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A Review of Current and Prospective Factors for Classification of Civil Unmanned Aircraft Systems

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Abstract

While progress is being made on integrating unmanned aircraft systems (UAS) into our national airspace on a broad scale, much work remains to establish appropriate certification standards and operational procedures, particularly with respect to routine commercial operations. This paper summarizes research to examine the extent to which today's civil aircraft taxonomy applies to UAS, and, if needed, how that taxonomy could be amended to better cover different UAS designs and operations. Factors that shape the current taxonomy, as defined in the Federal Aviation Regulations, were assessed for applicability to UAS, potential incompatibilities were identified, and additional factors were proposed that might be useful for an updated aircraft taxonomy intended to cover UAS. The results suggest the possibility of constructing new groups in the taxonomy for UAS under a restricted category that share common airworthiness standards. Establishing distinct groups for UAS and associated standards that enable low risk operations for compensation or hire could be a timely step toward full integration. Such a step would allow the civil aviation industry and regulators to gain valuable experience with UAS while carefully controlling access and potential harm to the aviation system as a whole.

Acronyms and Abbreviations

AC	Advisory Circular
ARC	Aviation Rulemaking Committee
ASTM	American Society of Testing and Materials (formerly)
CASA	Civil Aviation Safety Authority
CFR	Code of Federal Regulations
CNS	Communication, Navigation, and Surveillance
COA	Certificate of Authorization (or Waiver)
CPA	Conventionally Piloted Aircraft
DAL	Design Assurance Level
DoD	United States Department of Defense
EASA	European Aviation Safety Agency
FAA	Federal Aviation Administration
FARs	Federal Aviation Regulations
GAO	General Accounting Office
ICAO	International Civil Aviation Organization
kg	kilogram
lb	pound
LOS	Line-of-Sight
MTSI	Modern Technology Solutions Incorporated
NAS	National Airspace System
NASA	National Aeronautics and Space Administration
P_f	probability of failure
RLOS	Radio Line-of-Sight
RPA	Remotely-Piloted Aircraft
RPAS	Remotely-Piloted Aircraft System
UA	Unmanned Aircraft
UAS	Unmanned Aircraft System
UAV	Unmanned Aerial Vehicle
UMS	Unmanned System
US	United States
UVSI	Unmanned Vehicle Systems International
VLOS	Visual Line-of-Sight

1. Introduction

The unmanned aircraft systems (UAS) industry is projected to grow substantially in the near term, with respect to the number of UAS available on the market as well as the range of commercial capabilities [AUVSI-2013]. This vision of economic growth is consistent with the Federal Aviation Administration (FAA) Modernization and Reform Act of 2012 [FAA-Mod]. That legislation mandates, among other things, that the FAA develop a comprehensive plan to safely accelerate the integration of civil UAS into the national airspace system (NAS) by September 2015, and define acceptable standards for certification necessary to support integration. While progress is being made on rules for small UAS[1], the FAA has not established certification standards or other regulatory requirements (e.g., crew qualification and operating procedures) for routine commercial operations [GUZ-2013].

For this paper, the term *certification* encompasses a broad gamut of processes that must be undertaken in order to comply with regulation, policy, standards, and oversight to ensure an acceptable level of safety and efficiency while operating in the NAS. Certification serves a critical role in achieving the aviation community's safety objectives [RTCA-TF4-1999]. The certification challenge for integration of civil UAS into the NAS is to develop guidance and standards that ensure that UAS operations do not compromise the safety of other airspace users or the safety of persons or property on the ground. This paper reports research findings that help to addresses this challenge, with particular emphasis on classifying UAS for the purpose of allocating airworthiness standards.

Most civil aircraft must comply with minimum design and performance criteria as specified in airworthiness standards. According to Title 14 of the Code of Federal Regulations [CFR], better known as the Federal Aviation Regulations (FARs), the term *airworthy* means, "…the aircraft conforms to its type design and is in a condition for safe operation" (Part 3, Section 5). Different types of aircraft have different airworthiness standards that cover topics including flight characteristics, structures, design and construction, powerplants, and avionics. Civil airworthiness standards for general aviation and transport category aircraft are specified in the FARs, while others are developed by industry standards organizations such as the American Society for Testing and Materials (ASTM).

As reported in [CPWF-2010], limited consideration has been given to date to how airworthiness standards and regulations may be appropriately applied across all UAS and their operations. On one hand, UAS regulations should be no less demanding than those currently applied to comparable manned aircraft; on the other, they should not penalize UAS "by requiring compliance with higher standards simply because technology permits." [ULTRA-D1.1] Research reported here aims to determine the extent to which the existing aircraft taxonomy and associated airworthiness standards can be applied to different UAS types, and if they fall short, how can they be amended to better fit.

The research reported in this paper qualitatively tests the hypothesis that the taxonomy used today in the FARs for allocating airworthiness standards is appropriate for UAS if two conditions are met: (1) the existing aircraft classes and categories sufficiently cover UAS designs, and (2) corresponding standards would neither overregulate nor underregulate UAS. The first condition indicates that existing airworthiness standards apply to UAS if the attributes that distinguish existing aircraft classes and categories can also be used to differentiate UAS designs in a similar way, notwithstanding the need to address UAS unique attributes such as command and control links and ground control stations. The second condition implies that airworthiness standards associated with each aircraft class and category combination need to be appropriate to the level of risk posed by UAS. If the current taxonomy and classification factors do not adequately capture either distinct design attributes of UAS or unique

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[1] Small UAS are generally considered those that weigh less than 55 pounds and operate within visual line-of-sight.

operational aspects that affect risk in different ways from conventionally piloted aircraft (CPA), then other factors and potentially other standards may be required.

Testing this hypothesis relies on interpretation of the intent of the FARs. This paper should not be considered or used as an authoritative source for regulatory guidance, nor does it represent current or future US Government or FAA policy. Instead, this examination of aircraft classification factors is intended to highlight some of the UAS design attributes and operations that affect the definition and application of airworthiness standards. The aim is to support development of an effective and practical approach to UAS classification that facilitates routine approval of UAS for commercial operation in the NAS.

This report is organized into 6 Sections. Section 2 describes the research scope and rationale for why aircraft classification is important for enabling routine access to the NAS, as well as terminology fundamental to a coherent discussion on the topic. The current aircraft taxonomy used for CPA in the US is described in Section 3. Sections 2 and 3 may be skipped for those familiar with civil certification and issues relevant to UAS. The next two sections contain an analysis of the current classification factors for CPA, and discussion of prospective factors for unmanned aircraft. In particular, Section 4 identifies the factors that underlie the aircraft taxonomy discussed in Section 3, evaluates the hypothesis that those factors are sufficient for UAS, and identifies gaps where the existing taxonomy may not be well-suited for UAS. Then, Section 5 discusses additional factors that may be considered for augmenting the current classification system. Section 6 provides a summary of work to date and shares some final observations regarding the possibility of classifying UAS within the current aircraft taxonomy and factors potentially useful for doing so.

2. Background

Existing FARs and associated policy and guidance serve as a reasonable starting point for research inquiry into UAS certification issues, especially given that design standards and regulations for UAS are expected to conform with existing certification frameworks [FAA-RM-2013, CAP-722, DVP-2009, EASA-EY013]. To properly frame this research, clarifying what classification and airworthiness mean within this context is important.

2.1 Scope

Certification requirements specific to aircraft, to airborne and ground-based systems and equipment, to operations within different airspace classes, and to pilots and other personnel involved in operating or managing aircraft are all covered in the FARs. In this paper, the primary focus is on certification aspects pertinent to airworthiness standards for aircraft and their constituent systems and equipment. According to FAR Part 3.5, *airworthy* means that an aircraft "conforms to its type design and is in a condition for safe operation." As per [ICAO], airworthiness requirements account for the safety of not only the participants in the airspace system, but third parties and property, too. Airworthiness certification is one of several different certifications required for an aircraft to operate legally in the NAS. Examples of other required certifications include those for pilots, flight crew members, and mechanics. FAR Part 21 specifies the basic procedures for civil certification of aircraft products and parts in the US, including those for airworthiness.

Airworthiness spans the lifecycle of an aircraft, from initial airworthiness during design and production, to continued airworthiness during operations and maintenance. This paper only considers airworthiness at the design level. According to FAR Part 21.203, every civil aircraft that operates in the US must have a valid airworthiness certificate; and that certificate is issued when the aircraft conforms to an approved type design and is in a condition for safe operation (FAR Part 21.183). Per [FAA-RM-2013], all UAS will require design and airworthiness certification for civil operations in the NAS, except for some special cases, such as small UAS with very limited operational range. Aircraft type design and performance standards for most CPA are provided in several parts of [CFR] (namely, Parts 23, 25, 27, 29, 31, 33, and 35), and in industry standards for other aircraft such as gliders and light sport. These standards reflect general consensus on minimum design and performance requirements necessary for safe flight, and are derived from engineering judgment and experience, especially lessons learned from accidents and incidents.

Three different certificates are relevant to airworthiness: a type certificate, a production certificate, and an airworthiness certificate. A type certificate is issued for a particular design of a civil aircraft, engine, or propeller insofar as it complies with applicable airworthiness requirements. The quality system used for manufacturing aircraft is addressed through production certification. A production certificate is issued to confirm that a manufacturer can produce duplicate products under an FAA-approved type design. For an aircraft with a type certification, information about production and maintenance must be provided to obtain an airworthiness certificate. An airworthiness certificate indicates approval that each aircraft, as built, complies with its type design and is in a condition for safe operation. As such, airworthiness is applied on an airframe-by-airframe basis, whereas the type design applies to all aircraft of that design. However, the same airworthiness standards, such as those in FAR Part 25 for transport category airplanes, are the basis for both certificates. This paper focuses on the technical aspects of airworthiness at the design phase (i.e., type certificate). This paper does not consider issues related to production certificates or continuing airworthiness for individual aircraft, nor does it consider the particular legal and procedural issues involved in the certification process.

While on the topic of certificates, it is important to note that airworthiness certificates may be issued as "standard" or "special". Most commercial operations require a *standard* airworthiness certificate. Under a standard airworthiness certificate, an aircraft typically has relatively few operating restrictions. *Special* airworthiness certificates are more restrictive, typically including operational limitations on maneuvers, speed, number of passengers, activities undertaken, or where flights may be conducted. The classification system in the FARs maps each combination of aircraft class and aircraft category into one of these two types of airworthiness certificates. For example, light sport and experimental aircraft operate under special airworthiness certificates, while general aviation and transport aircraft typically operate under standard airworthiness certificates. Certificates that allow commercial operation for compensation or hire have more stringent requirements than recreational or other types of use, including requirements on levels of redundancy and fail-safe features to meet reliability requirements. In this study, the focus is on classification factors relevant to commercial operation of UAS, rather than recreational use.

The scope of the research presented here is focused on safety-related risks associated with classification of UAS within the existing regulatory framework in the short term. Certainly, UAS design possibilities in the long term may far exceed those for conventional aircraft. Concepts such as fully-autonomous UAS, passenger aircraft without a pilot on board, reconnaissance or monitoring swarms, and hypersonic UAS were not considered in this research. Other considerations not specific to safety, such as privacy [GAO-2012], security, and environmental impact, were also not considered. Offering classification analysis for these advanced concepts, without sufficient data on the hazards they may introduce, is not warranted.

2.2 Terminology

This section explains the key terms used throughout the paper relevant to classifying UAS. To the extent possible, this paper uses terminology consistent with the FARs[2] and other FAA regulation and policy.

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[2] The notation FAR Part X.Y is used throughout this paper when referring to specific regulations, and should be understood to mean "Title 14 of the Code of Federal Regulations, part X, section Y" [CFR].

- Airworthy: In civil aviation, airworthiness is specific to the aircraft; that is, the airborne vehicle. Most UAS comprise several distinct parts in addition to the aircraft, including a ground control station, command and communication links, and possibly launch and recovery equipment—physically separate from the aircraft. This paper uses the term *airworthy* to consider all components of a UAS necessary to enable safe flight from take-off to landing.
- Class: "As used with respect to the certification of aircraft (i.e., *aircraft class*), means a broad grouping of aircraft having similar characteristics of propulsion, flight, or landing. Examples include: airplane; rotorcraft; glider; balloon; landplane; and seaplane". (from FAR Part 1.1)
- Category: "As used with respect to the certification of aircraft (i.e., *aircraft category*), means a grouping of aircraft based upon intended use or operating limitations. Examples include – transport, normal, utility, acrobatic, limited, restricted, and provisional." (from FAR Part 1.1) [Note: The terms *class* and *category* are also referred to in the FARs for airmen ratings, including single engine, multi-engine, land, water, gyroplane, helicopter, airship, and free balloon. These definitions are not applicable to this paper.]

The term *classification* is not defined explicitly in the FARs, although the term is used several times when referring to different aircraft types, airworthiness certificates, air traffic service routes, etc. For aircraft, *class* and *category* are used as attributes in combination to define a taxonomy that groups similar aircraft type designs with similar risk profiles for the purpose of assigning airworthiness standards. The physical and operational characteristics and capabilities that distinguish the aircraft classes and categories are referred to here as *classification factors* (i.e., those criteria that are used to determine class/category). Throughout this paper, the term *group* is used for the set of aircraft that fall in the same combination of class and category. Understanding the classification factors and how those may or may not apply to UAS is a primary objective of this research.

Any discussion of classification and airworthiness standards must include a discussion of *hazards* and *risks* related to safety. Per FAA policy on safety risk management [FAA-8040.4A], a *hazard* is any condition that could foreseeably cause or contribute to an unplanned event or series of events that result in death, injury, or damage to, or loss of, equipment or property. A *risk* (in the safety sense) is the composite of the predicted severity and likelihood of the potential effect of a hazard that could cause harm to persons or damage to property. As an aside, *safety* has often been defined as "the absence of risk."

The terms above are used in this work in the context of CPA. Terminology specific to unmanned aircraft is less well established. Different terms have evolved over the years, including *drone*, *unmanned aerial vehicle* (UAV), as well as UAS, which is the term most-commonly used within the US today. This terminology continues to evolve: in a recent report from the ICAO, the terms *remotely piloted aircraft* (RPA) and *autonomous aircraft* are introduced as two distinct types of unmanned aircraft (UA) [ICAO-328]. As per the ICAO definitions, a UA is any aircraft intended to operate without a human pilot on board; an RPA is an aircraft where the flying pilot is not aboard the aircraft; and, an autonomous aircraft is an unmanned aircraft that does not allow pilot intervention in the management of the flight. The term *system* is commonly appended, (e.g., UAS and RPAS) to take into account associated support equipment such as a ground control station, command and control links, and launch and recovery equipment. This report uses the term UAS, and also adopts the term CPA (*conventionally piloted aircraft*) to refer to manned aircraft, as recently used in other papers [ALPA-2011, CPWF-2011].

2.3 Civil and Public Aircraft Use

Another important aspect of the civil certification context is the distinction between civil and public aircraft and their use as described in the FARs. The responsible regulatory authority and applicable regulations vary depending on who is operating an aircraft and its intended use.

Civil use refers to aircraft operated by an individual or company, for commercial purposes (e.g., scheduled air transport of passengers and cargo operated for compensation or hire) or private ones (e.g., for recreation or business purposes without selling services to the public). Radio-controlled model aircraft also fall under the umbrella of civil use for recreation, and are operated under the guidelines of [AC91-57]. These guidelines do not restrict the aircraft (size, weight, etc.) or contain requirements regarding airworthiness. Instead, these guidelines restrict model aircraft operations to visual line-of-sight (VLOS), altitudes below 400 feet above ground level, day/visual meteorological conditions[3], away from noise sensitive areas, and away from airports and other air traffic. A recent decision by an administrative law judge has questioned whether the current FARs can be used to regulate model aircraft, even when they are used for commercial purposes [NTSB-2014]. On June 25, 2014, the FAA released an interpretation of the special rule for model aircraft that addresses this ruling [FAA-2014-0396].

The FAA authorizes UAS to operate for some limited civil uses in the NAS today by issuing a special airworthiness certificate in the experimental category (FAR Part 21.191) or the restricted category (FAR Part 21.185). A special airworthiness certificate is issued to an aircraft that does not have a type certificate or does not conform to its type certificate but is in a condition to operate safely. Operation under an experimental certificate is typically done for research and development, flight testing, market survey, or crew training. Amateur-built, kit-built, or light-sport aircraft are also operated under an experimental certificate. Operating limitations and airworthiness standards are developed for each experimental aircraft to ensure the safety of other airspace users and persons and property on the ground. An important constraint is that aircraft operating under an experimental certificate cannot be operated for compensation or hire. [FAA-8130.34B] provides guidance for certification of UAS in the experimental category. UAS may also be authorized to operate for compensation or hire for some special purpose operations under a restricted certificate. As of June 2014, only two UAS with prior military certification have qualified for such operations.

Public use refers to aircraft that are operated for governmental purposes, such as military operations, border patrol, law enforcement, firefighting, or scientific research. These aircraft are typically operated by local, state, or federal government agencies. An important difference between civil and public use aircraft is that public use aircraft cannot conduct commercial operations whereas several (but not all) categories of civil aircraft can.

Airworthiness standards may differ depending on whether an aircraft is intended for civil or public use. Under [USC49-44704(d)], a civil aircraft operator must demonstrate compliance to the FAA's requirements in order to receive an airworthiness certificate for their aircraft. Public operators provide their own assurance that their aircraft are airworthy. Public aircraft standards may be more or less stringent than civil standards depending upon individual mission requirements. Even though this paper is concerned with airworthiness standards for civil UAS, learning from airworthiness-related experiences of UAS in public service is important. Indeed, the bulk of the information that exists on safety-related hazards and design criteria for UAS comes largely from public use cases and thus, will influence the development of civil standards.

Both civil and public aircraft are required to comply with FAA operational requirements (distinct from airworthiness requirements) to fly in the NAS. For most UAS (public and civil), operational approval comes in the form of a Certificate of Authorization (COA) or Waiver issued by the FAA [FAA-8900.227]. A significant number of UAS are operating in the NAS today under COAs. UAS may operate without COAs when operations remain within active warning and restricted areas, which is typically the case for military operations.

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[3] Visual meteorological conditions are most-commonly a cloud ceiling greater than 1000 feet and a visibility greater than 3 nautical miles.

2.4 Standards-based Airworthiness Certification

The primary purpose of airworthiness certification is to ensure that hazards and corresponding risks posed by the design, production, and continued operation of an aircraft are sufficiently mitigated. Risk posed to the NAS varies significantly depending on the type of aircraft, equipage, and its intended operation. For example, rotorcraft present some different physical hazards than airplanes due to aerodynamic design differences; whereas, a light sport airplane presents different operational hazards than a commuter airplane. FAR Part 21 and corresponding standards in Parts 23, 25, 27, and 29, provide an airworthiness certification framework that groups conventional airplanes and rotorcraft in a way that accounts for differences with respect to high level safety requirements and design considerations. As stated in [CPWF-2010], "A prerequisite to the realization of a viable civil UAS industry is the definition of an appropriate airworthiness certification framework for UAS. This framework must take into consideration the unique aspects of the technology, their operations, the market drivers, and the broader socio-political issues associated with the integration of a new aviation technology into society." Routine access by UAS to the NAS implies that type design and airworthiness certification requirements for a UAS should mitigate risk to the same level (or better) as those required for CPA.

Assuring compliance with the FARs as a primary means to certify the design of an aircraft could be called *standards-based* or *prescriptive certification*. A standard, consisting of minimum design or performance criteria that must be met, is typically established before an organization applies for type certification. Airworthiness standards include specific design criteria (e.g., structural load limits), required design features (e.g., existence of fire extinguishers), and performance parameters (e.g., required ratios of rotation speed to minimum control speed) necessary to mitigate known hazards and achieve an acceptable level of safety. Efficiencies in the certification process are gained by applying the same standards to any aircraft with a similar design and operational intent.

Conceptually, standards-based certification is a straightforward process. An applicant: (1) defines a product, (2) establishes the product's applicable certification standards, based on the FARs, in collaboration with the certification authority, and (3) presents evidence that they have met the certification standards [AGF-2004, McCormick-2007]. The certification authority then evaluates this evidence for compliance. Benefits of standards-based certification include: (1) a priori knowledge of the expectations for certification, which facilitates planning from a design and cost perspective, and (2) establishment of a consistent and level playing field for all applicants.

For most aircraft, the standards-based approach is used. However, for aircraft that do not obviously fit into the conventional mold, certification authorities can establish appropriate criteria, as per FAR Part 21.17b. A tilt rotor aircraft is an example of a novel design for which a standardized set of airworthiness criteria does not exist. The advantage of the FAR Part 21.17b approach is that it can accommodate any particular type design immediately, often leveraging relevant portions of existing standards, without waiting for the standards development process to take place. This approach is the only current alternative for UAS certification since airworthiness standards specific to civil UAS do not yet exist. The disadvantages of this approach are: (1) it is much more labor-intensive for the certifying authority; and (2) since all of the criteria are not known upfront, it is more difficult for the applicant and the regulator to plan for the cost of the certification effort given that there may be much more uncertainty in the outcome.[4]

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[4] In the US, costs associated with the involvement of regulators are not borne by the applicant. In Europe, the applicant must account for the involvement of the European certification experts.

2.5 The Role of Classification in Airworthiness Certification

A standards-based approach to certification is desirable, if not essential, to achieve routine, versus case-by-case, access to the NAS for UAS. Classification supports this approach by providing a means for grouping aircraft together with similar design attributes (e.g., rotorcraft); but, less obviously and perhaps more importantly, grouping aircraft together that pose comparable safety risk and holding them to the same standards. More rigorous certification standards (e.g., calling for additional redundancy to meet reliability requirements) are levied on aircraft that pose a greater risk; whereas those that pose less risk are held to a lower standard (e.g., general aviation aircraft vs. light sport aircraft). Classification recognizes such differences in aircraft and the need for different standards.

Because UAS differ from CPA in meaningful ways, these differences should be manifested in meaningful differences in certification standards, but not necessarily differences in the certification framework. For example, certification standards will be needed for UAS components such as ground control stations and communications functions related to aircraft control that do not exist with CPA. Including off-board systems and functions within the certification of UAS umbrella has been suggested for many years [Sabatini-2006]. Additionally, there are likely design differences among the wide range of UAS in existence today that would drive differences in required design criteria. For example, a "sense and avoid" function may be provided through an on-board system or it may be provided through a ground-based system. Although the function—sense and avoid air traffic—is the same for either approach, the airworthiness standards may vary depending on how the function is accomplished. In a similar way, a UAS that uses a beyond VLOS communications system may have different certification standards than one that uses VLOS communications.

Classification supports risk reduction in at least two additional ways. First, it uses the notion of risk reduction through *operational compensation*. Some potential aircraft operations do not provide enough economic or other benefits to justify the expense involved in a standard airworthiness certification effort. Thus, these operations will not be conducted. However, other operations that do not derive their benefit through general access to the NAS may be restricted in a way that still retains the desired benefit, without adversely affecting the risk to the general public or other NAS users. This risk tradeoff is handled in the FARs through the *restricted* aircraft category. A restricted category aircraft is limited to special purposes identified in its type certification approval. This category is used for limited special purpose operations in manned aviation today, e.g., agricultural spraying and aerial surveying. The FAA recently invoked this category to approve limited commercial use of UAS in the Arctic for the first time [FAA-PR-2013]. Based on this premise, an agricultural UAS may be allowed to fly under operational restrictions similar to conventionally piloted agricultural aircraft. Furthermore, it may be possible to develop appropriate restricted certifications for other operations that are outside of normal air traffic routes and away from populated areas (e.g., pipeline monitoring, commercial fishing, etc.). At least in the short term, the restricted category may prove to be useful in the certification of UAS.

The second way classification supports risk reduction is through the notion of *certification compensation*. FAA Advisory Circular (AC) 23.1309 describes how certification standards are lowered for avionics in some general aviation airplanes [AC23.1309]. The guidance was motivated by an assessment that low-time general aviation pilots have made mistakes that might have been prevented with advanced avionics, and therefore the avionics certification requirements are lowered to encourage greater equipage. Essentially, regulators concluded that the risk of a general aviation pilot with limited experience making a mistake is greater than the risk of the avionics failing or providing misleading information. The operational risk is mitigated through acceptance of an airworthiness risk, and by this assessment overall system risk is lowered. Using this approach for lowering certification requirements is controversial for UAS. On one hand, UAS have no people on board, thus acceptable risk may be judged inherently less (at least to participants). On the other, establishing that a UAS is equivalent in capability to a CPA is not trivial. The certification requirements in [AC23.1309] were only relaxed after detailed study, supported by years of accumulating and analyzing safety-related data. Similar data will be critical to support appropriate certification standards for UAS.

In summary, an important role of classification is to facilitate a standards-based approach to airworthiness certification of UAS. However, this can only be done by defining and applying classification factors that are sufficient for grouping together UAS with similar risk characteristics that would then justify similar airworthiness standards.

3. Overview of the Civil Aircraft Taxonomy

The aircraft taxonomy encoded in the FARs was developed over many years as new aircraft types came into the market and real-world issues—including technical, economic, and political issues—needed to be resolved. Aircraft weight is a key distinguishing factor between most categories within the CPA classification system and is a significant factor in overall risk to both people and property. However, a number of other considerations are also included in the aircraft taxonomy.

In the FARs, CPA are divided into a few standardized groups based on a combination of their physical characteristics (i.e., *aircraft class*) and operational characteristics (i.e., *aircraft category*). Together these determine the airworthiness standards that will serve as the starting basis for establishing minimum design criteria for type certification. Additional considerations, such as specific requirements for system reliability and design assurance levels, further divide these groups. The following section discusses some of the most relevant criteria for determining aircraft class and category, followed by a discussion of additional considerations.

3.1 Aircraft Classes and Categories

FAR Part 1.1 lists the following examples of *aircraft classes*:

- Airplane
- Rotorcraft
- Glider
- Balloon or Manned Free Balloon
- Landplane
- Seaplane

The primary difference between classes is the means by which the aircraft achieves aerodynamic lift. In an airplane, lift is generated by the flow of air over the wings. If an aircraft gets its aerodynamic lift from rotating blades, including gyroplanes, the aircraft is classified as a rotorcraft. A balloon gets its lift due to buoyancy. Each means of lift generation requires different standards to maintain flight and mitigate the possibility of unexpected loss of lift. Landplanes and seaplanes are, for the most part, subsets of airplanes (in a physical sense), but because they have different landing characteristics and corresponding hazards, a different classification is required.

Airworthiness standards for airplanes and seaplanes are given in Parts 23 and 25 of the FARs. Airworthiness standards for rotorcraft are found in Parts 27 and 29, and airworthiness standards for manned balloons are in Part 31. The FARs do not specify airworthiness standards for gliders; however, glider standards are available in [JAR-22]. For aircraft outside of these classes, such as a tilt-rotor, certification is handled on a case-by-case basis under the special provisions of FAR Part 21.17b. In the future if they become more prevalent, tilt-rotor aircraft may justify a new designated aircraft class in the FARs with corresponding standards. UAS and tilt-rotor may follow a similar path in this regard.

Defining an aircraft's intended use (i.e., *aircraft category*) is essential to discern the particular certification standards that apply to that aircraft and the type of operations that are allowed. Table 1 lists the aircraft categories with the intended use specified in the FARs, and identifies whether each category typically needs a type design certificate, whether it typically operates under a standard or special airworthiness certificate, and whether this category allows operations for compensation or hire.

Table 1. Aircraft Categories, Use, and Certificate Types

Aircraft Category	Intended Use	Type Certificate Needed	Airworthiness Certificate	Compensation or Hire
Normal	Normal flying (nonutility, non-aerobatic, or non-commuter operations)	Yes	Standard	Yes
Utility	Flying with limited acrobatics allowed; e.g., spins	Yes	Standard	Yes
Acrobatic	Acrobatics	Yes	Standard	Yes
Commuter	Commuter operations: scheduled with at least 5 round trips/week with published flight schedules	Yes	Standard	Yes
Transport	Regular public transport of passengers and/or cargo for hire or compensation	Yes	Standard	Yes
Restricted	Special purpose operations, e.g., agriculture and aerial surveying (14CFR21.25)	Yes	Special	Yes
Primary	Pleasure and personal use	Yes	Special	No
Light-sport	Pleasure and personal use	No[5]	Special	No
Limited	Operation of surplus World War II military aircraft [FAA-8130.2G]	No	Special	No
Experimental[6]	Operation of novel or kit-built aircraft for evaluation, crew training, etc. (14CFR21.191)	No	Special	No
Provisional	Operation of an aircraft that has not met all the requirements for a type and/or airworthiness certificate in another category (14CFR91.317)	Yes	Special	No

From a standards perspective, there is a general trade-off between operating limitations and rigor of the certification standard. Under a standard airworthiness certificate, an aircraft typically has few operating restrictions, beyond the flight rules captured in 14CFR91, 14CFR121, 14CFR125, and 14CFR135. Aircraft operating under a standard airworthiness certificate are held to a high standard commensurate with general operation in the NAS, including operation over populated areas. Special airworthiness certificates include operational limitations such as restrictions on maneuvers, speed, number of passengers, activities undertaken, and where flights may be conducted. Some standards for a special airworthiness certificate, compared with a standard certificate, may be relaxed as a result of the operational limitations.

Operations for compensation or hire must comply with more stringent standards than operations for recreation or personal use. As shown in Table 1, most paid operations require both a type certificate and a standard airworthiness certificate. The restricted category is an exception. Restricted category aircraft can operate with a special airworthiness certificate for compensation or hire for a number of "special

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[5] Light Sport Aircraft are not type certificated. Instead a statement of conformance to industry consensus standards must be provided to the FAA (see [ASTM-F2245-12c]).

[6] Experimental is not listed as an aircraft category in 14CFR. It is included in Table 1 because its use is similar to the other categories listed. Some FAA sources refer to "special airworthiness certificate-experimental category."

purpose operations," specified in FAR Part 21.25, such as agriculture, aerial surveying, and banner towing.

The aircraft categories in Table 1 that allow operations for compensation or hire are listed in Table 2 with key limitations with respect to weight and number of seats. As shown in Tables 1 and 2, aircraft categories are defined using a number of different characteristics. Weight plays a significant role, as does the number of seats. However, other characteristics based on intended use also help distinguish one category from another. Maneuverability to support acrobatic maneuvers, frequency of flights, and whether those flights are scheduled are all factors. Different usage models, such as aerial survey and transport of passengers and cargo, also contribute to category distinctions. Each distinction in some way reflects differences in risk to the people on board the aircraft.

Table 2. Description of Aircraft Categories and Key Limitations

Aircraft Category	Key Limitations
Normal	weight ≤ 12,500 lb (airplanes) ≤ 7,000 lb (rotorcraft) seats ≤ 9, excluding pilot seats
Utility	weight ≤ 12,500 lb seats ≤ 9, excluding pilot seats
Acrobatic	weight ≤ 12,500 lb seats ≤ 9, excluding pilot seats
Commuter	weight ≤ 19,000 lb seats ≤ 19, excluding pilot seats
Transport	weight > 12,500 lb, seats > 9, (jets) weight > 19,000 lb, seats > 19, (props) weight > 7,000 lb (rotorcraft)
Restricted	No operation over densely populated areas, in a congested airway, or near a busy airport. Passengers are not allowed in flights for compensation or hire.

Table 3 relates each aircraft class and category combination that can be operated for compensation or hire to the FAR Part containing the airworthiness standards that serve as the starting point for type certification.

Table 3. Starting Point for Type Certification for Aircraft Class/Category Combinations

Aircraft Category	Aircraft Class	
	Airplanes	Rotorcraft
Acrobatic	Part 23, with some regulations specific to acrobatic aircraft	There is no acrobatic category for rotorcraft
Normal	Part 23	Part 27
Utility	Part 23, with some regulations specific to utility aircraft	There is no utility category for rotorcraft
Commuter	Part 23	There is no commuter category for rotorcraft
Transport	Part 25	Part 29
Restricted	Part 23 or 25	Part 27 or 29

3.2 Additional Considerations

Further criteria for classifying aircraft with respect to airworthiness are specified in other regulatory documents, such as FAA Advisory Circulars. Of particular relevance is [AC23.1309] on system safety analysis for Part 23 aircraft, which includes a description of four "certification classes of airplanes" within Part 23[7], shown in Table 4. The fact that further distinctions are drawn for normal, utility, and acrobatic category aircraft is significant with respect to classification factors, particularly physical characteristics. For example, both airplane weight and number and type of engines are factors that ultimately affect how airplanes are grouped together with respect to type design criteria.

Table 4. Influence of Weight and Engines on Classification

23.1309 Class	Normal, Utility, or Acrobatic Category	Commuter Category
23.1309 Class I	Weight ≤ 6000 lb Single reciprocating engine	N/A
23.1309 Class II	Weight ≤ 6000 lb Either multiple reciprocating engines or a turbine engine	N/A
23.1309 Class III	Weight > 6000 lb Either multiple reciprocating engines or a turbine engine	N/A
23.1309 Class IV	N/A	Weight ≤ 19,000 lb 19 or fewer seats

In Table 5, reliability and design assurance level (DAL[8]) requirements are listed for each class mentioned in [AC23.1309]. The classes specified in this table are particular to only one regulation specified in FAR Part 23.1309. More specifically, Classes I-IV do not apply outside of Part 23 airplanes, nor do they apply to any other regulations within Part 23. Parts 25, 27, and 29 all have similar standards for system reliability and design assurance, but do not have any subdivision similar to that in [AC23.1309].

Table 5. Reliability and Design Assurance Requirements for 23.1309 Classes

23.1309 Class	Reliability and Design Assurance Requirements			
	Minor	Major	Hazardous	Catastrophic
23.1309 Class I	$P_f < 10^{-3}$ DAL = D	$P_f < 10^{-4}$ DAL = C/D	$P_f < 10^{-5}$ DAL = C/D	$P_f < 10^{-6}$ DAL = C/C
23.1309 Class II	$P_f < 10^{-3}$ DAL = D	$P_f < 10^{-5}$ DAL = C/D	$P_f < 10^{-6}$ DAL = C/C	$P_f < 10^{-7}$ DAL = C/C
23.1309 Class III	$P_f < 10^{-3}$ DAL = D	$P_f < 10^{-5}$ DAL = C/D	$P_f < 10^{-7}$ DAL = C/C	$P_f < 10^{-8}$ DAL = B/C
23.1309 Class IV	$P_f < 10^{-3}$ DAL = D	$P_f < 10^{-5}$ DAL = C/D	$P_f < 10^{-7}$ DAL = B/C	$P_f < 10^{-9}$ DAL = A/B

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[7] This use of the term *class* in the advisory circular has no relationship to the term described in section 3.1.

[8] Design or development assurance level is the measure of rigor (denoted as levels A-E) applied to the design or development to limit the likelihood of errors occurring that have an adverse safety effect if they are exposed in service. [ARP-4754A] Level A is the most rigorous, corresponding to errors that have potentially catastrophic consequences, and Level E is the least.

The important point here with respect to UAS classification is that both airplane weight and the number and type of engines reflect perceived differences in the acceptable level of risk among non-transport category airplanes. From a standards-based certification perspective, the aircraft classes, categories, and additional considerations described above together define distinct groups of aircraft that can use the same airworthiness standards as a starting point for type certification. For example, a 23.1309-Class III airplane typically would use Part 23 as a starting point for type certification, and must comply with a 10^{-8} target probability of failure for components whose failure could cause a catastrophic accident.

4. CPA Classification Factors

Using the descriptions of aircraft classes, categories, and additional considerations in the previous section, factors that distinguish CPA today can be identified, as shown in Table 6. Each factor relates either individually or in combination with others to aircraft-specific hazards or operational risks that are mitigated by means of the airworthiness standards.

Table 6. Primary Aircraft Classification Factors from the FARs

	Aircraft Specific Factors	**Operational Factors**
Factors Supporting Class Distinctions	Lift Generation Take Off and Landing Capability	
Factors Supporting Category Distinctions	Weight Number and type of engines Maneuverability Number of passenger seats	Scheduled operations Frequency of operations Motivation for use Responsible party

Some individual airworthiness standards are tied to aircraft characteristics other than those in Table 6. For instance, an aircraft's certificated maximum altitude is used to determine the requirements for the crew's oxygen system (FAR Part 23.1441) or for a high-speed envelope in a normal category rotorcraft (FAR Part 27.87). Although these additional factors could be included in the analysis reported here, only factors used to make distinctions between aircraft class and category down to the level described in Table 4 are relevant. The factors derived from [AC23.1309] are intentionally included here because design assurance and reliability are expected to be key certification considerations for UAS. Further, it is expected that UAS will require additional factors be considered, beyond those listed in Table 6.

To support the analysis of the classification factors in Table 6, a short description of each factor and the partitions that it creates in the CPA design space are given below.

4.1 Factor Descriptions

Lift Generation

Aircraft class is largely determined by how the aircraft generates lift. This factor partitions the design space of aircraft into three main classes: fixed wings (airplanes), rotating blades (rotorcraft), or lighter than air (balloons). One of the primary hazards for any aircraft is an unexpected loss of lift. Because different fundamental mechanisms are used to keep an aircraft in the air, different design standards are needed. That is, the design and construction standards necessary to ensure that a rotary wing aircraft can generate and maintain lift are different from those for fixed wing aircraft. The same is obviously true for balloons.

Take Off and Landing Capability

The take-off and landing capability factor partitions the design space for CPA in two groups: those that are only capable of take-off and landing on land versus those that are capable of doing so on water. This distinction is applied only to airplanes and, as such, is more akin to a subclass distinction. Airplanes with these different configurations are susceptible to different hazards and require different mitigations to ensure safe flight and landing. Seaplanes, whether they are float planes or flying boats, have structural requirements not necessary for landplanes. These requirements include design and construction requirements for the airplane hull and floats to ensure that the seaplane is sufficiently buoyant to protect those onboard the airplane.

Weight

Maximum takeoff weight is the maximum weight at which the pilot of the aircraft is allowed to attempt to take off and is primarily determined based on structural limits. The FARs recognize that weight has both static and dynamic interactions with the aircraft structure and directly and indirectly influences controllability and performance to help assure safety of flight. Generally speaking, the severity of an incident or accident increases as the weight of the aircraft increases, since operational speeds also generally increase and the kinetic energy that must be dissipated in an accident increases. Another significant factor in risk exposure is that heavier aircraft tend to carry more people or more cargo. As such, weight is currently the primary factor used in defining a number of distinctions between aircraft categories, such as commuter category from transport, normal/utility/acrobatic from commuter, and Class I & II in [AC23.1309] from Class III. In recent years, questions have been raised as to whether original weight assumptions (and inferred risks) are still valid differentiators for determining airworthiness requirements given increased use of lightweight materials and advanced technology [ARC-Part23]. For this study, the following weight ranges are considered: (0-6000 lb), (6000-12,500 lb), (12,500-19,000 lb), and (≥ 19,000 lb) for airplanes, and (0-7000 lb) and (≥ 7000 lb) for rotorcraft.

Number and Type of Engines and Propellers

FAR Part 23 distinguishes aircraft performance, stability, and controllability requirements based on the number of engines along with their type, either piston or turbine, usually in combination with other factors, such as weight. In a similar way, [AC23.1309] partitions airplanes into subclasses partially based on the number and type of engines and assigns reliability and design assurance requirements based on this partitioning. This factor creates three partitions of the CPA design space expressly for airplanes: (1) single reciprocating engine, (2) multiple reciprocating engines or one turbine engine, and (3) multiple turbine engines.

Maneuverability

Aircraft intended to do acrobatic maneuvers require additional structural strength and controllability beyond that required for aircraft not intended for these maneuvers. Although listed here as a single factor, maneuverability is an amalgam of a number of parameters that influence structural strength and controllability. These include, for example, performance, stability, trim, stall, and spin characteristics. Maneuverability is used in the FARs in conjunction with other factors such as weight and number and type of engines to define three categories: normal, utility, and acrobatic.

Number of Passenger Seats

The number of passenger seats is a proxy for the potential number of people on board an aircraft. As the number of passenger seats (and hence passengers) increases, overall risk increases, and hence more stringent airworthiness requirements must be satisfied to mitigate that risk. In some ways this factor is related to the weight factor since an aircraft with more passengers implies an aircraft with a higher weight. The number of passenger seats generally partitions the CPA design space into one of three ranges: (0-9 seats), (10-19 seats), and (> 19 seats).

Scheduled Operations

In FAR Part 110.2, a scheduled operation is defined as "any common carriage passenger-carrying operation for compensation or hire conducted by an air carrier or commercial operator for which the certificate holder or its representative offers in advance the departure location, departure time, and arrival location. It does not include any passenger-carrying operation that is conducted as a public charter operation." This factor, coupled with frequency of operations, contributes to the distinction of commuter category from normal category. By itself, the fact that an operation is scheduled does not seem to have a significant effect on determining the applicable airworthiness standards, especially with respect to reliability and design assurance requirements. For this study, operations are considered as either scheduled or unscheduled.

Frequency of Operations

Frequency of operations is the number of times that an aircraft completes its intended operation over a defined period of time, and is most often measured on a weekly basis. For example, commuter operations are defined in the FARs as at least five round trips per week. This factor accounts in some sense for the risk of an accident on takeoff and landing. Because risk is greater for takeoff and landing than for any other phase of flight, more frequent operations require more stringent standards to achieve an equivalent level of safety in terms of accident rate. Two partitions of the CPA design space are considered with respect to frequency of operations: 0-4 operations/week, 5 or more operations/week.

Motivation for Use

Motivation for use is a factor that describes the general purpose for operating an aircraft. To a large extent, this factor distinguishes between private use (e.g., corporate jet operation) and operation for compensation or hire. It should be noted that not all operations by a company are considered compensated operations. Generally, if a flight operation is incidental to the business, then it is considered a private operation. However, private versus compensated use is not the only distinction in CPA classification. FAR Part 21.25 lists several specific operations that can be conducted for compensation under a special airworthiness certificate-restricted category. These include, for example, agricultural (spraying, dusting, seeding, and livestock and predatory animal control), forest and wildlife conservation, aerial surveying (photography, mapping, and oil and mineral exploration), patrolling (pipe lines, power lines, and canals), weather control (cloud seeding), and aerial advertising (skywriting, banner towing, airborne signs, and public address systems). Operation under a restricted certificate allows some relaxation of airworthiness standards by invoking operational limitations. Overall, the motivation for use factor affects airworthiness standards for CPA in the sense that standards are more stringent when the motivation for use is compensation or hire, versus private use. As such, two partitions of the CPA design space are considered for this factor: private operations and operations for compensation or hire.

Responsible Party

The responsible party is the person or organization responsible for the safe operation of the aircraft. If the operation is a private operation, then the responsible party is typically an individual or a private organization (whose primary business is not air travel). If the operation is for compensation or hire, then the responsible party is the one who holds the operating certificate. Different types of operating certificates allow different types of compensated operations (FAR Part 119), with the general notion that the requirements to obtain an operating certificate correlate to operational risk. For example, more requirements are levied on an operator carrying 20 passengers versus two passengers. With respect to aircraft classification, an aircraft used by a certificate holder performing a higher risk operation must comply with more stringent airworthiness standards. For example, standards for transport aircraft are more stringent than those for normal aircraft. For this factor, two partitions are considered: private carriage and common carriage.

In the following section, each of the factors described above are analyzed with respect to the original research hypothesis.

4.2 Overview of Analysis Approach

A proper taxonomy that accurately reflects the major risks associated with aircraft within each class/category combination can reduce the burden associated with tailoring standards through exemptions and special conditions. That notion is reflected in our research hypothesis: regulation as applied in the FARs for allocating airworthiness standards (for CPA intended for compensation or hire) is appropriate for UAS if two conditions are met:

1. Existing aircraft classes and categories sufficiently cover UAS designs, and
2. Standards associated with each class/category combination do not, when applied to UAS, overregulate or underregulate.

The second condition assumes that existing standards would be appropriate for UAS if they place only necessary burdens on applicants or regulators to achieve a comparable level of safety to CPA in the same class/category combination. Testing the hypothesis relies on comparing the design space for CPA to UAS using each classification factor, and judging whether risk would be comparable for UAS and CPA in the same class/category combination.

The first step in the analysis considers whether the design space partitions for CPA account for plausible UAS designs. That is, are there UAS designs that would not fit in any existing partition? For example, do most UAS fit in the airplane, rotorcraft, and balloon partitions per the lift generation factor? The design space of UAS may be a proper subset of the design space of CPA, or the design spaces of CPA and UAS may intersect to some degree. If the design space of UAS possesses elements not included in the design space of CPA, then there may be airworthiness risks in these UAS designs that are not mitigated by compliance with the standards. On the other hand, application of standards intended to mitigate risks that appear in CPA designs may overregulate UAS, if UAS do not share all of the same design attributes. This may occur if regulation is applied to mitigate a risk or control a hazard that does not exist in the UAS design. The simplest example of this is the seatbelt regulations required for CPA. Even though exemptions can be made for specious regulations, the exemption process burdens both regulators and applicants if the number and complexity of the differences are large.

The second step in the analysis considers the degree of similarity in risk between CPA and UAS that share the same design partition. For CPA and UAS with similar type designs (share the same partition), this step examines whether risk associated with the UAS design or operations may be less or greater than that for CPA in the same class/category combination. If the risk is substantially less, then the standards could unnecessarily overregulate UAS. If the risk is greater, then the existing regulation may be inadequate.

The analysis presented in the following subsections only considers factors that are used currently to distinguish risk, and hence standards among CPA. Admittedly, these factors may not be sufficient to capture all of the meaningful distinctions in UAS design or risks that should be covered by new or different airworthiness standards. As such, the following analysis is not definitive. Rather, it is qualitative and arguably speculative, and intended to provide useful insights about distinctions between CPA and UAS relevant to airworthiness standards. It is hoped that this analysis can help pinpoint dissimilarities that may be important in prescribing future standards for UAS. However, analysis results should be considered preliminary until sufficient data is collected to validate design and risk assumptions.

4.3 Analysis Results for Each Factor

Two specific questions were addressed in the analysis for each classification factor:

1. Does the range of factor x, as applied to CPA, adequately cover the UAS design space? That is, are there existing UAS designs that would not fall in any of the partitions for that factor?
2. For UAS and CPA in the same design space partition for factor x, would the corresponding airworthiness standards likely apply to UAS without the possibility of over- or underregulation? That is, do UAS and CPA in the same partition pose similar risks to the NAS?

Table 7 summarizes the answers to these questions. A “yes” answer to the first question indicates that the classification factor and its partitions include essentially all UAS types. A “no” answer indicates that there exist UAS types with design features or attributes that do not fit in any partition. Question 1 is relatively easy to answer for physical characteristics of the aircraft because information on actual UAS designs is readily available. Answering the questions for operational factors involves more speculation because UAS are not routinely operating for compensation or hire. There are more unknowns regarding how they will likely operate. For the second question, a “yes” answer indicates that applying the existing standards relevant to that factor to UAS seems reasonable. That is, credible counterexamples could not be formulated that would suggest otherwise. A “no” response to the second question indicates that a reasonable argument could be made that UAS and CPA of similar design types (within the same partition) might pose different levels of risk. As such, the airworthiness standards that correspond to that factor may either over- or underregulate UAS. In general, a “no” response to either question indicates the potential need for tailoring the partitions between class/category combinations or the airworthiness standards for a class/category combination, as related to that factor. Each factor is discussed below, along with rationale for the responses in the table.

Table 7. Design Space and Risk Considerations for each Aircraft Classification Factor

Classification Factor and Partitions	**Does this factor cover the UAS design space?**	**For UAS and CPA in the same design space partition, do the corresponding airworthiness standards apply to UAS?**
Lift Generation: airplanes, rotorcraft, balloons	Yes	Yes
Take-off/Landing Capability: Land, Water	No	No
Weight airplanes: (0-6000) (6000-12,500) (12,500–19,000) (> 19,000) rotorcraft: (0-7000) (≥ 7000)	Yes	No
Number & type of engines: 1 reciprocating, 1 turbine or multiple reciprocating, multiple turbines	No	Yes
Maneuverability: normal, utility, acrobatic	No	No
Number of passenger seats: (0) (1-9) (10-19) (> 19)	Yes	No
Scheduled operations: scheduled, non-scheduled	Yes	Yes
Frequency of operations: (0–4 operations/week), (≥ 5 operations/week)	Yes	No
Motivation for use: private, for compensation or hire	Yes	Qualified Yes
Responsible party: private carriage, common carriage	No	Yes

Analysis of Lift Generation

Most UAS designs are similar to CPA fixed- or rotary-wing designs with respect to lift generation. This assertion is supported by Unmanned Vehicle Systems International (UVSI), who publishes an annual yearbook that catalogs UAS throughout the world and crossing many domains including law enforcement, commercial, military, and research. [UVSI-2013] Figure 1 shows the division of UAS listed in the 2012 and 2013 yearbooks, according to the primary FAA aircraft classes. Tilt-body, tilt-rotor, and flapping-wing aircraft are included under "Other."

As shown in the figure, only a small fraction (< 4%) of UAS would not fit in any class, as is true for CPA. Thus, the design space partitions created by this factor for CPA do reasonably cover the UAS design space. Further, for CPA and UAS of comparable size, the design and construction standards related to lift generation are likely agnostic to whether an aircraft has a pilot or passengers onboard. With this in mind, there is no obvious reason why existing design standards for lift would, if applied, overregulate UAS. However, a significant number of UAS, currently much smaller in size than CPA, have multi-rotor designs. For these, it is not clear whether existing standards for lift would be sufficiently stringent. Additional data on hazards and risks associated with multi-rotor UAS designs is needed.

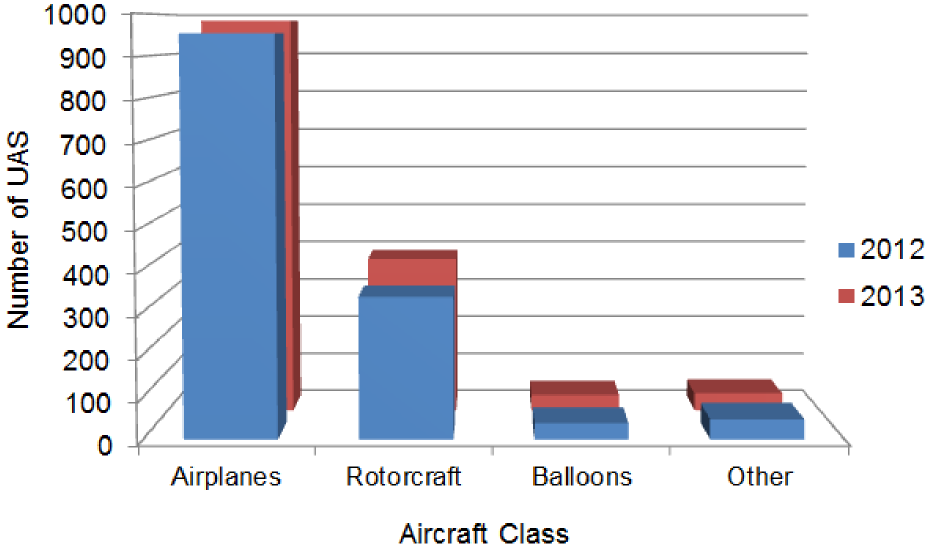

Figure 1. UAS in Production in 2012–2013 According to Aircraft Class [UVS-2012, UVS-2013]

Analysis of Take-Off and Landing Capability

The design space for UAS, with respect to take-off and landing capabilities, encompasses more design options as compared to CPA. This is because UAS have additional options not practical for CPA. For example, some relatively small UAS use catapults for takeoff and nets for landing, while other UAS use arrested landings that would be hazardous for any CPA. Those capabilities would give rise to hazards and mitigation options different from those for CPA. Depending on the prevalence of those capabilities, new subclasses similar to landplane and seaplane may be warranted.

Risks associated with takeoff and landing for UAS and CPA with similar take-off and landing capabilities may not be the same, especially with respect to risks related to harm to crew and passengers. Airworthiness requirements that protect the crew and passengers during takeoff and landing would possibly overregulate UAS.

Analysis of Weight

Strictly speaking, the weight partitions for CPA listed in Table 7 cover the design space for UAS, since there is no minimum weight specified for either airplanes or rotorcraft. However, many UAS weigh much less than CPA. CPA designs must accommodate any people on board, in addition to the minimum equipment needed to comply with rules that govern their operation. Consequently, there is a practical minimum weight for CPA that is greater than many UAS. This is reinforced by a recent UAS market survey [UVSI-2012] that reports that approximately 80 percent of UAS airplanes weigh less than 500 lb, and roughly 82 percent of UAS rotorcraft weigh less than 500 lb, below what is practical for any CPA operating for compensation or hire.

Applicability of the airworthiness standards that align with the weight partitions is a different matter. The weight of a UAS impacts the severity of an adverse event, such as a mid-air collision or impact with persons or property on the ground, just as weight does for a CPA. For UAS and CPA of comparable weight and design doing comparable operations, severity of the consequence of a failure could be similar, and application of the same standards seems reasonable. However, it is not clear whether the risk associated with a 60-lb UAS is necessarily comparable to that of a 6000-lb CPA, even though they are in the same weight partition. It is conceivable that the lower weight possibly equates in some circumstances to lower risk than for CPA. If this is true, application of the same standards could overregulate UAS. Additionally, lower weight could allow UAS maneuvers not possible for CPA, which might entail different risk than CPA. UAS designs, especially in the lowest weight partition, may be inappropriately regulated if standards are allocated based primarily on the current weight partitions used for CPA.

Analysis of Number and Type of Engines and Propellers

The three partitions that currently exist for number and type of engines typically used in CPA do not cover the range of design possibilities for UAS in either dimension (number or type). An obvious difference is in the number of engines used in some UAS. “Multi-engine” for a UAS could mean 10 or more engines in some long endurance designs, such as NASA’s Helios aircraft, or multiple rotors used to increase stability and maneuverability in hexacopters and octocopters. In addition, some UAS have very different engine types to meet unique mission requirements (e.g., mission times on the order of days or weeks). For instance, many UAS will be electrically driven, possibly with solar power or fuel cells as sources for electrical power, whereas other UAS may use hydrogen power sources. The variation in UAS designs with respect to engine and propeller utilization is much more extensive than for CPA. Those UAS outside of the CPA design space will likely require different minimum design standards.

For UAS and CPA with similar designs with respect to engine number and type, it seems reasonable that the same airworthiness standards may apply. However, change of scale in aircraft size and corresponding size for engines or propellers could affect the risk associated with loss of thrust capability. Additional data on hazards and risks associated with multi-rotor UAS is needed.

Analysis of Maneuverability

Analysis of how maneuverability affects airworthiness standards is challenging given that many different aspects of existing standards are influenced by this factor (e.g., performance, controllability, stability, trim, stall, and spin characteristics). It is reasonable to assume that UAS designs will need to maintain some minimum level of maneuverability to safely operate, especially to avoid other aircraft and obstacles (i.e., vertical structures). However, it is unclear whether the current maneuverability criteria for normal, utility, and acrobatic aircraft are appropriate for UAS, or whether maneuverability should be used to partition the UAS design space for other reasons, such as the ability to meet minimum standards to avoid other air traffic. For UAS, it is not obvious if normal flying consists of similar operations to CPA, because what normal flying means is not well explained. As such, it is not obvious whether there will be a need for different structural and performance capabilities to support acrobatic maneuvers. What is clear is that many UAS designs currently are not comparable to CPA designs with respect to maneuverability, some being much more maneuverable and some much less maneuverable. As a result, the CPA design space does not cover the UAS design space with respect to this factor.

In general, for smaller CPA (i.e., not commuter or transport category aircraft), safety-oriented maneuverability constraints are aimed at protecting the pilot, crew, and passengers by protecting the integrity of the vehicle. For UAS, this need is no longer paramount, and thus risk mitigations appropriate for CPA could potentially overregulate UAS.

Analysis of Number of Passenger Seats

The CPA design space with respect to passenger seats trivially covers UAS which have no need for passenger seats at this time. Therefore, any requirement specific to seats would overregulate UAS; at a minimum there would be added burden associated with requesting an exemption. When passenger-carrying UAS are considered in the future, the effect of the number of passenger seats would become extremely relevant to risk and the need for corresponding design standards would need to be revisited.

Analysis of Scheduled Operations

It seems reasonable that UAS operations for compensation or hire could be grouped similar to CPA, as either scheduled (per a published schedule) or non-scheduled, overlooking the fact that the current definition of scheduled operations is specific to passenger carrying operations. From that perspective, the CPA design space covers the UAS design space. By itself, the fact that an operation is scheduled does not have a significant effect on design and performance standards, though it may affect continued airworthiness requirements. Generally speaking, scheduled operations for compensation or hire are expected to be more dependable than those that are not. It is not obvious that UAS would incur any different expectation. There are no obvious reasons why airworthiness standards relevant to scheduled operations would overregulate UAS design.

Analysis of Frequency of Operations

Clearly, the existing partitions for the frequency of operations, infrequent (less than five flights per week) versus frequent (five flights or more per week), do cover the UAS design space. The more interesting points concern the impact on risk due to differences in operational frequencies and the phase of flight that poses the most risk for UAS. UAS may operate on vastly different operational schedules due to significantly different operational capabilities. These may include both long endurance operations lasting days or weeks at a time, or super-short operations lasting only a few minutes. Standards that account for likelihood of failure based on assumed flight frequencies or flight durations may not adequately account for operational frequencies or durations that are significantly different from CPA.

The frequency of operations factor accounts in some sense for the risk of an accident on takeoff and landing (i.e., the highest risk phases of flight for CPA). However, for UAS, it is not clear that takeoff and landing necessarily represents the highest risk phases of flight. It can be argued that a catastrophic event for UAS may be more likely during en-route or loitering phases of flight. In fact, for UAS that remain aloft for days, long duration loitering or operations involving in-flight refueling can dominate with respect to total risk exposure. Thus, CPA risks linked to frequency of flight considerations could be significantly different from those for UAS. This observation suggests further study regarding the suitability of existing standards when applied to UAS designs.

Analysis of Motivation for Use

The bifurcation of the design space based on motivation for use (private use or use for compensation or hire) covers UAS in the same way as CPA. This factor affects airworthiness standards for CPA in the sense that standards are more stringent when the motivation for use is compensation or hire. This is driven by the need to protect the flying public, whose personal safety is in the hands of the service provider. The “qualified yes” response in Table 7 indicates uncertainty about whether risks are different between private and compensated UAS operations. An argument could be made that societal expectations for operation for compensation or hire would be the same regardless of whether the operation is manned or unmanned. A counter-argument could also be made that there is no substantive difference in hazards between operations for compensation and those that are for private use. In that case, existing standards based on motivation for use could potentially overregulate UAS.

Two primary differences between CPA and UAS with regard to this factor, though, are the wider variety of UAS operations and the larger number of UAS types. For example, there are many UAS expected to operate close to the ground, in Class G airspace, doing utility type operations, such as crop surveillance, pipeline patrol, and wind turbine inspections. This is in contrast to most CPA (excluding some specialized uses of airplanes and rotorcraft) that tend to climb higher for efficient cruise to fulfill a transportation role. The important point is that many UAS will not need full or unconstrained access to the NAS to be commercially viable. This may lead to more opportunities for UAS to operate for commercial use under the restricted category than CPA. The degree of risk reduction possible by establishing operational limitations under a restricted certificate is much less for CPA than for UAS because there is always risk to human life for CPA. But this is obviously not the case for UAS.

Analysis of Responsible Party

The responsible party bifurcation for CPA into private carriage and common carriage covers the UAS design space. The concept that aircraft operated for common carriage should be held to a higher standard (at least for continued airworthiness) than aircraft operated for private use is expected to apply to UAS. Consequently, standards related to this expectation would not obviously over- or underregulate UAS designs.

This factor, however, is more complicated than it may appear. The particular designations of operators in current use for CPA today (i.e., private carriage, common carriage, and subgroups, including commercial and air carrier) may not match well with UAS and how they are operated. That is, the entities responsible for the airworthiness of the aircraft and the safety of its operation may be different for UAS than for CPA.

From a liability perspective, years of case law and legislation have defined the responsible party for CPA. Given the potential different operational modes for UAS, a similar legal process can be expected dividing liability between and among the customer, owner, operator, integrator, and manufacturer.

4.4 Implications

Analysis of the classification factors individually does not give a complete picture of how well the CPA design space relates overall to the current UAS design space, but it does expose some crucial differences. Several factors cover the design space well (e.g., lift generation and scheduled operations). Other factors and their corresponding ranges and partitions, however, do not adequately cover at least some aspects of the UAS design space that may be important to airworthiness. The following implications relevant to allocation of airworthiness standards were derived from the analysis results:

(1) There are unique design attributes of some UAS (beyond communication links, ground control stations, aircraft detection systems, and launch and recovery systems) that are relevant to airworthiness, but that are not addressed in existing standards. Examples include UAS with catapult launchers, as well as quadrotor UAS. Additions to the existing airworthiness standards will likely be needed to mitigate new risks arising from such design aspects.

(2) For some factors, such as weight, the existing partitions may not be adequate to accommodate significant differences in risks for UAS. Additional partitions for a factor (e.g., further divisions within the 0–6000-lb weight group) may be needed. For other factors, ranges will likely need to be extended, for example, increasing the number and types of engines and propellers.

(3) The different designs and operational use cases for UAS suggest that care should be taken in applying existing standards to UAS in equivalent CPA partitions because overregulation, and in some cases

underregulation, may occur. In particular, airworthiness standards related to maneuverability (normal, utility, and acrobatic categories) merit attention.

(4) Operational factors, such as frequency of operations, can potentially impact the level of risk posed by UAS that are similar in design to CPA. Consequently, application of existing regulation, without tailoring, has the potential to overregulate some UAS and underregulate others.

Based on these observations, it seems reasonable to conclude that the aircraft classes and categories, as described in the current FARs, may not be adequate *as is* for many civil UAS designs. Existing aircraft class and category combinations do not fully cover the design space for current UAS. UAS are simply more diverse physically and operationally than CPA, as demonstrated by the examples in Section 4.3. Furthermore, the imposition of current standards, even in the case where UAS and CPA share similar design attributes (as per existing design partitions), could potentially overregulate some UAS and thus unnecessarily limit industry growth, or underregulate some UAS leading to insufficiently mitigated risk to the NAS. These findings do not discredit the current class and category definitions for CPA or approach to allocating standards, but do indicate that some non-trivial modifications likely are needed to fully accommodate UAS.

This conclusion is consistent with other research findings that report significant differences between UAS and CPA, even within similar classes, to the extent that "using existing classification schemes as the basis for regulating the UAS fleet is unlikely to adequately account for these differences" [Palmer]. The conclusion is also echoed in the fact that several organizations, discussed in Section 5, have developed UAS taxonomies that do not rely solely on the current set of classification factors for CPA. As such, it seems reasonable to explore additional factors and contemplate if and how they might be useful in augmenting the taxonomy imposed by the FARs.

5. Prospective UAS Classification Factors

Over the past few years, organizations around the world have wrestled with the issue of UAS classification and regulation. Various taxonomies for UAS have been proposed, different from those used for CPA. Some are specific to airworthiness, others are used for allocating operational limitations, and still others comprise a combination of the two. Two surveys conducted independently by NASA [NASA-TM] and Modern Technology Solutions, Inc. in 2012 [MTSI-2012] describe many of those taxonomies. Both surveys served as sources for identifying additional factors that may influence how UAS could be classified.

In the following subsections, prospective factors are described, and then examined to determine to what extent they could be used for UAS within the current taxonomy. A factor is useful in this regard if it extends the coverage of the UAS design space (i.e., beyond the current taxonomy), or if it defines an identifiable group of UAS designs that have similar operational risks.

5.1 Factor Descriptions

The factors listed in Table 8 were extracted from the various UAS taxonomies identified in the two UAS classification surveys [NASA-TM, MTSI-2012]. A few additions from the analysis summarized in Chapter 4 are also included. Some of these factors are similar to the current classification factors, and are listed in Table 8 as duplicative factors. The other factors are not currently used in making CPA class/category distinctions.

For this study, the new factors are considered prospective factors for UAS classification within the current aircraft taxonomy. A brief description of each of these new factors, as viewed for this study, is provided below. Considerations and suggestions are made in Section 5.2 regarding appropriate values for partitioning the UAS design space based on these factors.

Table 8. Prospective UAS Distinguishing Factors

Factors from Existing FARs	New Factors	
• Weight • Lift Generation • Motivation for Use	• LOS Operational Range • Frangibility • Flight Time • Aircraft Disposability/Cost • Avionics Complexity • Degree of Autonomy	• Airspeed • Kinetic Energy • Altitude • Operational Area • Population Density Overflown • Operational Failure Consequence

LOS Operational Range

LOS operational range can have numerous interpretations. Here, LOS operational range refers to the maximum distance within which an aircraft can operate for a particular control mode. For UAS, this includes VLOS, radio line-of-sight (RLOS), and beyond RLOS (e.g., enabled by satellite communications). Although RLOS is usually greater in range than VLOS, this is not always the case. A UAS could have a remote pilot far away from the operation site, and have visual observers at the operation site who relay information to the remote pilot. In the context of this report, LOS operational range affects both the situational awareness of the pilot and the control mode of the aircraft. Within VLOS, the pilot or a visual observer can observe the aircraft and the surrounding environment; but, for operations beyond VLOS, all information about the flight must come from sensors. The control mode will affect the length of time between pilot observation, pilot action, and aircraft response. As this time increases, the pilot generally will have fewer responsibilities, while automated systems will have more responsibilities.

Frangibility

Frangibility is defined here as a design feature of an aircraft that allows it to break into pieces in order to mitigate and distribute the consequences of collision or impact. This feature may also be reflected in designs by use of a material or structure to absorb energy through deformation, thus minimizing injury. Frangibility is an attribute not normally seen in CPA as cockpit and cabin integrity is paramount. Although some parts of a CPA may be purposely designed to break away or break into pieces in case of certain failure modes, the notion of a completely frangible aircraft is unique to UAS. Frangibility was mentioned as a factor in recommended system standards for small UAS [SUAS-ARC]. As a design feature, frangibility may present some challenges with respect to conventional definitions for severity of accidents and incidents.

Flight Time

Flight time is defined here as the maximum time the aircraft can stay aloft without refueling or otherwise re-energizing. This factor captures the notion of endurance, that is, how long a UAS can fly “on its own.” For most UAS, this factor inversely relates to frequency of operations. When combined with airspeed, this factor also relates to LOS operational range.

Aircraft Disposability/Cost

Consideration of aircraft cost has no precedent in the FARs. As such, contemplating its use may be controversial. This factor is considered here because it captures a unique aspect of UAS risk: the risk deemed acceptable by the owner of a UAS relative to potential re-use or total loss of the aircraft. Aircraft cost can greatly influence design strategies for potential loss events. If an aircraft is designed to be retrieved or re-used after a mission, loss of control mitigation strategies will attempt to mitigate first-, second-, and third-party risk. For this discussion, first party risk is the risk incurred on the part of the UAS operator (i.e., the operational crew and vehicle itself). Second party risk describes the risk encountered by other parties using the NAS (i.e., other aircraft). Third party risk, which is not always considered, encapsulates the risk incurred on the behalf of bystanders (i.e., people or properties on the ground). If a UAS is intended to be disposable, then only second- and third-party risk need be considered in mitigation strategies. As the cost of the aircraft increases in relationship to the limited liability the aircraft incurs with respect to second and third parties, mitigation strategies will shift to preserving aircraft integrity over preventing overall damage caused to other parties. Thus, UAS designed for use in unpopulated areas, second- and third-party risks may be minimal compared to cost incurred by the loss of the aircraft or its mission data. Cost also has a strong correlation with weight, performance, and complexity and thus might be a useful factor that combines many considerations into one.

Avionics Complexity

Complexity is a topic of frequent discussion in the avionics community, and particularly difficult to precisely define. The definition used here is the one identified in the survey; that is, an avionics system is considered complex "when its operation, failure modes, or failure effects are difficult to comprehend without the aid of analytical methods or structured assessment methods" from [AC 23.1309]. Examples of structured assessment methods include failure modes and effects analysis and fault tree analysis. The advantage of simple systems is that predicting behavior in failure scenarios is relatively straightforward and, presumably, sufficient mitigations can be developed to address these situations. Lack of transparency in complex systems, particularly with regard to inter-operability within and across subsystems, may lead to concerns about recognizing failure scenarios and developing mitigations. Consequently, complex systems may require more stringent reliability and design assurance levels to avoid failures and mitigate risk from unintended or unpredicted behavior.

The definition of avionics complexity used here does not speak to the level of automation in UAS or the difference in the degree to which UAS depend on automation to attain and maintain safe flight as compared to CPA. In general, UAS are more dependent on the proper functioning of their avionics than CPA, primarily because a remote pilot relies on avionics to control the aircraft and to report aircraft state information. More of the avionics systems and functions in a UAS also may be considered "flight critical", compared to CPA where many systems are deemed "for advisory use only" and the onboard pilot is responsible for determining whether and how to use the system. While these differences between CPA and UAS are important, a useful classification factor for possibly distinguishing one UAS from another was not obvious.

Degree of Autonomy

Degree of autonomy is not currently used to differentiate aircraft with respect to airworthiness standards, nor has it been addressed in a complete fashion by any of the literature on UAS classification surveyed to date. Autonomy, however, is often mentioned in discussions of UAS classification relevant to certification, and is listed here for that reason. An autonomous UAS, which according to ICAO is an aircraft that does not allow pilot intervention in the management of the flight [ICAO-328], is different in both design and operation and corresponding hazards and risks from remotely- or conventionally-piloted aircraft. As such, autonomy, or degree/level of autonomy, might seem like a relevant classification factor. However, how best to define and characterize autonomy, especially for use within a certification context, is still being debated. The analysis of the prospective factors in the next section does not include degree of autonomy because of this debate. Instead, some preliminary thoughts on autonomy as a potential UAS classification factor are given in Appendix A.

Airspeed

Here, airspeed is simply the velocity of an aircraft. Although airspeed is not a factor in the current CPA taxonomy, it is tied to several regulations, such as turn radii and closure rates with other aircraft. For UAS classification, airspeed is important primarily because of its role in kinetic energy, as per the kinetic energy factor, below. Many UAS are capable of safe flight at much lower airspeeds (and potentially lower kinetic energy) than most CPA.

Kinetic Energy

Kinetic energy is used as a distinguishing factor in several of the UAS taxonomies identified in the surveys. Kinetic energy is a measure of the energy that an object, in this case an aircraft, possesses due to its motion, and calculated as the product of one-half an aircraft's mass (m), and the square of its airspeed - (v), i.e., $\frac{1}{2} mv^2$. The attractiveness of kinetic energy as a classification factor for UAS is that it can be viewed as a proxy for the amount of damage that can be inflicted on impact.

Altitude

Altitude, like airspeed, is a parameter whose definition is based on the context in which it is used. An aircraft's altitude is typically measured with respect to mean sea level or local above ground level. Several airworthiness requirements, such as stability requirements, are dependent on altitude; but, altitude is not explicitly used for class/category partitioning for CPA. Altitude is used in slightly different ways in the various UAS classification schemes proposed to date. These include operational limitations such as maximum altitude and normal operating altitude. In all of the classification systems reviewed, altitude was coupled with weight and at least one other factor (e.g., airspeed or operational range).

Operational Area

The operational area factor distinguishes UAS based on the type of airspace where a UAS normally conducts its operations. In its most basic form, operational area partitions the design space into (1) areas where only UAS are allowed (i.e., "segregated"), or (2) areas where UAS mix with CPA (i.e., "non-segregated"). This factor does not represent a restriction on airspace usage for UAS. Rather, it defines categories with more and less stringent airworthiness standards. One can envision this factor using finer distinctions of airspace types, which may relate to the airspace classes A, B, C, etc. Operational area is not currently used to distinguish CPA class or category, except in the sense that standard type certificates do not generally contain operational area restrictions, but restricted type certificates may.

Population Density Overflown

Similar to operational area, population density overflown is based on what is underneath a UAS when it conducts normal operations. Concepts for partitioning the population density overflown are by populated and unpopulated, or densely populated and sparsely populated. There could be many more partitions provided viable measures of population density could be developed. This factor is not currently used for distinguishing CPA at the class/category level, but it is used as an operational limitation for a restricted category aircraft.

Operational Failure Consequence

While the other factors are specific to design, performance, or operational aspects, the operational failure consequence factor identifies particular hazards to be addressed. For example, the European Aviation Safety Agency (EASA) partitions UAS for certification purposes relative to two specific hazards: (1) loss of thrust leading to impact with the ground, i.e., "unpremeditated descent;" and (2) loss of control, under powered flight, resulting in impact with the ground [EASA-EY013]. EASA uses the aircraft's kinetic energy associated with those two events to assign airworthiness requirements.

In the following section, each prospective UAS factor is discussed with respect to its potential contribution to classification.

5.2 Potential Contribution of Prospective New Factors

The analysis in Section 4 showed that many UAS either do not fit well within the current classes or categories, or the airworthiness standards may not be appropriate because of significant differences in risk. The existing taxonomy could be improved to better fit UAS by either a careful refinement of current

CPA factors (e.g., modifying or adding new weight divisions), or by introducing new factors such as those described in Section 5.1 to capture relevant UAS risk dynamics.

As with the factors in Table 6, some of the prospective factors in Section 5.1 are associated with design features of UAS and others are associated with operational aspects. Most of the operational factors are intended to mitigate some aspect of risk related to impact with other aircraft or impact with persons or property on the ground. To examine the potential contribution of these new factors to classification, each was placed into one of three types based on how they might distinguish one UAS design from another. In a few cases, a factor applies to more than one type.

Type 1: Factors that account for novel UAS design features that present risks not addressed by CPA classification factors

Type 2: Factors that mitigate impact severity or consequences

Type 3: Factors that mitigate the likelihood or duration of an impact event

The following discussion conjectures benefits, limitations, and ways that each new factor might be used within the current class/category taxonomy to support UAS. This discussion is not definitive, just as the list of prospective factors in Section 5.1 is not comprehensive. The primary intent is to call attention to some of the UAS design and operational attributes that can affect risk and associated design criteria and, hence, classification.

5.2.1 Novel Design Feature Factors (Type 1)

The UAS design space includes novel design features that can enable new behaviors and risk mitigation strategies not ordinarily used or possible in CPA. Frangible aircraft would be an obvious example. These designs are not covered in the current taxonomy represented in the FARs. Other factors that contribute to novel design attributes include LOS operational range, flight time, disposability, and avionics complexity.

Discussion of LOS Operational Range

As a design feature, LOS operational range can be partitioned into VLOS, RLOS and beyond RLOS. Within each partition, different means are needed to mitigate or recover from hazards. VLOS operations allow a human to directly provide “see and avoid” capability. Without this capability, remote pilots must use instruments to maintain situational awareness, and these instruments will rely on communication, navigation, and surveillance (CNS) systems, as well as information management systems to coordinate and present information. For VLOS operations, the aircraft may be at such a distance from the remote pilot that the state information provided by instrumentation provides a superior situational awareness than anything gleaned from visual inspection of the fielded vehicle. However, failures can be better mitigated by the remote pilot in VLOS operations, because an in situ judgment can be made regarding the overflown area and seriousness of an uncontrolled descent. For operations beyond VLOS, communication links become critical in the transfer of state data to the remote pilot. Communication links can be grouped relative to RLOS: within RLOS or beyond RLOS. In general, a communication system that operates beyond RLOS is more complicated (involving satellites or ground-based communication relays) and thus has more failure modes. Situational awareness is enhanced by visual, audio, and otolithic (vestibular and proprioceptor) cues, which can be simulated for remote pilots; however, these cues are difficult to reproduce without accurate vehicle attitude information. Thus, any failures have the potential to adversely affect situational awareness.

LOS operation range as a type 3 factor affecting loss of control is discussed in section 5.2.3.

Discussion of Frangibility

Designing for frangibility opens up the airworthiness notion that the severity of an impact event can be mitigated by absorbing energy through the airframe and redistributing it through fracture. With no human on board, it may be desirable in certain contexts to fragment the aircraft at or prior to impact, thereby limiting energy transfer and thus, collateral damage. For lightweight, maneuverable UAS, the impact severity is dominated not by aircraft weight, but by its overall ability to absorb and dissipate energy in a non-destructive or harmless manner (e.g., through plastic deformation or fracture mechanics). In that sense, frangibility offers the possibility of reducing the severity of a collision between a UAS and another aircraft or persons or property on the ground. However, this notion may also increase the probability that an impact event may result in the scattering of debris (which may still inflict harm), and scatter it farther away from the projected overflown area than desired. Evaluation of the factor for classification purposes must take into account the population density overflown and altitude of the UAS for a clear risk assessment to be performed. A frangible aircraft may need different minimum design criteria with respect to structures and materials than one that is not intended to be frangible.

Discussion of Flight Time

The flight time factor provides distinctions within the UAS design space for those UAS with significantly different endurance capabilities. The typical length of some UAS operations may be measured in minutes, while others may be measured in days or weeks. For example, for a UAS designed for airborne refueling, mission lengths (and total time in air between takeoffs/landings) may be significantly longer than for CPA. For such a UAS, frequency of flights will be low, but the exposure time to people and property in the air and on the ground will be very high. That suggests different risk profiles. Since UAS platforms need not land and take off with the frequency dictated by piloted vehicles[9], maximum flight time, as a distinguishing factor, could serve a similar function for UAS as the frequency of flights factor does for CPA. In general, takeoff and landing are regarded as the phases of CPA flight with the highest risk. For UAS capable of remaining aloft for weeks, refueling operations and resolving maintenance issues will likely be the highest risk activities. With this in mind, flight time is likely a better distinguishing factor than flight frequency.

Discussion of Aircraft Disposability/Cost

Design for disposability is one possible strategy for mitigating potential impact events, for a UAS that is not intended to be recovered at the end of its mission. One can imagine operations in dangerous or toxic environments where the collection of data may be more valuable than the UAS itself. That aircraft may be considered disposable. UAS used to collect hurricane data is another example. If a disposable UAS has completed its mission, and undergoes an impact event resulting in its destruction, but with no other losses of life or property to any parties, then it may no longer be appropriate to term such an event as an 'accident'. Disposability strongly correlates with quality aspects of a UAS that affect safety risk (e.g., structural integrity and reliability), and may present different hazards and risks that may require design criteria different from non-disposable UAS. Disposability is just one aspect of cost that might affect UAS design. Aircraft cost will also affect aspects of airworthiness related to avionics complexity, component redundancy, system reliability, maintenance and lifecycle duration, structural and electronic integrity, as well as incurred liability.

Discussion of Avionics Complexity

In CPA, an avionics system that uses software or even slightly sophisticated hardware is considered complex. Using this standard, almost all UAS avionics designs will be considered complex; the main exception being a simple stick-to-surface radio-controlled UAS (e.g., radio-controlled model aircraft). As such, avionics complexity does not distinguish significantly between UAS designs. On the other hand, one could postulate a complexity metric and assign classification categories based on different levels of

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[9] Pilots can remain in the air no longer than the times specified in FAR Parts 91.1057, 91.1059-1062.

complexity. While work is underway to develop suitable complexity metrics, challenges exist with this approach.

The presumption for CPA, especially those carrying passengers, is that the pilot is in the best position to perform the correct action even in failure scenarios. As noted in section 5.1, complex avionics can hinder a pilot's ability in a CPA to recognize failure scenarios and develop appropriate mitigations for them. For UAS that are expected to have more complicated avionics to compensate for the removal of the pilot from the cockpit, the ability to recognize failure scenarios and develop appropriate mitigations may be further reduced; but, the degree of that reduction is not clear. One can imagine that complex avionics with automatic failure recovery modes may be better at handling failures than a remote pilot with limited situational awareness. Additional data is needed to better characterize the relationship among automation, its complexity, and the impact of those on the ability of remote pilots to recognize and react to failure conditions.

With the exception of avionics complexity, four of the novel UAS design factors can help distinguish UAS designs with different risk profiles that are not sufficiently differentiated by the CPA classification factors. This addresses the first implication drawn in Section 4.2. Table 9 summarizes how these factors could be applied to UAS within an aircraft class/category framework.

Table 9. Applicability of Type 1 Factors for Novel Design Features to UAS Classification

Prospective Factor	Novel design feature or attribute	Aspect of risk different from CPA	Potential applicability to UAS classification
LOS Operational Range	Conventional flight deck functionality not on board the aircraft	Loss of situational awareness	Accounts for unique design features (VLOS, RLOS, beyond RLOS) that affect situational awareness given that remote pilots must maintain situational awareness in a different manner than in CPA.
Frangibility	UAS designed to disintegrate	Severity of loss of aircraft integrity	Acknowledges new safety-related design attribute that suggests need for different standards. Could be used to partition frangible from non-frangible UAS. May require work to define criteria for frangibility and recognition of frangibility as an acceptable attribute.
Flight Time	UAS that can remain aloft for very short or long periods (e.g., minutes, days, weeks)	Time needed between maintenance checks (continued airworthiness)	Identifies different norms in operational time that might suggest different standards. It could possibly replace the frequency of operations factor or modification of its partitions.
Disposability/ Cost	Cabin and flight deck integrity is no longer paramount	Severity of loss of aircraft integrity	Disposability may drive new safety-related design attributes that suggest a need for different standards. Could be used to partition disposable from non-disposable aircraft. May require work to define criteria for partitioning and recognition of disposability as an acceptable attribute.
Avionics Complexity	Remote control adds different dimension to complexity	Reduced ability to detect or react to failures	Questionable value as a classification factor, in part because of the difficulty in defining complexity.

5.2.2 Impact Severity Factors (Type 2)

For a UAS, which carries no passengers, the most significant risk is impact into densely populated areas or other aircraft. Airspeed, kinetic energy, and altitude all have two attributes in common with respect to impact severity. First, each factor relates to the energy that a UAS may have upon impact, either with the ground, an obstacle (e.g., building), or another vehicle. Second, each of these factors can be used to restrict the severity of an impact event by means of operational mitigation.

Of particular interest is whether Type 2 factors might be more appropriate for UAS classification than weight, and whether they can be considered in an independent fashion (as weight is currently). This connection allows exploration of the first implication in Section 4.4, that some current CPA classification factors may not possess adequate gradation to sufficiently partition the risks for UAS designs in the context severity of an impact event. In particular, the current breakdown of weight ranges is not well-suited for lightweight UAS systems, and may result in overregulating them.

Discussion of Airspeed

Airspeed limitations minimize the severity of the impact to other airborne objects and to people or property on the ground. Airspeed affects UAS operations in a similar way to existing CPA operations. However, design considerations with respect to UAS airspeed may be substantially different, because UAS may operate at speeds above or, especially, below speeds typical for CPA. Thus different minimum design standards may be required, considering the expanded operating envelop for many UAS. Further, airspeed is inextricably intertwined with the ability of an aircraft to detect and avoid surrounding traffic. Thus, the effect of this factor on discretizing the risk space with respect to impact severity will depend on context, in terms of maneuverability of the UAS as well as the nature of the overflown area. Finally, airspeed is a clearly defined and measurable parameter, which encourages its use in the determination of operational restrictions. Airspeed may also be a useful substitute for the weight factor, in terms of setting limitations to mitigate impact severity for lightweight UAS.

Discussion of Kinetic Energy

Kinetic energy is relevant to risk in that it can estimate the amount of damage that can be inflicted upon impact as a function of mass and velocity. In this regard, it can account for impact differences between UAS and CPA in a way that weight alone cannot. Kinetic energy measurements, however, are not straightforward. Kinetic energy can be computed using several different velocity types, and it can be a time-varying quantity throughout the flight of an aircraft. Therefore, kinetic energy may be non-trivial to accurately estimate for the purposes of determining design or operational restrictions. A more nuanced approach should be considered when contemplating a damage-related factor for UAS classification, as the total energy of any aircraft is dependent on the sum of its kinetic and potential energy (which is a function of altitude), and whether or not the collision is inelastic or elastic (frangibility). The population density overflown (e.g., densely vs. sparsely populated) also could be considered, because it directly impacts the potential severity of any impact event. Ultimately, replacing weight as a classification factor by any energy metric, including kinetic energy, could be challenging, especially in terms of assessment and enforcement.

Discussion of Altitude

Altitude contributes to impact severity in the sense that the potential energy of an aircraft increases as its altitude increases, hence severity of impact increases. Thus, altitude should be considered in conjunction with weight as it relates to impact energy, and is implicitly related to the population density overflown factor, in terms of assessing impact severity. While peripherally limiting total energy upon impact, altitude can provide for operational restrictions which limit the field over which the impact event can take place, as well as potentially acting to segregate CPA from UAS traffic.

A clear point of interest is that none of the Type 2 factors can be considered independently when attempting to characterize the severity of impact of a UAS, unlike the weight factor. Table 10 summarizes the assessment of the Type 2 factors in the context of mitigating severity of an impact event.

Table 10. Applicability of Type 2 Factors Aimed at Mitigating Impact Severity to UAS Classification

Prospective Factor	Does the factor alone distinguish between similar designs with different risks?	Related factors for formulating operational restrictions to mitigate impact severity	Potential applicability to the current CPA taxonomy
Airspeed	Yes	Maneuverability, Overflown Area, Frangibility	Airspeed could account for safety-relevant differences in airspeed norms between UAS and CPA. Maximum airspeed could be used to create partitions that bound severity of impact; or used to define different minimum standards for airspeed-related regulations.
Kinetic Energy	Yes	Altitude, Overflown Area, Frangibility	Kinetic energy could account for differences in impact severity between UAS (especially high speed, lightweight UAS) and CPA that cannot be realized by weight alone. Maximum energy could be used to create partitions that bound impact severity.
Altitude	Qualified Yes	Overflown Area, Frangibility	Questionable value as a classification factor, though it may relate to impact energy.

As shown in Table 10, the nature of the operational area overflown (e.g., populated versus uninhabited) directly impacts the discussion of all three Type 2 factors. This observation is examined further in the next subsection, by investigating factors that provide a means to distinguish between similar UAS designs due to operational restrictions that limit the likelihood or duration of an impact event.

5.2.3 Impact Exposure Factors (Type 3)

Operational aspects are considered important drivers for risk in many of the UAS taxonomies in [NASA-TM]. Five factors from those taxonomies (LOS operational range, altitude, operational area, population density overflown, and operational failure consequence) relate to risks associated with exposure to an impact event. In this work, impact exposure refers to an amalgam of duration and likelihood of a hazardous event. If a UAS can successfully accomplish its mission in a limited operational area, then operational restrictions may sufficiently compensate for not meeting all airworthiness standards expected under a standard airworthiness certificate—allowing operation of the UAS without increased risk to the NAS. One could then imagine the creation of refinements of the current class/category taxonomy under restricted category. Sub-groups or sub-categories under the restricted category, each with their own minimum design standards, could facilitate the certification of UAS without extensive tailoring of design and performance criteria needed for standard airworthiness certificate.

Discussion of LOS Operational Range

As discussed in Section 5.2.1, VLOS, RLOS, and beyond RLOS operations represent unique design features that affect situational awareness different from CPA. This discussion focuses on LOS operation range from the perspective of risk associated with loss of control, specifically if a UAS loses radio contact and becomes uncontrolled by any human. If a UAS operation is taking place within VLOS, a visual observer can determine the actions of the aircraft and possibly ascertain whether the area of operation is populated; this may not be the case under RLOS operation. A UAS with a beyond-RLOS capability may have a complicated communication system (perhaps involving satellites or multiple ground-based communication relays) or may be capable of operation without human intervention (i.e., autonomous operation). Reliance on communication relays increases exposure because the relays introduce opportunities for commands or other messages to be lost, corrupted, or delayed, increasing the likelihood of an impact event. Additionally, communication relays may cause degradation in the quality of state information used to create relevant visual, audio or otolithic cues intended to enhance situational awareness. Time delays inherent in RLOS and beyond RLOS operations can increase likelihood of a hazardous event in several ways: (1) the operator is unable to perform an action due to a delay in receiving state information, (2) the operator performs an incorrect action due to use of state information that is not up to date, or (3) the operator performs the correct action but it is not executed in a timely manner. This risk can be mitigated via additional design requirements (e.g., autonomous navigation capability, redundant communications, etc.) or through operational restrictions. Restrictions applied to LOS operational range directly influence the impact exposure of identical UAS; for instance, reliability and design assurance requirements may differ for the same UAS, depending on whether the UAS is restricted to RLOS operations or beyond RLOS.

Discussion of Altitude

Altitude by itself does not clearly drive unique design characteristics for UAS as compared to CPA. Certainly the presence of cloud cover affects the visual line of sight that can be maintained by a UAS, thus rendering the cloud ceiling as a potential operational barrier for VLOS maneuvers. However, this would not be dissimilar to altitude restrictions regarding the applicability of visual flight rules for CPA under clouded conditions.

Instead, altitude is most useful for UAS classification from the perspective of operational mitigation via segregation of air traffic. For example, UAS may be restricted to operate below 400 feet, which provides segregation from other air traffic, since FAR Part 91.119 states that CPA should fly at least 500 feet above any obstructions in uncongested areas (1000 feet in congested areas). Because there is very little air traffic above class A airspace (approximately 60,000 feet), a UAS with an operational restriction to maintain an altitude above this level will effectively be separated from CPA air traffic. Furthermore, as discussed in Section 5.2.2, a UAS that experiences a loss of control at a higher altitude possesses a larger potential overflown area in which it can impact the ground.

Discussion of Operational Area

Certainly a UAS operating in segregated airspace would pose different risks than if it were operating in non-segregated airspace. Whether or not that would drive different design requirements, beyond minimum required equipment, is not clear. The value of creating airspace solely for UAS operations can only be assessed based on the operational context and intended use. If operational area is distinguished at a very high level, segregated versus non-segregated airspace, then the utility of the factor for UAS classification is questionable, given the goal of integration into the NAS. For CPA, operational area is used to limit operations for restricted category aircraft or other purposes (e.g., temporary flight restrictions). If restrictions on operational area for UAS are applied in a similar manner, this could be a transitional step for enabling UAS to participate in the NAS.

Discussion of Population Density Overflown

Population density overflown is one of the most prevalent factors used or proposed for use in UAS taxonomies. This is based on the fact that the risk posed by operating a UAS over an unpopulated area (assuming it could not go beyond that area) would be lower specifically with respect to harm to people than a CPA's risk operating over the same area. In both cases, there is limited risk of harm to people on the ground; however, there is risk to people on board the CPA and no risk of such for the UAS.

At the very least, reliability requirements could possibly be reduced for a UAS of consequential weight constrained to operate over lightly or unpopulated areas compared to a UAS without such a restriction. Population density overflown can be used to partition similar UAS designs based on whether or not the reachable impact area of the UAS is, at any time, populated. Population density overflown may be a good factor for representing risk to humans or property on the ground because it relates directly to likelihood and duration of impact risk. Such a factor would need to include the effects of power loss, lost link, glide potential, and such on reachable impact area. Like the operational area factor, this factor does not represent a restriction on the areas overflown by a UAS. Rather, it defines groups that require more and less stringent airworthiness standards.

Discussion of Operational Failure Consequence

Operational failure consequences are used by EASA to group UAS for certification with respect to two major hazards: loss of thrust (i.e., unpremeditated descent) and loss of control (i.e., uncontrolled flight). EASA uses this factor in conjunction with kinetic energy to differentiate between UAS failure modes and associated risk. Because all UAS evince these hazards, design space partitions formed by the application of this factor do not aid in distinguishing between similar UAS designs, as the mechanisms for loss of thrust and loss of control may be very different given the wide range of possible UAS designs. A useful role for this factor in an aircraft taxonomy is not clear, and it may be better suited as a driver for designing mitigation strategies to alleviate risk.

With the exception of operational failure consequence, the other four Type 3 factors identify operational profiles relevant to impact exposure that are not applicable to CPA risk. Specifically, the factors LOS operational range, altitude, operational area, and population density overflown provide a foundation for developing operational restrictions that could allow operational benefit for many conceivable UAS applications without increased risk to people or property in the air or on the ground. Table 11 summarizes the assessment of the five type 3 factors that relate to impact exposure via the area in which the UAS is intended to operate.

Table 11. Applicability of Type 3 Factors Aimed at Mitigating Impact Exposure to UAS Classification

Prospective Factor	Example of how this factor can mitigate impact exposure	Potential applicability to the current CPA taxonomy
LOS Operational Range	VLOS provides increased situational awareness and responsiveness for the remote pilot, as compared to RLOS	Could account for the hazard that an aircraft is fully functional but unintentionally uncontrolled by any human.
Altitude	Segregation of CPA from UAS air traffic	Limiting a UAS's altitude has questionable value as a classification factor. Instead, this factor is better suited as an operational restriction to mitigate impact exposure by segregating UAS from other aircraft.
Operational Area	Segregation of CPA from UAS air traffic	Limiting the operational area to segregated and non-segregated has questionable value as a classification factor. Instead, this factor is better suited as an operational restriction to mitigate impact exposure by segregating UAS from other aircraft within range.
Population Density Overflown	Low population density or property value versus high population density or property value	Could account for a lack of some hazards when operating over sparsely populated areas, compared with CPA. Potential during off nominal or loss of control events should be considered in addition to the expected operational area.
Operational Failure Consequence	None	Questionable value for use as a UAS classification factor because it fails to distinguish between UAS or CPA.

5.3 Implications

While the current aircraft classes and categories may seem suitable for some UAS, as per Section 4, those classes and categories may not be appropriate as is for many credible UAS designs. This section identifies factors that could act to cover UAS designs or facets of them not evinced by CPA, or to distinguish between similar UAS designs with different operational risk profiles.

Table 9 identifies some novel design attributes common to many UAS that are not accounted for in the FARs. The novel design factors could act to distinguish UAS from each other, and facilitate standards-based certification through the development of minimum design and performance criteria to address the unique hazards or risks posed by these designs. The factors in Section 5.2.1 may not represent the best or only novel facets of the UAS design space, but they suggest that there are UAS design types that might benefit from explicit recognition of these attributes (e.g., frangibility, disposability, and flight time) within an aircraft taxonomy. Some of these factors could link different groups of UAS to individual standards in much the same way as is currently done for seaplanes, or others may lend themselves eventually to new aircraft categories. Additional data is needed to determine the necessity and particulars of any new standards needed to support these novel design attributes of UAS.

Table 10 illustrates the use of factors aimed at mitigating the severity of impact events to resolve the UAS risk space more effectively than weight alone can. These factors could provide new ways to group UAS for risk mitigation. Though kinetic energy offers some advantages in accounting for the damage from impact with a UAS better than weight alone, it is not without its challenges as a classification factor. The use of a blended combination of factors, such as airspeed, weight, and population density overflown, may be more valuable for grouping most UAS designs with respect to operational risks.

Perhaps the most important observation comes in Section 5.2.3. Table 11 shows that factors that control the exposure of a UAS to impact with other aircraft or people or property on the ground may provide a foundation for defining standardized groups of UAS based on operational restrictions. When coupled with factors that can limit impact severity, one could imagine that operational restrictions could be defined that correlate with practicable operational use cases (e.g., aerial surveillance for precision agriculture), similar to those called out already in FAR Part 21.25. The nuance here is that there may be sufficient numbers of UAS in each special purpose operation to justify the development of airworthiness standards specific to each. UAS, within those groups, could operate for compensation or hire without increasing risk to the NAS, and do so without the burden of extensive case-by-case tailoring of more rigorous standards (i.e., requiring numerous exemptions and special conditions). Grouping UAS by these operational factors to create further gradation of restricted category aircraft may be a promising direction to enable the certification and entry of specialized and operationally-restricted UAS into the NAS.

6. Summary

In the pursuit of enabling UAS to routinely access the NAS, much attention is being devoted worldwide to the challenges of developing UAS-specific certification processes, regulations, and standards, including those for airworthiness. These are essential to moving the process of integrating UAS into the NAS beyond the current practice of case-by-case accommodation. Notably though, there is an absence of consensus on what airworthiness standards should be and how they might apply across the diverse spectrum of UAS types. This paper is not intended to propose answers to those questions, but instead to provide insight into some of the numerous features and qualities of UAS that affect minimum design and performance standards. The research approach in this paper examines factors that shape the current civil aircraft taxonomy and the extent to which those factors apply to different UAS designs.

This paper calls attention to several considerations that are relevant in the discussion of classification of aircraft types. Today, classification supports a standards-based approach to CPA certification, through airworthiness standards specifically tailored to the physical characteristics (class) and operational characteristics (category) of the aircraft; e.g., Part 25 for transport airplanes, and Part 27 for normal rotorcraft. This function of aircraft class and category neatly captures risk associated with design attributes of a particular type of aircraft, and also risk associated with intended use and operational limitations. Classification also supports risk reduction through operational compensation or through certification compensations such as those for different subclasses of Part 23 airplanes. Altogether, the classification approach codified in the FARs and other regulatory policy represents a sensible and successful approach to mitigating airworthiness hazards in CPA with the efficiencies gained when a set of airworthiness standards can be applied to a significant group of aircraft types. This research examined the extent to which the existing approach to allocating airworthiness standards applies to different UAS types, and, if needed, how that system could be amended to better enable UAS to benefit from the application of common airworthiness standards.

6.1 Applicability to UAS

An obvious question is whether the current aircraft class and category taxonomy can accommodate the wide range of UAS design types and their desired range of civil operations. That is, is it reasonable to apply the existing airworthiness standards in the FARs to UAS that fall into the same broad class and category designations as CPA (e.g., normal airplanes, commuter airplanes, transport rotorcraft, etc.)? This study addresses that question, but with focus only on those aircraft classes and categories that support operations that could be conducted for compensation or hire. This research addressed that question by testing the hypothesis that the existing aircraft taxonomy is appropriate if the current classes and categories sufficiently cover UAS designs and if corresponding standards apply to UAS without the possibility of over- or underregulation. The hypothesis test proceeded by analyzing each of the factors and their corresponding breakpoints used to define the current set of aircraft classes and categories.

The hypothesis test showed that the existing CPA classes and categories may be a reasonable fit for UAS that are indistinguishable in type design from CPA and operate in a manner similar to CPA under a standard airworthiness certificate. This assumes addition of standards necessary for the mitigation of hazards due to communication links, ground control stations, the distributed nature of command and control, electronic sense and avoid, and unusual launch and recovery systems. However, that subset of the UAS design space does not represent the majority of UAS expected to enter the commercial market in the short term. That is, the aircraft classes and categories currently in the FARs may not be appropriate *as is* for many UAS designs intended for commercial use. The existing aircraft class and category combinations do not fully cover the physical and operational diversity of UAS. Further, the imposition of current standards could potentially overregulate some UAS and thus unnecessarily limit industry growth, and underregulate others, possibly increasing risk. These findings do not discredit the current taxonomic system for CPA or approach to allocating standards. These findings do, however, indicate that some non-trivial modifications likely are needed if full accommodation of UAS within a standards-based system is sought. This research effort examined one possible approach to doing that based on adding classification factors.

6.2 Enhancements to Accommodate UAS

This research investigated whether factors identified in UAS-specific classification schemes might be useful additions to those that define the current class/category taxonomy. Eleven prospective factors were identified and reviewed to determine whether they might distinguish UAS with different risk profiles. Several factors clearly account for risks associated with UAS-unique design features not applicable to CPA, such as frangibility, disposability, and long duration flight. New airworthiness standards for these features will likely be needed.

Other factors used to mitigate operational risk, such as population density overflown, may be useful for grouping UAS based on restricted operational usage models. This finding suggests the possibility of constructing new groups for UAS under restricted category (i.e., restricted subcategories) that lend themselves towards the development of common minimum design and performance standards for airworthiness. This differs from conventional certification practice for restricted category in that the starting type certification basis would be a set of standards expressly for that subcategory, not a case-by-case tailoring of Part 23, 25, 27, or 29. The set of standards applied to a restricted subcategory of UAS could start with a pre-streamlined subset of Part 23, 25, 27, or 29 because the risk associated with that UAS group would be significantly less than the risk for CPA. Some combinations of the prospective factors, such as frangibility, disposability, population density overflow, and altitude may actually render the consequence of an impact negligible (i.e., it no longer presents harm to other aircraft or persons or property on the ground). Restricted subcategories, based on those, could be defined where impact may no longer be the dominating influence on the risk profile, leading to a possibly small set of airworthiness requirements that would allow civil UAS operations in the NAS, however limited. Creating airworthiness standards at this level for UAS is not conventional, but could more quickly enable an emerging industry. This approach could provide a feasible path towards certification of UAS that could successfully operate under restrictions in the short term.

6.3 Closing Thoughts

The idea of having distinct groups for UAS tied to operational usage models is consistent with others advocating a step-wise process using restricted type certification [Allouche], and not far removed from the current COA process for public UAS. Establishing distinct restricted subcategories and associated standards that enable very low-risk UAS operations could be a timely stepping stone toward full integration. Such a step would allow the industry and regulators to gain valuable experience with UAS while carefully controlling access and potential harm to the aviation system as a whole. Identifying an effective set of classification factors and appropriate gradations of them is key to appropriately grouping UAS together that could share a common set of design criteria. This paper supports the possibility of doing this in accordance with the framework governing manned aircraft as a way to enable standards-based airworthiness certification for UAS in the near term. Without question, significant issues would need to be resolved to realize such an approach (e.g., determining whether attributes such as frangibility and disposability would be acceptable or defining gradations for flight time that correlate to different risk profiles).

This paper presents a small step in advancing the cause of UAS classification for civil airworthiness, and supports the possibility of classifying UAS within the confines of the aircraft taxonomy in the FARs. Additional research is needed to support decisions regarding a UAS classification approach that meets the needs of both regulators and applicants. Future research directions include a more comprehensive analysis of the prospective factors to better understand how they may characterize hazards and risks for UAS, with consideration of whether changes to the taxonomy might negatively impact CPA. Further data also is needed to better ascertain the hazards and risks associated with the breadth of UAS designs and operational models.

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Appendix A: Autonomy

Autonomy is not currently used to differentiate aircraft under 14CFR with respect to airworthiness standards, nor has it been addressed in a complete fashion by any of the literature on UAS classification systems surveyed. Autonomy, however, is often mentioned in discussions of UAS classification relevant to certification. Before considering autonomy as a potential classification factor for UAS, one needs to understand the myriad notions of autonomy and their implications on risk. This appendix takes a first step at providing context for an informed examination of the topic, specific to autonomous aircraft.

Autonomy has been defined in different manners in diverse domains, such as robotics, artificial intelligence, and machine learning, leading to ambiguity in assessing which elements clearly characterize autonomy in the context of UAS certification. As certification is seen as a means by which risk to safety is mitigated, examining the aspects of autonomy that are unambiguously quantifiable and enforceable from a certification perspective is helpful. Thus, we first turn to formal definitions of autonomy, in the context of certification.

A.1 Definitions of Autonomy

International Civil Aviation Organization

Currently, ICAO defines[10] an autonomous aircraft as an "unmanned aircraft that does not allow pilot intervention in the management of the flight." Furthermore, autonomous operation of an aircraft is defined as "operation during which a remotely-piloted aircraft (RPA) is operating without pilot intervention in the management of the flight." Currently, ICAO only considers remotely piloted aircraft as suitable for standardized international civil operations, due to unclear responsibility for the autonomous portion of the flight [ICAO-328]. For the purposes of the paper, this definition is adopted, as this is an international regulatory agency, which prescribes regulation for flight across the globe.

Note that this definition is binary in nature, and solely discriminates based on if a human can interact during the operation. This definition does not capture the notions of complexity usually encompassed in other definitions of autonomy, which address the nature of the environment as well as the difficulty of the task being performed. These two additional aspects to autonomy can be difficult to characterize, and pose several issues in terms of enforceability. However, other definitions, not constrained by enforceability, might provide information about scope and direction of advances in autonomy.

Alternative Definitions of Autonomy

There are many alternative definitions of autonomy, some of which do not consider autonomy to be a binary state. Ubiquitous amongst these is the seminal definition advanced by Sheridan [Sheridan], where the proposed role for humans in highly automated systems is to undertake what is called supervisory control. This is a new relation between the human and the machine, as an automatic machine may be said to be intelligent in some rudimentary sense. The new form of interaction differs from the traditional interaction of the human with tools and devices that possess no intelligence, in which all sensing and control are done by the human operator. In the Sheridan definition, each task can be performed with varying degrees of automation, and is resolved into a scale from (1) to (10), where level (1) corresponds to the situation where the computer offers no assistance to the human, and level (10) corresponds to the condition where the computer possess both full-decision-making functionality and the authority to enact these decisions without human input. Alternative academically-developed definitions of autonomy use different numbers of levels or scale the sensing (afferent) and the motor (efferent) functions separately

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[10] ICAO provides this definition in a publication [ICAO-328] listed as a *circular*. Circulars are not official policy of ICAO.

[EndsleyKaber, WMW, SheridanVerplank]. The Federal Agencies Ad Hoc Autonomy Levels for Unmanned Systems Working Group in its first workshop, held in 2003, attempted to define metrics for autonomy and to develop a framework for autonomy levels for unmanned systems [ALFUS]. During the course of this and subsequent workshops, the autonomous operation of an Unmanned System (UMS) was defined as follows – Operations of a UMS wherein the UMS receives its mission from either the operator who is off the UMS or another system that the UMS interacts with and accomplishes that mission with or without further human-robot interaction. Autonomy was defined as a UMS's ability of integrated sensing, perceiving, analyzing, communicating, planning, decision-making, and acting/executing, to achieve its goals as assigned. A UMS's autonomy is characterized by the missions that the system is capable of performing, the environments within which the missions are performed, and human independence that can be allowed in the performance of the missions.

Unlike other organizations, NASA views autonomy as distinct from automation in accordance with its space initiatives. Automated systems provide control or execution of a system without human intervention or commands. This does not preclude the possibility of operator input, but such input is explicitly not required for an automated function [Constellation]. Autonomous systems are capable of operating independent of external communication, commands or control (i.e., commands from mission control on Earth). This definition allows the crew, but not mission control, to be involved in the operation of an autonomous vehicle. NASA also operates vehicles without an on-board crew, where the notion of autonomy is similar to other organizations. In these instances, the desire for autonomy occurs when the time delay between the vehicle and mission control is too large for the required dynamic maneuvers. This motivation for autonomy is quite different from the motivation for autonomy in UAS.

In summary, all of these alternative examinations view autonomy on a spectrum rather than the binary approach of ICAO. Furthermore this spectrum can vary based on several different scales – (1) the amount of human involvement to perform a function, (2) the mission phase when human involvement is needed, or (3) the degree of sophistication in how the automated system accomplishes its function. In addition to adapting these definitions to the specific domain of aviation, refinement of these approaches must also occur for these gradations to be objective and enforceable for certification purposes.

A.2 Certification Issues with Autonomy

The complexities inherent in the notion of autonomy yield a conundrum when it comes to the purposes of certification. It is difficult to construct clear, unambiguous language that allows for the assessment and enforcement of fundamental aspects related to autonomy [MEPW]. In the context of the ICAO definition, autonomy is cast as the capacity of an aircraft to operate in a real world environment without any form of external control for a given period of time. This allows autonomy to have a clear and enforceable definition, namely a system requiring no human input during its flight operation. However, there are subtle factors upon which this notion is dependent. The ability to use autonomy as a classification factor for UAS requires a fundamental understanding of the notion of autonomy and its implications on risk.

How is human input defined?

If the ICAO definition of autonomy is used, the issue of "human control inputs" needs to be defined clearly. To enforce a lack of human control input, operator qualification must be determined clearly, as well as authorizations for regimes of flight or functionality. For example, would an indication from a human operating a camera regarding a feature of interest be viewed, for purposes of certification, as a human control input? At an extremely high level, a software developer or mission designer can be considered to be an operator, which may cause unintended software consequences to be considered human inputs. Another complexity arises when autonomous aircraft interact with humans in the fielded environment (for instance to avoid or track humans). Presumably, at some level of interaction, a human in the environment becomes an operator. Objectively defining this point is quite subtle.

What is the impact of mission complexity on autonomy?

The ICAO definition does not tie the idea of autonomy to mission goals. For example, a bullet is an autonomous system, using the ICAO definition, as it requires no further human control input after it is fired. To avoid these obvious corruptions of the term, it is natural to wish to include some notion of complex decision making to achieve mission goals into the definition. However, it is difficult to define, in an un-biased manner, what exactly a complex decision entails. Furthermore, defining an un-biased hierarchy, which allows for the ranking of decision types in order of increasing complexity, is a non-trivial task. There is no easily definable metric, which discerns the difficulty of a decision. Finally, it is unclear whether the measure of complexity should be informed by the difficulty of the goals being met, or the intricacy of the decisions being correctly made, that should inform. At a higher level, the primary purpose of aviation regulation is to maintain safety of the airspace. So, perhaps the definition of mission complexity should be limited to those aspects that affect the aircraft's ability to maintain flight safety.

How could the level of reasoning exhibited by an autonomous system be evaluated and certified?

Many implementations of autonomous systems contain techniques that include a notion of reasoned decision making or "thinking." The certification issues associated with these techniques are just beginning to be examined. Taxonomies for classifying reasoning abilities primarily hail from the machine learning or artificial intelligence domains [RussellNorvig]. These efforts attempt to compare the mechanized decision-making paradigms to those human behaviors they most closely mimic. However, mechanized decision-making paradigms are difficult to assess, and questionable to certify. An adaptive neural net may have an extremely intricate model of the world, and be able to aggregate percepts into highly complex notions of state, as well as successfully project the effect of many decisions on future states, but the means by which this process occurs can be ambiguous. The ability to pinpoint key points in the decision process and assess unambiguously defined metrics at these points to ensure safe and correct operation is critical to the evaluation and certification of any algorithm. The ability to document environmental assumptions, and assess when they are exceeded, in order to determine the operational ranges for which the algorithm performs correctly is vital to determine its safety.

How should liability in the context of autonomous systems operation be established?

The notion of autonomy has a specific legal meaning related to the right of an agent to choose freely its course of action. That is, autonomous agents possess a rule-of-self that is free from controlling interferences by others and from individual limitations that prevent meaningful choice [Black]. The degree to which these concepts apply to an autonomous aircraft is unknown. When an autonomous system fails, there are serious issues about who is liable as there are many stakeholders–the operator, the firm or agency that owns the equipment and/or employs the operator, the designer, the manufacturer, the installer, the maintainer, the regulator, etc. Notions of causality and foreseeability critically influence certification issues pertaining to autonomy, leading to a system possessing different degrees of autonomy under different operational conditions. This introduces the idea of variable autonomy, by partitioning the modes and areas of operation for autonomous aircraft. For example, a UAS can be highly autonomous during nominal operation or in particular regimes of flight but require further intervention during pre-determined off-nominal regimes. However, this presents certification challenges, as it involves issues of detection and mitigation that must occur concurrently.

A.3 Implications of Autonomy

The purpose of certification is to assess and provide assurance of the safety of a product or service. Regulation also is applied to protect people and property on the ground or on other aircraft who generally do not have a direct influence on the quality of the service being offered in the design and implementation stages. The safety of the aviation system evolves as systems are operated, flaws are discovered, and further advisories or regulations are created to eliminate those flaws. For the vast majority of regulation developed for manned aircraft, there are corresponding hazards that are mitigated by these rules. Applying these rules to autonomous aircraft may not eliminate hazards that manifest themselves differently in an autonomous system. Research must be conducted to identify hazards, risk mitigation techniques, corresponding regulation and means of compliance for autonomous systems, to ensure that certification actually assures the overall safety of the NAS.

A possible advantage of autonomy, from a safety and certification standpoint, comes from the idea of removing the pilot from the critical control loop, eliminating pilot error. However, the pilot also acts to mitigate and control off- nominal and hazardous situations. It is unclear how the creativity of the human in these problematic situations can be captured, and criteria developed to which all autonomous avionics should be certified in order to replicate this risk mitigation factor.

Different techniques for implementing autonomy will have different challenges associated with certification. One key desire for an autonomous system is to handle rare or unexpected cases in a reasonable manner. The concept of "reasonable action" must be examined, and then defined in an unambiguous fashion, in relation to decision-making procedures as well as environmental and mission constraints for all foreseeable situations.

Finally, if an autonomous system is certified on the basis that all actions taken by that system conform to a pre-defined degree of reasonableness, and not correctness, then the effects of these decisions on the future state of the system need to be investigated. The cause-consequence analysis of a system whereby all behaviors are not certified as strictly correct, but rather as reasonable (i.e., minimize harm), is extremely intricate. Techniques for performing this analysis in a compactly expressible manner, for readability and reviewability issues, must be developed to certify these systems. Demonstrating compliance to certification criteria must be built in to any techniques developed for assessing these systems.

Additionally, using the expanded notions of autonomy, which allow variable control of a UAS between a human operator and a computer, the authorized operator for the RPA must be clearly identified at any given time. This raises the question of whether or not this operator is uniquely determined at all times. It is possible for there to be an operational pilot (at a ground station) operating the aircraft, a safety pilot who is onsite with the aircraft, as well as a mission planner, inputting high-level goal changes for the aircraft, at any given time. Moreover, there may be several remote pilots, each dedicated to different regimes of flight. It is then difficult to declare that there is a single operator of the RPA, rather than a system of operators. Furthermore, an RPA is a highly cooperative human-machine system, and it behooves us to define the levels of human input commensurate with the responsibility that input entails. Furthermore, the protocols for handing off critical control functions between any of these operators amongst themselves, as well as to the RPA, must be defined clearly, and be specified in an enforceable manner.

A.4 Summary

The subject of autonomy, as concerns the certification of aircraft in a civilian airspace system, is fraught with many issues. Primary among these issues is developing the requirements for an autonomous system. Typically, the role of human operators is not well defined and an autonomous aircraft must perform all functions correctly whether they are written or not. Without clearly defined assessment techniques for the correctness of autonomous systems, under variable environmental conditions, it will be exceedingly difficult to create certification standards. The ability to define autonomy unambiguously and capture all of the necessary aspects associated with it in a measurable fashion is a non-trivial concept. There is a great need to further study measurable aspects of autonomy, as well as enforceable constraints and assumptions in the environment and mission goal parameters for autonomous systems.

Autonomy is significantly different from the other factors discussed in this paper. Currently, the full implications of autonomy in a civilian airspace, as well as its impact on overall safety, are unknown. The ability to regulate around a concept that is not yet clearly characterized will almost certainly lead to both overregulation and regulatory gaps. The ability to determine what aspects of autonomy impact the overall safety of a system is a topic of further research. Furthermore, the ability to assess the safety of an autonomous system (and ensure it maintains that safety under all conditions) is a topic of parallel research. Thus, while autonomy may be a critical factor for certification of a UAS, our present understanding of this factor is not yet at a level with which meaningfully certification characteristics can be derived.

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14. ABSTRACT

While progress is being made on integrating unmanned aircraft systems (UAS) into our national airspace system on a broad scale, much work remains to establish appropriate certification standards and operational procedures, particularly with respect to routine commercial operations. This paper summarizes research to examine the extent to which today's civil aircraft taxonomy applies to different UAS, and, if needed, how that taxonomy could be amended to better cover UAS designs and operations. Factors that shape the current taxonomy, as defined in the Federal Aviation Regulations, was assessed for applicability to UAS, potential incompatibilities were identified, and additional factors were proposed that might be useful for an updated aircraft taxonomy intended to cover UAS. The results suggest the possibility of constructing new groups in the taxonomy for UAS under a restricted category that share common airworthiness standards. Establishing distinct groups for UAS and associated standards that enable low risk operations for compensation or hire could be a timely step towards full integration. Such a step would allow the civil aviation industry and regulators to gain valuable experience with UAS while carefully controlling access and potential harm to the aviation system as a whole.

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