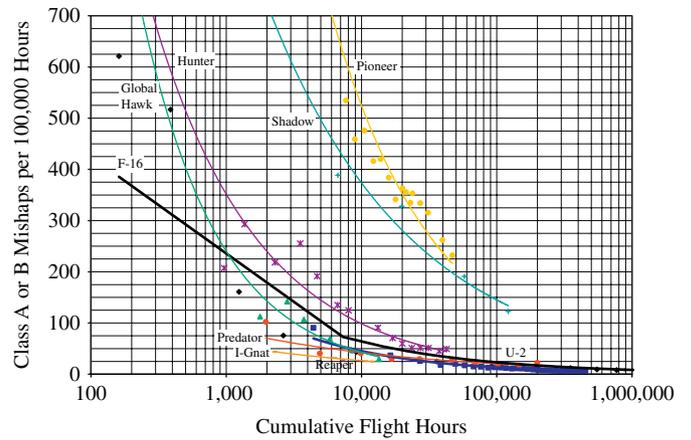


Fig. 9. Comparison of lifetime class. A mishaps of the F-16 military aircraft and various military UAS (1986–2006) [64].

Table 5
Sources of failures for US and Israeli Military UAS: [52]

	US (%)	Israel (%)
Power/propulsion	38	32
Flight control	19	28
Communications	14	11
Human/ground	17	22
Misc.	12	7

Higher UAS accident rates means that there are a lot of areas where these systems are not or should not be allowed to fly due to safety reasons. Furthermore, due to the nature of the missions that UAS are designed for, they are often required to loiter over a specific area. This is in contrast with manned aviation, which is normally involved in point to point operations and spent most of their flight above less densely populated areas [33,56]. For some UAS, even if they reach the 100,000 T_{GI} limit, operations over many areas, mostly in and around major cities, many not be allowable for safety reasons.

In all cases whether due to an accident rate or a fatality rate restriction, risk mitigation measures should be required to demonstrate airworthiness. Risk mitigation can include increased system reliability, redundancy, recovery from failures and contingency planning among others [66]. It should be noted that although the presence of flight termination systems (parachute, pyrotechnics, crashports) can effectively minimize impact energy and can be used for fail-safe purposes, most regulatory documents stipulate that such systems may not be taken into account when determining safety performance [41,42].

Results of a study related to reasons causing UAS accidents are presented in Table 5. The effect of human error is expected to decrease as the level of autonomy increases and operators gain more experience. Similarly communications are expected to be a smaller problem for civilian applications, since an adequate and reliable communications infrastructure can be assumed to be available for most of such applications. Improvements on the power/propulsion systems are also expected, especially in smaller UAS, where simple and reliable electric propulsion is available. As a result, mitigation measures for UAS should be primarily concentrated in the flight control system (FCS) and secondarily on propulsion.

There are several measures that can be taken to achieve the required FCS reliability levels in all types of UAS. There are two

¹ The accuracy of the UAS mishap rates is under question since it involves a limited number of platforms and the results have been extrapolated from a low number of flight hours.

main mechanisms through which a ground impact may occur. The first comes after a failure to identify accurately and in time an obstacle either moving or stationary. This mechanism can be controlled by a collision avoidance system.

The second mechanism corresponds to the occurrence of a fault or failure in the FCS, a sensor or actuator or from structural degradation of the vehicle that altered its dynamic characteristics. Under non-catastrophic failures the system should be capable of continued safe flight and landing, which is defined by FAA as [67]:

The capability for continued controlled flight and landing at a suitable airport, possibly using emergency procedures, but without requiring exceptional pilot skill or strength. Some airplane damage may be associated with a failure condition, during flight or upon landing

In UAS such failures should be accommodated transparently from the FCS and if that is not possible, then the UAS should be capable of failing gracefully, that is terminating flight in an as controlled manner as possible.

It should be noted that possible fatalities are not the only harm possible from UAS operations. As a result, instead of only considering the worst possible outcome for each accident, a bottom-up approach may be warranted where all possible outcomes are considered, especially when assessing the risk of operations in low population density areas where the risk of fatalities is very low. This means that besides the target safety levels for the expected number of fatalities, target cost levels are also required to determine the minimum acceptable T_{CI} . This is especially true for light UAS were, due to the improbability of fatalities from their operation, the required reliability levels are expected to be mostly cost-driven instead of safety-driven.

The cost of a UAS ground impact includes the cost of damages to the platform as well as damages to other property. Some UAS, depending on their size, may also carry dangerous payloads (chemicals, pyrotechnics for the fail-safe system) and/or significant quantities of fuel. After a crash, fire or chemical spillage is possible with measurable effect on the environment. Finally a high frequency of accidents even when they are not accompanied by injuries or fatalities can create discomfort to the general public and influence UAS operations in general. To control the cost and alleviate the other aforementioned issues, it can be expected that a maximum accident rate limit will be mandated regardless of the expected fatality rate from the operation of the UAS, especially for systems restricted to flying in remote, less populated areas.

14. Conclusions

Currently regulations involving public and civil UAS operations are in their early stages of development. However, there is also considerable activity in universities, research labs and commercial entities that has resulted in a significant number of civil UAS in various stages of development. People and organizations involved in these activities in the US should be aware of current FAA policy and the limitations imposed therein.

Although it is difficult to predict the exact form of future regulations, safe assumptions can be made on certain aspects of it. The primary goal of UAS regulation will be to ensure the safety of the public and this will entail increased reliability and effective SAA technology. Operation rules will be the same or similar to that of manned aviation which means that UAS will need to be capable of communicating with ATC and responding to instructions in a timely manner. The differences in operational characteristics will lead to a different pilot certification class, with different training requirements. Based on these assumptions UAS developers can

take appropriate measures and develop their plan to maximize their chances of compliance with future regulations.

Civil/commercial operations based on UAS may not be allowed for several years, nevertheless it is imperative that the required enabling technologies be developed and tested. These technologies include fault-tolerant control, fail-safe systems, accurate sense and avoid and reliable long-range communications among others.

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