Clothier, Reece A., Palmer, Jennifer L., Walker, Rodney A., & Fulton, Neale L. (2011) Definition of an airworthiness certification framework for civil unmanned aircraft systems. *Safety Science*.

Authors: Clothier, RA., Palmer, JL., Walker, RA., and Fulton, NL.
Title: Definition of an Airworthiness Certification Framework for Civil Unmanned Aircraft Systems (Article in Press, Corrected Proof)
Publication: Safety Science
Available online: 5 March 2011
DOI: http://dx.doi.org/10.1016/j.ssci.2011.02.004

TITLE:

Definition of an Airworthiness Certification Framework for Civil Unmanned Aircraft Systems

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Abstract

The development of effective safety regulations for unmanned aircraft systems (UAS) is an issue of paramount concern for industry. The development of this framework is a prerequisite for greater UAS access to civil airspace and, subsequently, the continued growth of the UAS industry. The direct use of the existing conventionally piloted aircraft (CPA) airworthiness certification framework for the regulation of UAS has a number of limitations. The objective of this paper is to present one possible approach for the structuring of airworthiness regulations for civilian UAS. The proposed approach facilitates a more systematic, objective and justifiable method for managing the spectrum of risk associated with the diversity of UAS and their potential operations. A risk matrix is used to guide the development of an airworthiness certification matrix (ACM). The ACM provides a structured categorisation that facilitates the future tailoring of regulations proportionate to the levels of risk associated with the operation of the UAS. As a result, an objective and traceable link may be established between mandated regulations and the overarching objective for an equivalent level of safety to CPA. The ACM also facilitates the systematic consideration of a range of technical and operational mitigation strategies. For these reasons, the ACM is proposed as a suitable method for the structuring of an airworthiness certification framework for civil or commercially operated UAS (*i.e.*, the UAS equivalent in function to the Part 21 regulations for civil CPA) and for the further structuring of requirements on the operation of UAS in un-segregated airspace.

Keywords

Airworthiness, Regulation, UAS, Unmanned Aircraft, Risk Matrix

1 Introduction

The development of an effective regulatory framework for unmanned aircraft systems (UAS[4]) is a major concern for manufacturers and operators. Civil and military UAS operations are currently subject to restrictions that significantly inhibit their flight within un-segregated civil airspace and over populated areas. These restrictions limit both the military and non-military use of UAS. A greater degree of operational freedom will only occur through the development of a framework inclusive of regulations, engineering and training standards, flight rules and operational practices that can be shown to deliver, at a minimum, a level of safety equivalent to that currently exhibited by civilian conventionally piloted aircraft (CPA). This requirement is referred to as the equivalent level of safety (ELOS) objective (JAA 2004; OSD 2007; CAA 2008). The particular regulations discussed in this paper relate to the "airworthiness" (ADF 2002) of the system being operated. A brief introduction to the concept of airworthiness and its regulation is presented in Section §2.1.

Much effort is being devoted to the definition of standards specific to UAS (*e.g.*, the specification of prescriptive requirements on aspects of their design, maintenance, manufacture and operation). However, little consideration has been given to how these standards and regulations may be appropriately applied across the diversity of UAS, their operations and the mitigation strategies widely employed. As discussed in §2.2, there is currently no consensus on the specification of airworthiness regulations for UAS. The default proposal is to apply the CPA airworthiness regulatory framework to that of UAS (Dalamagkidis *et al.* 2008b). Such an "off-the-shelf" (Clothier *et al.* 2008) approach is implicitly based on the premise that the application of "equivalent" regulations will yield an ELOS, despite UAS being described as a fundamentally different hazardous paradigm. Among many others, Hayhurst *et al.* (2006), Dalamagkidis *et al.* (2008b), Clothier *et al.* (2006, 2008) and DeGarmo (2004) identify numerous differences between UAS and CPA that challenge the suitability of the off-the-shelf approach. These include differences between the associated risks, design philosophies, applications, operational concepts, and supporting business cases and differences between the social and political attitudes towards the two technologies (further described in §2.3). As will be discussed in §2.3, the primary risks that governed the development of the CPA airworthiness regulatory framework are different to those that should be used to guide the development of an airworthiness framework for UAS. This dissimilarity can result in: airworthiness regulations that do not ensure the equitable management of the risks

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[4] The plural acronym is the same as the singular, in accordance with OSD (2007) *Unmanned Systems Roadmap, 2007–2032*. Washington, DC, United States Department of Defense, Office of the Secretary of Defense.

across all types of UAS and their operations; the potential over-regulation and hence imposition of unnecessary costs to the UAS industry; or worse, an airworthiness regulatory framework that does not satisfy the objective for an equivalent level of safety.

It has been concluded that UAS "will require a new regulatory framework to both maintain the safety of the national airspace system and to enable the full benefit of unmanned aviation" (Hayhurst *et al.* 2006). The objective of this paper is to present a practical framework for the effective regulation of the airworthiness of civil UAS.

1.1 Guiding Principles

This leads to the question as to what are the properties of an effective regulation? The high-level objective for aviation safety regulations is to ensure the safe and effective operation of aircraft, with priority on the former. Increased regulation often results in increased costs to the industry and, in turn, a reduction in the potential benefits available to society (Fischhoff *et al.* 1978). Regulations should therefore be defined and promulgated proportionate to the estimated risks associated with the activity. This ensures that safety objectives can be verified (*e.g.*, assurance that the regulations satisfy the ELOS objective) and that the regulatory-costs imposed on the industry are warranted. Under this premise, a justifiable position to guide the specification of a regulatory framework for UAS resides in an understanding of the risks associated with their operation.

To summarise, an effective[5] regulatory framework for UAS should be:

1. justifiable (*i.e.*, have a clear basis in risk and traceability to the ELOS objective),
2. flexible enough to accommodate the diversity of UAS designs, operations and mitigation strategies,
3. systematic in its management of the risks across this diversity,
4. objective (*i.e.*, the underlying methodology should be independent of any single stakeholder's preferences),
5. practicable in its implementation (*i.e.*, regulatory authorities should have a workable framework), and
6. cognisant of the costs that undue regulations impose on the industry, though not at the expense of the objective for an ELOS.

In consideration of the above guidance, a quantified risk matrix is proposed as a suitable framework for guiding the structuring of regulations for the airworthiness of UAS and their integration into the National Airspace System (NAS). The foundational concepts of the risk matrix are presented in Section §3 in the context of developing an airworthiness certification framework for UAS. The output is a systematic and flexible framework equivalent in regulatory function to the existing civil CPA Part 21 regulation (CASA 2003). The airworthiness certification matrix (ACM) developed supports both an approach of regulation by "safety-target" (Haddon and Whittaker 2002) and regulation by prescriptive codes of requirements.

Within the structure of the ACM, the composite of system type and operational environment defines airworthiness categories. Regulations may then be tailored to a specific airworthiness category through the quantification of measures of risk relative to the overarching goal for an ELOS. Such a top-down tailoring of regulations to the specific joint-categories of system and operation establishes the scope for a bottom-up hazard analysis, as advocated by Hayhurst *et al.* (2006) and comprehensively described by Luxhøj (2009). An example of the top-down tailoring of regulations is described in Section §3.7.1. for the case of determining Part 1309 regulations for UAS that are equivalent in terms of regulatory function to those mandated for CPA [*e.g.*, Federal Aviation Administration (FAA) advisory circulars 23.1309-1D (FAA 2009) and 25.1309-1A (FAA 1988)]. An expanded and generalised risk matrix may also be used to structure other dimensions of regulation, including the operational requirements governing the integration of UAS within the NAS. This application is briefly discussed in Section §4.

In summary, it is proposed that the risk-management approach described in this paper provides a justifiable, flexible, systematic, objective and practical method for structuring the regulation of UAS. It permits the incremental development of regulations and, in turn, the phased integration of UAS into the NAS. The

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[5] The definition of a formal evaluation scheme is an area of ongoing research. The reader is referred to the forthcoming work of Michael Nas (2011), *Classifying Unmanned Aircraft Systems: Development of an Objective Framework for Evaluating UAS Classification Schemes*, Murdoch University, WA (unpublished).

structuring of regulations based on the principles of a risk matrix also ensures that regulations are verifiable against the overarching objective for an ELOS and that any impositions due to regulations are a justifiable expense to the industry.

2 An Airworthiness Certification Framework for UAS

The precedence for the establishment of international regulations governing the airworthiness of a civil aircraft stems from the Chicago Convention of 1944 (ICAO 2000). Article 31 of the Convention (ICAO 2000) requires aircraft to be certificated as airworthy, and under Article 33 these certificates must be recognised as valid by the other contracting States provided they are equal to or above the minimum requirements specified in the Convention (detailed in Annexes). Article 8 of the Convention stipulates the extension of these requirements to UAS. As described in Annex 8 (ICAO 2005) to the Convention, the objective of these regulations is to achieve, "among other things, protection of other aircraft, third parties and property".

There are several definitions for the concept of airworthiness, the most comprehensive of which identifies the key components of airworthiness regulations and is provided in the Australian Defence Force (ADF) instructions:

> *…a concept, the application of which defines the condition of an aircraft and supplies the basis for judgement of the suitability for flight of that aircraft, in that it has been* ***designed*****,** ***constructed*****,** ***maintained*** *and is expected to be* ***operated*** *to approved standards and limitations, by* ***competent and approved individuals****, who are acting as members of an* ***approved organisation*** *and whose work is both* ***certified*** *as correct* ***and accepted*** *on behalf of the ADF.*
>
> p. AL1, ADF 2002

2.1 Airworthiness Certification

This section provides a brief overview of airworthiness regulations for civil CPA. For further detail the reader is referred to CASA (2000), FAA (2004a) and Dalamagkidis *et al.* (2009).

In general, a Certificate of Airworthiness (COA) is issued for an individual aircraft if it meets the conditions of the certification of its type (*e.g.*, make and model) against prescriptive requirements stipulated under different airworthiness categories. According to the Australian Civil Aviation Safety Authority (CASA), an aircraft airworthiness category "… is essentially a homogeneous grouping of aircraft types and models of generally similar characteristics, based on the proposed or intended use of the aircraft, and their operating limitations." (CASA 2000)

As described in civil aviation Part 21 regulations [*e.g.*, CASR 1998 Part 21 (CASA 2003) or CFR Title 14 FAR Part 21 (FAR 2009)], aircraft types may be certificated in two classifications:

1. Standard – broad categories of aircraft for which detailed prescriptive codes of requirements (standards and limitations) are defined (*i.e.*, normal, commuter, transport, normal rotorcraft, and transport rotorcraft, *etc.*), or

2. Special – for those aircraft that do not meet the requirements of an applicable comprehensive and detailed airworthiness code as required by a standard category (CASA 2000). Special categories include: primary, intermediate, restricted, limited and light sport aircraft, *etc.*, and the designations: experimental, gliders, ultralights, *etc*. (CASA 2000).

For all aircraft certificated in a special category of airworthiness, operational limitations become part of the conditions of the COA (FAA 2004b). These limitations may include restrictions on manoeuvres, speed, number of passengers, activities undertaken and where flights may be conducted. Experimental certificates are issued to individual aircraft and only for specific activities (*e.g.*, research and development, demonstration and training, *etc*.). An aircraft operating under an experimental certificate cannot be flown for commercial reward.

Special flight permits may also be granted to an aircraft that does not meet the applicable airworthiness requirements, but can reasonably be expected to be capable of safe flight for a specified list of activities (*e.g.*, demonstration, delivery of an aircraft, search and rescue, or assisting in a state of emergency).

2.2 Current Airworthiness Certification Regulations for Civil UAS

Currently, there are no specific standards and regulations for the type certification of civil UAS. In their absence, the risks to people and property on the ground are assured through substantial restrictions on where UAS operations can take place. An individual UAS may be certificated in the experimental designation [*e.g.*, as described in AC 21-43(0) (CASA 2006)], for specific applications and not for commercial reward, but remain subject to operational restrictions [*e.g.*, in Australia these restrictions are contained in CASR Part 101 (CASA 2004)]. Operational regulations such as CASR Part 101 (CASA 2004), prescribe the requirement for a COA based on the nature of the operation performed [*e.g.*, whether the unmanned aircraft (UA) is operated over a populous area or not]. The regulations do not define type categories or categories of airworthiness for which COA can be issued.

The absence of an airworthiness certification framework, and the subsequent operational limitations imposed, come at significant expense to the UAS industry. Requisite to the realisation of routine UAS operations in the NAS are regulations that facilitate the certification of an UAS as airworthy. At the highest level these regulations comprise:

1. a certification framework specifying the conditions for prescribing different airworthiness regulations to different types of UAS operations, *i.e.*, a framework equivalent in regulatory function to civil CPA regulation Part 21; and

2. standards, procedures and recommended practices governing the design, manufacture, maintenance and operation of UAS tailored to each of the airworthiness certification categories, *i.e.*, airworthiness standards equivalent in regulatory function to the prescriptive codes of requirements contained in civil CPA regulations Part 23, 25, 27, 29, *etc*.

Much effort has been directed towards addressing the second of these two components. In particular, regulations that provide assurances in the airworthiness of the “system”, which encompasses the UA, human elements, communications and ground infrastructure, as opposed to that of just an “aircraft”. For example, Hayhurst *et al.* (2006) and Luxhøj (2009) identify unique hazards that must be addressed in low-level airworthiness regulations (*i.e.*, standards, and operational requirements covering unique aspects of UAS including: autonomy, communication links, and ground control systems, *etc.*). Standards development organisations, such as ASTM Committee F38, and the NATO Standardization Agency (NATO 2009), have also made progress in defining airworthiness standards specific to UAS. However, limited research has been conducted into the definition of the overarching certification framework that dictates the conditions for promulgation of these low-level regulations.

The apparent consensus, a default position of regulatory groups, is that the airworthiness framework for UAS should be based on that for CPA of the same category (Dalamagkidis *et al.* 2008b), with a number of novel strategies being proposed for determining equivalency between categories of UAS and CPA [*e.g.*, see Grimsley (2004)]. However, to prescribe the same airworthiness framework to UAS fails to address significant differences between the two technologies. As described by DeGarmo (2004):

> *Premising a UAV regulatory structure based on manned aircraft makes sense, but developing such regulations to cover the vast array of UAVs will be a challenge. There are too many differences, especially concerning the small UAVs. Therefore, expectations that all UAVs can conform to existing regulatory requirement may not be realistic.*
>
> p. 2-46, DeGarmo (2004)

Amongst many others, Hayhurst *et al.* (2006), DeGarmo (2004), Dalamagkidis *et al.* (2008b), and Clothier *et al.* (2008) identify numerous differences between the risk paradigms of CPA and UAS that influence the development of airworthiness regulations for UAS. The following section describes some of these differences. The objective is not to categorically prove that the existing CPA airworthiness certification framework would not work for UAS, but rather, to justify the need to explore potentially more effective strategies.

2.3 Challenges of UAS

Historically the primary purpose of airworthiness regulations for civil CPA has been to ensure the safety of the people over-flown (Haddon and Whittaker 2002; JAA 2004); however, with the rise of commercial passenger operations, the focus now includes aircrew and passengers (JAA 2004). Analysis of accident statistics reveals that the primary people at risk due to the hazards of CPA operations are those onboard the aircraft (Clothier and Walker 2006). Consequently, CPA safety regulations implicitly aim to limit or eliminate harm to those aboard the aircraft, and secondarily to those over-flown (Hayhurst *et al.* 2006). This prioritisation facilitates the “common philosophy” (Haddon and Whittaker 2002) foundational to CPA airworthiness regulations, specifically the philosophy that “as far as is practicable, they (airworthiness codes of regulatory requirements) avoid any presumption of the purposes for which the aircraft will be used in service” (Haddon and Whittaker 2002) and hence are largely independent of the regions being over-flown. This is a defensible position for CPA, as there will always be someone at risk (*i.e.*, at a minimum the pilot) and that addressing the risks to those onboard an aircraft will inherently address the risks to those over-flown (Haddon and Whittaker 2002; Clothier and Walker 2006).

For UAS, it cannot be assumed that there are people onboard the aircraft. The primary risks due to UAS operations are to entities of value (EOV) that are external to the system (*i.e.*, external to the immediate subject of regulation). These EOV include the people and property over-flown and other airspace users within the operational environment. For regulatory matters pertaining to the integration of UAS operations within the NAS, the primary EOV are other aircraft and the people onboard them through the hazard of mid-air collision. If the primary consequence of concern was the degree of damage to the aircraft, then airworthiness could be considered largely independent of the operating environment (although one could argue that type of terrain and other environmental conditions would play a part). However, recalling Annex 8 to the ICAO Convention (ICAO 2005), the primary risks of concern are to the EOV (*i.e.*, the people and property) over-flown, which have the potential to experience harm due to falling parts or a crashing aircraft. Thus, the levels of risk to be controlled by UAS airworthiness regulations are highly dependent on where the system is operated. For example, a large UAS operated over a built-up residential area presents a higher level of risk (with respect to the people and property over-flown) than the same UAS operated over an unpopulated area. Graphical illustrations of the nature of this dependency are provided in Weibel and Hansman (2004), Clothier and Walker (2006), and Dalamagkidis *et al.* (2009). Thus, the required certification basis for a particular UAS is a function of the system and the properties of its intended operational environment (*e.g.*, the density and distribution of EOV over-flown, sheltering, *etc.*). McGeer *et al.* (1999) encapsulate the nature of the problem:

> *… with a manned aircraft you have to build to the same standard no matter what is underneath you, but among unmanned aircraft, acceptable safety for flights exclusively over oceans can be achieved with rather more rickety machines than would be fit to fly over a city. Hence the abundance of possibilities which everyone recognises and is struggling to manage.*
>
> p. 11, McGeer and Vagners (1999)

To further complicate the problem, there is significant diversity in UAS compared to CPA. The comparative histograms of UA and CPA maximum takeoff weight (MTOW) and maximum operating speed shown in Figure 1 and Figure 2, respectively, provide a graphical illustration of the magnitude of this diversity. Evident from Figure 1 and Figure 2, is that the MTOW of the UAS fleet ranges from a few grams through to hundreds of tonnes, whereas for the CPA fleet, the MTOW ranges from a few hundred kilograms through to thousands of tonnes. The existing certification categories provided in CPA regulations do not adequately cover this range. Also evident in the histograms are UAS types that can operate in much lower and higher speed regimes than that of the CPA fleet. Both speed and MTOW are factors that influence the risks presented to people and property on the ground. Hence, the risk profile to be managed for UAS is larger than that for the CPA fleet. A certification framework should ensure that risks are managed systematically across the diversity of systems and operations (*i.e.*, that low-level airworthiness regulations are prescribed commensurate with the degree of risk associated with the operations for all types of UAS). If the CPA airworthiness certification framework is applied to UAS, it would not be possible to objectively show compliance to the ELOS requirement at a minimum imposed cost, particularly for those types and operations that are unique to UAS.

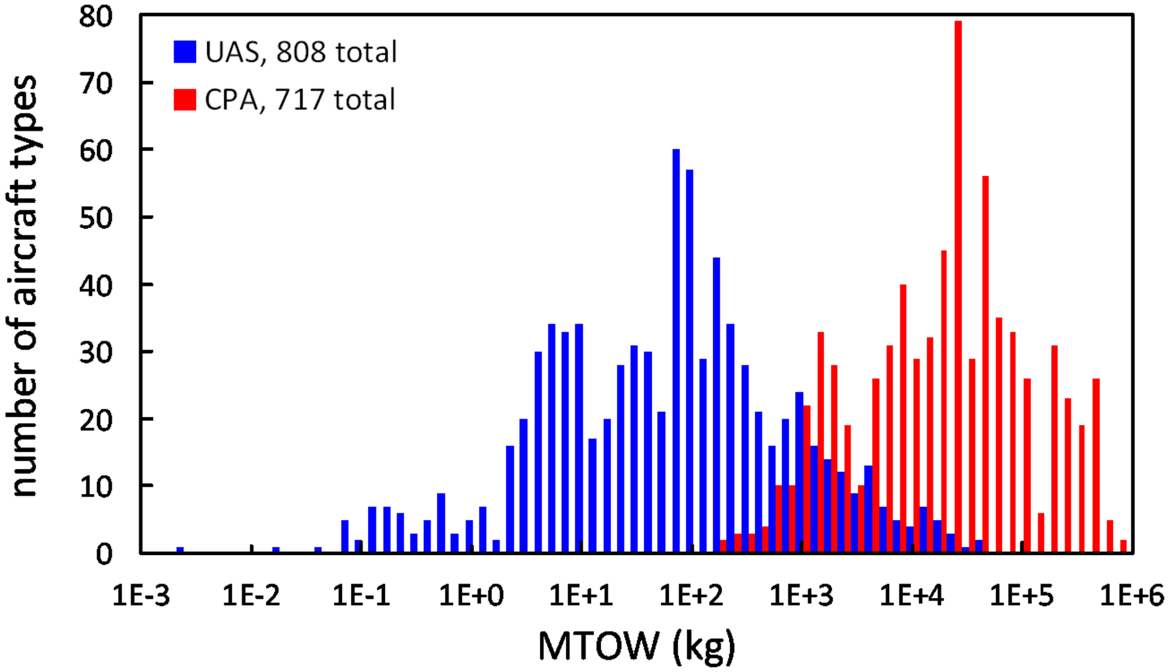

Figure 1 – Histogram of aircraft maximum take-off weight[6]

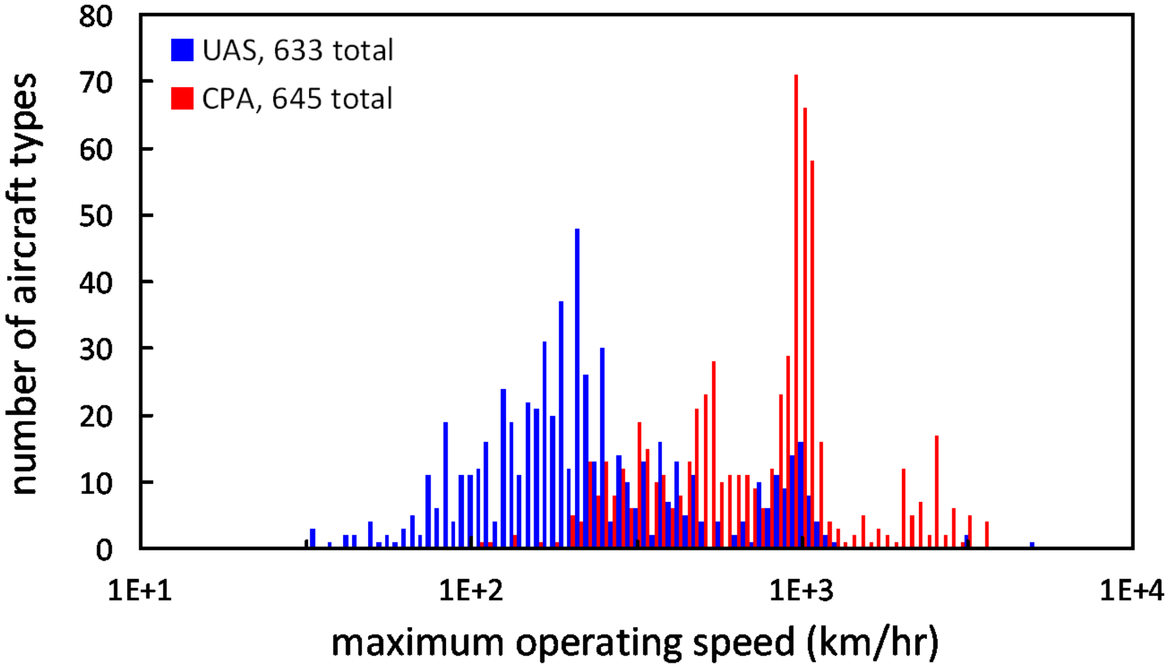

Figure 2 – Histogram of aircraft maximum operating speed [6]

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[6] UAS data supplied from a database compiled and maintained by the Defence Science and Technology Organisation (DSTO), Australia. CPA data obtained from Aviation Week and Space Report (http://www.aviationweek.com) and Jane's All the World's Aircraft (http://catalog.janes.com/catalog/public/index.cfm?fuseaction=home.ProductInfoBrief&product_id=96083).

For CPA a single certification category typically covers a broad range of applications for the particular type. Take, for example, a helicopter performing traffic surveillance over highly populated areas and inspecting power lines in remote areas. With the exception of specific payloads, pilot training and other operational approvals both operations could be conducted under the same COA. Consider the same applications being performed by an unmanned helicopter. A higher level of regulation would be required for the unmanned helicopter to be able to perform traffic monitoring over a populated area than that required to monitor power lines in remote regions. This is due to the dependency on the operational environment over-flown. A single UAS design may be used for a wide range of applications, from fire fighting, search and rescue over a remote region, tracking wildlife migrations, to persistent surveillance over a heavily populated area. As illustrated in the above example and as further discussed by Clothier *et al.* (2006; 2008), the different UAS applications may be required to meet different airworthiness standards. There may also be cases where the level of system airworthiness could be determined by the cost of system attrition, as opposed to the required level of reliability of an "equivalent" CPA performing the same operation (McGeer *et al.* 1999; McGeer 2007; Clothier *et al.* 2008). Hence, the "common philosophy" described by Haddon and Whittaker (2002) that underpins the certification of CPA may not be directly applicable to UAS.

For CPA, a standard COA is issued against a type certificate that prescribes a certification baseline (a fixed description of the aircraft components and their approved configuration). Some UAS, particularly small UAS, can be highly modular in their airframes, payloads and supporting equipment, allowing them to be quickly and radically tailored to a particular mission or environment. For example: fuselage and wing sections can be changed between operations. It may be difficult to define a single certification baseline for a UAS type and instead a large number of configurations may need to be defined as part of the type certification.

Finally, there is also a range of mitigation measures commonly used by UAS, for example, parachute recovery systems, frangibility, and self-termination systems, all of which may be implemented to reduce the risk that a UAS presents to the EOV over-flown. Within the CPA certification framework, such mitigation measures are evaluated on a case-by-case basis, as they are not traditionally considered part of the certification baseline for a standard COA. For UAS, these mitigation strategies may form a significant part of the safety case; therefore, a systematic method for accommodating them is needed.

2.3.1 Summary

Among others, McGeer and Vagners (1999), DeGarmo (2004), Hayhurst *et al.* (2006), Dalamagkidis *et al.* (2008b), and Clothier *et al.* (2006, 2008) identify numerous differences between UAS and CPA that challenge the suitability of an off-the-shelf approach for the regulation of UAS. The principal issue identified being the difference in the risks to be managed by the airworthiness regulations.

In summary, the level of airworthiness for civil UAS should be determined by the potential for harm to people and property over-flown, which is a function of the reliability of the system and a function of where it is operated. On the other hand, for CPA the level of airworthiness is principally defined by the risk to those onboard and is largely treated independent of the region over-flown (Haddon and Whittaker 2002). As a consequence, the application of the CPA airworthiness certification framework (*i.e.*, existing airworthiness certification categories and low-level regulations that are mandated independent of the area over-flown) to civil UAS could result in:

- the inequitable management of the risks across the different airworthiness certification categories (*i.e.*, different categories being managed to different levels of risk);
- different UAS operations over particular regions may be over-regulated, or worse, present an unacceptable level of risk [refer to illustrations of geospatial operational dependency provided in Weibel and Hansman (2004), Clothier and Walker (2006), and Dalamagkidis *et al.* (2009)]; or
- the imposition of unjustified costs to the UAS industry [as shown in the example presented by Clothier *et al.* (2008)].

Recalling that the primary purpose of air-safety regulations is to provide assurances in the safety of aviation at a justifiable cost to the industry; then the justification for applying the existing CPA certification framework to UAS on the basis of safety is significantly weakened. Other issues identified included unique UAS types, operations and risk profiles, and the dynamic configuration of some UAS.

To summarise, the CPA framework consisting of a small number of type-certification categories that are mandated independent of the operation may not provide the flexibility required to accommodate the spectrum of risk associated with the diversity of UAS, their operational environments, their applications, the reconfigurable nature of the systems, and potential mitigation strategies that are readily employed. The direct application of the existing CPA airworthiness framework may not ensure the consistent and equitable management of the risks associated with UAS operations and may not justify the costs imposed on the UAS industry and operators. It is important to note that the authors do not make the categorical assertion that the application of the existing CPA regulatory framework will not work for UAS, nor that existing low-level standards and regulations (*e.g.*, those contained in Part 25) are not relevant to UAS. Instead, the emphasis is on the identification of some limitations in the structure governing their application to UAS; and hence there is justification to explore an alternative structure (*i.e.*, an equivalent Part 21 regulation specifically for UAS).

3 A Risk-Management Approach

One approach to the regulation of airworthiness for UAS is to prescribe standards and regulations on a case-by-case basis dependent on the degree of risk of the operation. The approach has been referred to as a safety-target approach (Haddon and Whittaker 2002) and has been advocated for the regulation of smaller UAS (McGeer *et al.* 1999). The safety-target approach is justifiable and offers flexibility in the regulation of a diverse and dynamic industry. However, as discussed by Haddon and Whittaker (2002) a number of disadvantages arise. In particular, there are issues concerning the practicality of implementation and international standardisation and harmonisation. In addition, the absence of general prescriptive codes of low-level airworthiness regulations may lead to subjectivity as to how applicants interpret regulations and to inconsistencies in the evaluation of a safety case by the regulator. Consequently, trade-offs can exist between the:

1. flexibility afforded by the framework,
2. consistency of the regulatory oversight afforded, and
3. practicality of implementation.

To ensure a workable management strategy, this paper proceeds on the basis that it will be necessary to define fixed airworthiness categories within the diversity of UAS and their operations. However, it is the authors' belief that some of the defined airworthiness categories (*i.e.*, small UA and/or operations over unpopulated regions) may be more effectively regulated under a safety-target approach. Thus, in this paper the method of regulation (*i.e.*, whether a prescriptive code of regulation or safety-target) to be applied to each UAS airworthiness category is not prescribed. This paper instead addresses the crux of the problem, determining the framework of airworthiness categories (*e.g.*, what constitutes a small or low-risk UAS?) to which regulations and standards may then be tailored.

The purpose of airworthiness regulations is to provide assurances that the risks associated with the operation of UAS over populous areas are managed to an appropriate level. Secondarily, the process of defining these regulations should be cognisant of the potential costs imposed on the industry and the reduction in benefit to society. Solving such a multi-objective problem is the outcome of a risk-management process. According to internationally accepted standards (AS/NZS 2009), the implementation of the risk-management framework encompasses processes for the identification, assessment, evaluation, mitigation, communication and monitoring of a hazardous activity or technology. All components of the risk-management activity are relevant to the development of regulations for UAS; however, of specific interest in this paper are risk matrices, a tool widely used to evaluate risk.

Risk matrices provide a simple and clear framework for the systematic review of individual risks and portfolios of risk (Cox 2008). A risk matrix structures a quantitative or qualitative assessment of risk into its fundamental components: a loss outcome for a given scenario and a measure of the uncertainty in realising that scenario and outcome. A qualitative, continuous or ranked scale is defined for each component, and together they form the dimensions of the risk matrix. The columns of the risk matrix may be defined through the discretisation of the range of potential loss or the ordinal ranking of qualitative specifications of loss. Similarly, rows can be defined through the discretisation of the range of uncertainty or the ordinal ranking of qualitative specifications of uncertainty. It is important to preserve orthogonality in the specification of the two component axes, a property fundamental to the concept of risk as a multidimensional and multi-echeloned space (Kaplan *et al.* 2001; Clothier *et al.* 2011), as opposed to the more simplistic notion of risk as a single-dimensional measure. The output rows and columns then provide a contiguous and complete partitioning of the risk space with respect to its two components of loss/harm and uncertainty. These components are briefly described in the following sections.

3.1 Loss

Loss must be defined with respect to an EOV, a property/attribute of that entity, and an associated scale describing the level loss to the attribute (Clothier *et al.* 2011).

The specification of what constitutes loss will also depend on which stakeholder is performing the assessment. The "vector of loss" is the finite set of types of loss considered, which could include people, buildings, flora and fauna, and less tangible EOV to society. In defining the vector of values, the comprehensive management of the scenario may necessitate consideration of secondary hazards (*e.g.*, the ensuing collapse of a building, bushfire, or release of environmental contaminants) that may have an impact on different EOV. Under some circumstances the potential loss from secondary hazards could be greater than that associated with the occurrence of the primary hazard. In addition, a single hazard may have an impact across a range of EOV-attributes. For example, for a large UAS, the primary attribute of concern is typically the potential physical harm to a person or building. For a small UAS, striking a house may have a greater psychological impact on the occupant than that of a physical impact on the occupant or the building itself. The appropriate management of the UAS fleet may therefore need to consider a range of EOV and EOV-attributes for which loss may be registered (*e.g.*, for people this could include physical, psychological, or financial attributes).

Associated with each attribute is a continuous or discrete spectrum describing the degree of loss (Clothier *et al.* 2011). This spectrum may be expressed through quantitative or qualitative measures. A type of loss can be defined independent of a particular hazard (*e.g.*, for physical harm to people this could be no injury, minor injury, serious injury or fatality). The spectrum of loss should consider the potential loss to an individual EOV as well that to applicable EOV groups (*e.g.*, for physical injury to people, a spectrum of loss could be defined ranging from no injury to a single person through to multiple fatalities within a group of people). Society may also place a higher value on certain sub-types of EOV (*e.g.*, the distinction between first- and third-party people and property). Society subsequently may assign a higher level of loss to these EOV, despite the measure of the loss outcome (*e.g.*, a fatality) being the same.

3.2 Uncertainty

Klinke and Renn (2002) state that there is no established classification of uncertainty and that it is a topic of major debate within the risk community. For the purposes of this paper, the high-level concept of uncertainty is the state, even partial, of deficiency of information related to the understanding or knowledge of a loss outcome, inclusive of all of its components and its component-relationships [definition modified from ISO Guide 73 (2009)]. This definition encompasses uncertainty that arises through stochastic variation or a lack of knowledge of the scenario leading to the loss outcome, the particular level of loss, and the likelihood of its occurrence.

In a traditional risk matrix, the concept of uncertainty is narrowed to a measure of the potential of a loss event occurring. A range of measures can be used to describe potential, including probability (DoD 2000), likelihood (ISO 2009), frequency (Cox 2008), and expected value. These measures can be expressed on qualitative or quantitative scales. For example, MIL-STD-882D defines five probability levels: improbable, remote, occasional, probable, and frequent [refer to Table A-II of DoD (2000)]. To generalise, and without prescribing the particular method of assessment, this dimension can be thought of as a scale describing the potential for realising loss.

3.3 Risk

The cells of the matrix represent an assessment of the risk for a given scenario. Although widely used, we argue that the quantitative assessment of risk is not the arithmetic multiplication of loss and uncertainty. An assessment of risk is the Cartesian product of a level of loss (*i.e.*, a given column) by a degree of uncertainty (*i.e.*, a given row), and the output is the set of all ordered pairs of the elements from the two sets (*i.e.*, the ordered set of the pair-wise combination of the elements of the components of risk: those of loss and uncertainty). Thus, an assessment of risk may be thought of as a mapping within a multidimensional space (the generation of the cells of the matrix).

A particular assessment of the risk may be compared against risk criteria or ranked alongside assessments made for other scenarios. Systematic decisions may then be made as to the setting of controls and the appropriate treatment of the risks to ensure criteria are satisfied and that risks are managed equitably over the industry (*i.e.*, across all scenarios).

To summarise in the context of developing an airworthiness certification framework for UAS, a risk matrix provides a simple and accepted tool for the systematic assessment, comparison and ranking of risks (*e.g.*, those risks associated with the operation of different types of UAS over inhabited areas). This information may then be used to guide the setting of risk controls (*i.e.*, the tailoring of airworthiness regulations) to ensure risk criteria (*e.g.*, the ELOS objective) are met. Thus, it is the hypothesis of this paper that a risk matrix could provide the guiding principles necessary to structure an airworthiness certification framework for civil UAS.

3.4 Application to the Development of Part 21 Regulations for UAS

A risk matrix is used as inspiration for the structuring of an airworthiness certification framework and the resultant airworthiness certification matrix (ACM) is illustrated in Figure 3. The components (axes, cells and cell-values) of the ACM are:

1. *Type category of UAS* (the columns) – This dimension of the ACM is defined based on a discrete, continuous and increasing scale of loss (or consequence). Each type category thus represents a grouping of UAS where, given the occurrence of an unrecoverable, flight-critical failure and independent of any particular area over-flown, the potential magnitude of the resultant damage that could be caused to EOV over-flown is of a similar magnitude. An example of such a categorisation is provided by Clothier *et al.* (2010);

2. *Category of operational environment* (the rows) – This dimension of the ACM is defined based on a discrete, continuous ranking of potential for realising a degree of loss. Each category of operational environment thus represents a grouping of operational areas where the potential for realising loss, given a UAS impacting the area, is of a similar magnitude;

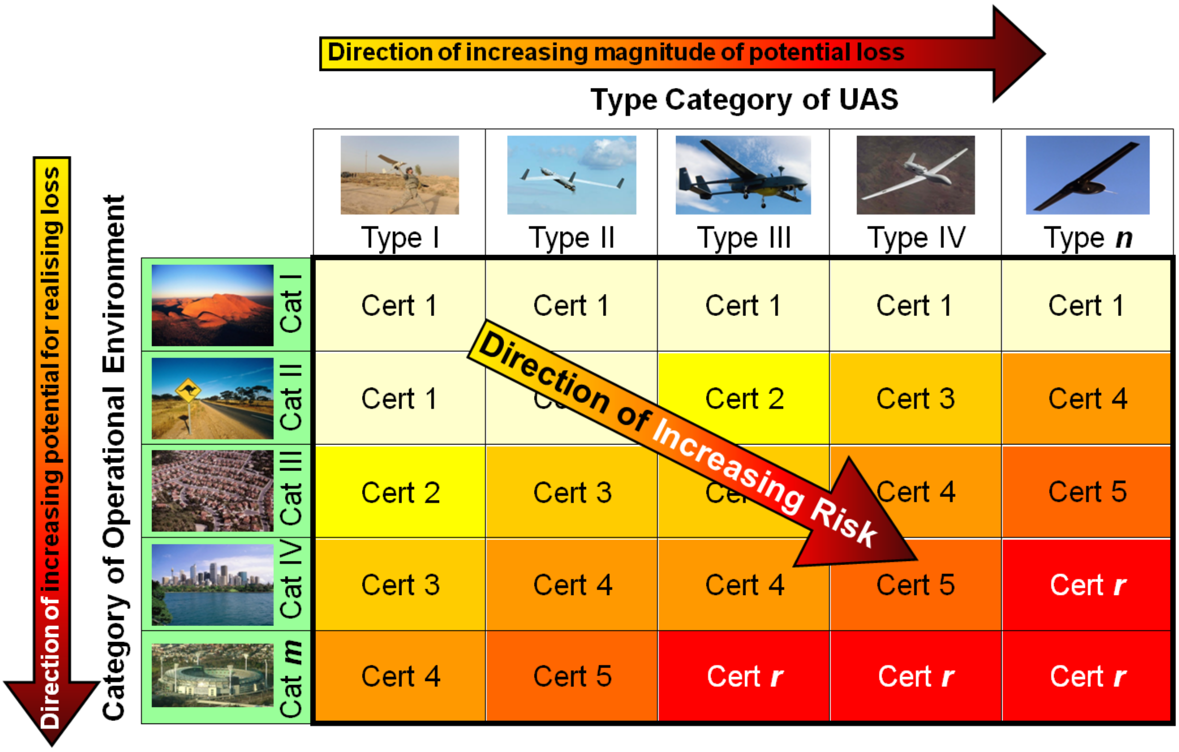
3. *Operational scenarios* (the cells) – This component of the ACM is analogous to the assessment of risk within a risk matrix, which is determined by the Cartesian product formed over the sets of row and column elements. The Cartesian product is used to construct a matrix with a finite number of cells ($\boldsymbol{q}$), determined by the number of rows ($\boldsymbol{m}$) multiplied by the number of columns ($\boldsymbol{n}$). Thus, each cell represents a unique operational scenario defined by the combination of a specific UAS-type category together with a specific category of the operational environment; and

4. *Airworthiness certification categories* (the values assigned to the cells) – This component is determined first by an assessment of the risks associated with a given operational scenario (*i.e.*, the given cell) and, then, an assignment of the operational scenario to one of $\boldsymbol{r}$ certification categories, based on this assessment, where $1 \leq \boldsymbol{r} \leq \boldsymbol{q}$.

In general, and by virtue of the definition of the values assigned to the axes, the level of risk associated with each scenario (and subsequently the certification categories assigned to them) defined in the lower-right quadrant of the ACM is higher than the levels of risk associated with those scenarios/categories situated towards the upper-left quadrant.

In order to map the type of UAS and operational area to the spectra of increasing loss and potential, respectively, it is necessary to define a common set of hazards and EOV. As will be described in the following sections, the condition for independence between the rows and columns can be maintained through conditional modelling.

In summary, the ACM provides a systematic method for partitioning the numerous possible combinations of UAS types and operations into a finite number of scenarios. Certification categories are then assigned to each scenario (cell) based on the assessed levels of risk.



	Type I	Type II	Type III	Type IV	Type ***n***
Cat I	Cert 1	Cert 1	Cert 1	Cert 1	Cert 1
Cat II	Cert 1	Ce	Cert 2	Cert 3	Cert 4
Cat III	Cert 2	Cert 3	Ce	Cert 4	Cert 5
Cat IV	Cert 3	Cert 4	Cert 4	Cert 5	Cert ***r***
Cat ***m***	Cert 4	Cert 5	Cert ***r***	Cert ***r***	Cert ***r***

Figure 3 – Illustration of an airworthiness certification matrix for civil UAS (defined for a given type of loss outcome and a given stakeholder perspective)

3.4.1 UAS-Type Categories (The Columns)

As illustrated in Figure 3, each of the ***n*** columns of the ACM represents a finite UAS-type category. In a traditional risk matrix, this dimension represents a scale of increasing loss, consequence or harm resulting from a mishap. For example, Table A-I in MIL-STD-882D (DoD 2000) defines four levels of severity: negligible, marginal, critical, catastrophic. The basis for defining UAS-type categories is a spectrum describing the potential magnitude of loss that the different types of UAS may cause. This spectrum is one of conditional and hypothetical loss that is independent of the characteristics of a particular operational area (*i.e.*, preserving the orthogonality of the two component axes of the matrix). More simply put:

Given the occurrence of an unrecoverable flight-critical failure, what is the maximum degree of loss the UAS could cause, irrespective of where it crashed?

Each type category subsequently describes a grouping of UAS where the magnitude of potential loss due to a mishap is within some pre-defined bounds, irrespective of where the UAS is operated. The type categories must be disjoint (*i.e.*, provide an unambiguous classification of UAS) and together provide complete and continuous coverage of the range of plausible loss (*i.e.*, cover the spectrum of UAS types and their ability to cause loss). The fundamental concept of loss as a basis for categorisation may be observed in current CPA type categories (*i.e.*, the classification criterion of the number of people onboard); however, this basis is not applied consistently across the CPA categorisation scheme. Thus, pivotal to the specification of type categories for use within the proposed ACM is an understanding of the potential types and levels of loss associated with UAS operations.

As described in §3.1, it may be appropriate to consider more than just the potential loss to people. With respect to UAS operations over inhabited areas, the spectrum should cover the range of potential loss to an individual EOV as well that to applicable EOV groups (*e.g.*, for physical injury to people, a spectrum of loss could be defined ranging from no injury to a single person through to multiple fatalities within a group of people).

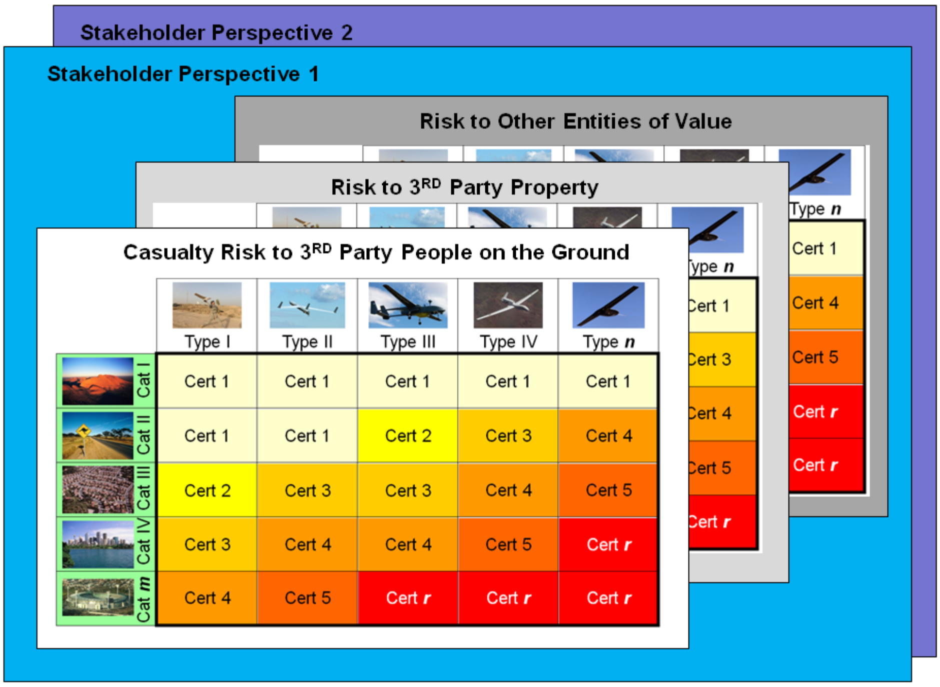
3.4.1.1 Categorisation of Loss

Proceeding on the premise that a workable airworthiness certification framework requires some degree of categorisation of the diversity of UAS types to be operated, then a mechanism for discretising the spectra of loss associated with this diversity is needed.

Predominantly, the process used in the specification of existing categorisation schemes has been subjective, providing little or no objective justification for the particular partitioning chosen. Often these schemes reflect the needs (and commercial desires) of the particular stakeholders involved. Dalamagkidis *et al.* (2009) subjectively assign categories based on the "natural classification" observed between MTOW and a derived measure of reliability. Given the potentially significant influence type categories will have in shaping the future of the UAS industry, a transparent and defensible strategy for determining a suitable number of categories and the classification criteria that define each category is needed. One such method, concerned with the risk of human casualties is discussed by Clothier *et al.* (2010).

Typically, categorisation processes seek to collapse the distinct spectra of loss outcomes (as described in the previous section) into a single loss dimension for which discrete categories are then defined. For example, the loss dimension defined in MIL-STD-882D (DoD 2000) includes the distinct loss outcomes to people, property and the environment. The combination of these outcomes onto a single dimension does not preserve the distinct likelihood of realising each individual loss outcome. In addition, such processes represent a subjective judgement on the comparative value that stakeholders place on the different EOV [*e.g.*, in MIL-STD-882D (DoD 2000) the mishap severity category of catastrophic equates the loss of a human life to that of permanent total disability, to irreversible environmental damage, and to the loss of more than US$1 million].

In contrast, the approach proposed in this paper seeks to preserve the separate dimensions of loss and acknowledge subjectivity in the specification of loss. The matrix illustrated in Figure 3 is defined for a particular stakeholder perspective and type of loss outcome; however, the dimension of loss may also be defined by the distinct spectra of loss outcomes specified by each individual stakeholder involved in the decision-making process. The result, illustrated in Figure 4, is a set of matrices describing the loss outcomes of concern for each particular stakeholder.



	Type I	Type II	Type III	Type IV	Type *n*
Cat I	Cert 1	Cert 1	Cert 1	Cert 1	Cert 1
Cat II	Cert 1	Cert 1	Cert 2	Cert 3	Cert 4
Cat III	Cert 2	Cert 3	Cert 3	Cert 4	Cert 5
Cat IV	Cert 3	Cert 4	Cert 4	Cert 5	Cert *r*
Cat *m*	Cert 4	Cert 5	Cert *r*	Cert *r*	Cert *r*

Figure 4 – Preservation of the different types of loss

3.4.1.2 Summary

Currently, there is no consensus on the definition of type categories for UAS (DeGarmo 2004; Dalamagkidis *et al.* 2008b). Many of the existing schemes have not been defined specifically for the purposes of certification. For a comprehensive review of UAS categorisation schemes refer to Nas (2011). In addition, there is no consensus on a process for defining a suitable scheme (DeGarmo 2004). As described by DeGarmo (2004), consensus on a particular UAS-type-categorisation scheme is fundamental to the progress of regulations.

Under the proposed ACM, a type-categorisation scheme for UAS should be defined based on the qualitative or quantitative specification of the potential levels of loss to people, property, and other EOV over-flown. To preserve the generality of the proposed ACM framework, the vector of values has not been prescribed. Instead (and as discussed in Sections §3.1, §3.4.1 and §3.4.1.1) the specification of type categories for UAS may need to consider a range of loss outcomes in order to appropriately manage the diverse risk profile associated with UAS and their operations.

Finally, there will be factors that may not be directly related to loss that need to be taken into consideration. For example, it may be practical to distinguish between rotorcraft UAS and fixed-wing UAS (as is done in the airworthiness framework for CPA) due to the unique aspects of each type and the availability of existing low-level codes of regulation that could be applied. Such factors are related to the context of practical regulation and should be second-order considerations in the refinement of the type-categorisation scheme.

The above sections briefly introduce some of the issues that need to be considered in the definition of type categories for UAS. A suitable process for defining these categories is described by Clothier *et al.* (2010).

3.4.2 Operational Categories (The Rows)

As illustrated in Figure 3, each row of the ACM represents one of ***m*** categories of operational environment. The definition of the operational categories can be considered as representative of a spectrum of increasing potential for loss that is determined independent of the characteristics of any particular type category of UAS. More simply put:

> *Irrespective of the type of UAS that comes to earth, how susceptible is an area to experiencing loss?*

Like the specification of type categories, the categories of operational environments should be disjoint (*i.e.*, provide an unambiguous classification of the different types of areas over-flown) and together provide complete and continuous coverage of the range of possible areas over-flown (*i.e.*, cover the entire spectrum of operational areas). It is important to note that independence between the specification of operational and type categories (the two component-dimensions of the ACM) is maintained, as the assessment is for all types of loss not specific to a particular type category of UAS. In essence, the operational categories are defined based on the “susceptibility” of the area to loss given a UAS mishap.

3.4.2.1 Categorisation of Operational Environments

Under the ACM approach, the different operational environments need to be mapped to a scale of increasing potential for harm independent of the particular type of UAS flying overhead. The characterisation of this axis of the ACM is a complex problem requiring knowledge of the susceptibility, number and distribution of different types of EOV for which loss could be registered. Once mapped to a common scale of potential, the operational environments can be grouped into a finite number of categories.

The primary EOV of concern with respect to safety is people, and this provides the basis for existing qualitative categorisation schemes identified in aviation literature. CASA describes a populous area as an area of:

> *…sufficient density of population for some aspect of the operation, or some event that might happen during the operation (in particular, a fault in, or failure of, the aircraft or rocket) to pose an unreasonable risk to the life, safety or property of somebody who is in the area but is not connected with the operation.*
>
> CASR Part 101.025 (CASA 2004)

Federal Aviation Regulations (FAR 2009) and supporting material yield numerous terms for the description of operational areas: densely populated, congested, other than congested, unpopulated, sparsely populated, and over water. However, no prescriptive definitions are provided. The RTCA Special Committee 203 (SC-203) for Unmanned Systems defines four qualitative categories for the classification of operational areas, specifically:

1. Densely populated – described as urban and suburban areas, particularly with residential developments.
2. Sparsely populated – generally rural areas and agricultural regions where individual homes are separated by large tracts of land.
3. Unpopulated – uninhabited areas.
4. Open-air assemblies of people – described as outdoor gatherings without overhead shelter.

DO-304, p.I-18, RTCA (2007)

Prevalent factors in the above definitions are the distribution of the population within the area and the degree of sheltering provided. Thus the simplest specification of operational areas could be:

1. Populated – given a UAS impacting the area, the potential for loss is greater than zero. *E.g.*, this would be any area where an EOV is present.

2. Not populated – given a UAS impacting the area, the potential for loss is approaching zero. *E.g.*, a sanitised test range, a desert, or the high seas.

The alternative approach is to not explicitly classify operational areas into a predefined set of categories. As illustrated by Weibel and Hansman (2004), Clothier *et al.* (2007), and Dalamagkidis *et al.* (2009), it is possible to use population and other geographical information system (GIS) databases to gain a continuous quantitative and geo-referenced characterisation of the distribution of an EOV for every operational area considered. The definition and number of operational areas is instead determined by the resolution of the data available as opposed to a finite number of subjectively defined categories.

Defining a greater number of categories provides greater resolution of the diverse areas available for UAS operations. However, there are disadvantages in having a large number of operational categories. Under the proposed framework, UAS issued with a COA in a given airworthiness category cannot be flown over areas where a higher category of airworthiness certification is required. As a consequence, "pseudo" airways or pockets of UAS activity may eventuate (*i.e.*, similar to how concentrations of VFR air traffic can develop due to the distribution of controlled airspace). The greater the number of operational categories defined, the narrower and the denser these airways and pockets of UAS operations can become. In addition, the greater the number of categories defined, the more sensitive the qualitative schemes are to diverse interpretation and hence the greater the need for a quantified categorisation scheme. A greater number of operational categories can also permit UAS operations over areas where previously they were prohibited from flying (*i.e.*, through the specification of sub-categories within the existing category of "populous area"). Therefore, careful consideration should be given to the specification of the operational categories, as they can influence how the airspace system is used by UAS.

Finally, a practical implementation of the airworthiness framework requires the operational categories to be identified in navigation charts (*e.g.*, similar to the depiction of built-up areas in CPA navigation charts). For UAS, it may be appropriate to develop separate charts representing the category of operational area assigned to geographic regions. The more categories there are, the more complicated such charts would become. Hence, the challenge is to specify the optimal number of operational categories that adequately encapsulates the diversity of operational areas and, in turn, provides a workable regulatory outcome.

Finally, there a number of other factors influencing the potential for causing harm to EOV and hence the categorisation of operational environments. These include, for example, factors influencing the response of an individual EOV to a mishap (*e.g.*, the demographic of the population: age and health, *etc*.), the tendency for clustering within a population of EOV, which is needed to characterise the likelihood of a mishap resulting in multiple causalities, and sheltering [*e.g.*, the population-sheltering models used in the Columbia accident investigation (Lin *et al.* 2003)]. The susceptibility and hence potential for an operational environment to experience loss could also change with the time of day (*e.g.*, due to changes in the number and distribution of people exposed).

3.4.2.2 Summary

Under the proposed framework the categorisation of operational environments should be based on the potential for the realisation of loss given a UAS impacting that area. As described above, a range of factors characterise the conditional potential for loss in a given environment. A method for categorising these operational environments is also needed. The specification of these categories requires the consideration of broader issues relating their potential impact on the operation of UAS and other airspace users and the practical issues associated with the promulgation and management of regulations.

3.5 The Operational Scenarios (The Cells)

Each cell of the ACM describes a unique risk scenario defined by the combination of a specific category of operational area (a row) with a specific UAS-type category (a column). The complete set of ***q*** operational scenarios is defined by the Cartesian product of the two component axes of loss and uncertainty.

The matrix-based approach reduces the continuous spectrum of scenarios to a finite number of discrete, contiguous and organised categories. The structure of the matrix provides a simple mechanism for systematically relating the operational scenarios to the fundamental components of civil aviation regulations (*i.e.*, regulations pertaining to the design, maintenance and manufacture of aircraft, and the regulations pertaining to the operation of an aircraft).

The next step in the process is to assign each operational scenario to an airworthiness certification category. Diagrammatically, and referring to Figure 3, this is the process of determining the colour of each cell within the matrix.

3.6 The Airworthiness Certification Categories (The Cell-Values)

Risk is often expressed as the Cartesian product of its components of loss and the potential for realising each specified loss. Each cell may be characterised by:

1. a set of loss outcomes (scenarios), and
2. an associated set of measures describing the uncertainty in the realisation of these loss outcomes.

These assessments may be quantitative or qualitative and may be made for each combination of UAS-type and operational category (*i.e.*, for each operational scenario defined by the cells of the matrix). Typically, a single dimension is used to describe the loss and uncertainty components of the measure of risk. For example, Table A-IV in MIL-STD-882D (DoD 2000) defines a finite qualitative scale for assessing risk: low, medium, serious, and high. Quantified measures (*e.g.*, the expected frequency) are also used to reduce the multi-dimensional measurement problem to that of a single measure. A common example is the expected number of casualties per flight hour, as used in Grimsley (2004), Weibel and Hansman (2004), and Clothier and Walker (2006). However, as described by Paté-Cornell (1994) and the Range Commanders Council (RCC, 2007), the effective management of the risks should include measures of the:

1. individual risk (IR) to ensure that no individual entity is disproportionately exposed (Jongejan *et al.* 2006);
2. collective risk (CR) to ensure the levels of risk, when aggregated across the entire population of entities, are managed to an acceptable level; and
3. societal risk (SR) (Jongejan *et al.* 2006), also referred to as catastrophic risk (RCC 2007), to reflect society's adversity to mishaps that result in a larger magnitude of consequence.

Each operational scenario then needs to be assigned to a certification category. As discussed previously, this assignment should be based on the levels of risk determined for each operational scenario. This ensures that operational scenarios that present comparable levels of risk are required to demonstrate a comparable level of airworthiness (*i.e.*, are subject to the same body of airworthiness regulations and standards).

The first step in this assignment process is to determine the number of certification categories required, ***r***. The minimum number of airworthiness categories is one. This is the case where the same category of airworthiness is assigned to all operational scenarios and represents the undesirable "one-size-fits-all" regulatory approach. In effect, this approach prescribes the same level of airworthiness regulation irrespective of the degree of loss a UAS is capable of causing and irrespective of whether EOV are exposed or not. The maximum number of airworthiness categories is determined by the dimensions of the airworthiness matrix (*i.e.*, ***q***). The more airworthiness categories defined, the more tailored and flexible the airworthiness regulatory framework is in its management of the diversity of UAS and their operations. Standards and regulations must be defined for each airworthiness category; hence, the greater the number of categories, the greater the regulatory development task and the more difficult it becomes to manage.

To summarise, there is no ideal number of categories; it will depend on a number of trade-offs as identified above. In addition, there are many subjective issues specific to the context of the promulgation of a practical and workable regulatory framework that will influence the setting of the number of airworthiness categories. A process is then needed to assign each operational scenario to the airworthiness categories.

3.6.1 Assigning Airworthiness Categories

The basic principle for assigning airworthiness categories is to determine which cells of the airworthiness matrix pose a **comparable** level of risk and to then group these into a single airworthiness category so that a consistent level of regulation may be applied.

A risk matrix [*e.g.*, Table A-III of MIL-STD-882D (DoD 2000)] provides one method for mapping an operational scenario with a given “mishap severity” (Table A-I) and a given “mishap probability” (Table A-I) to a “risk-assessment value” (A-IV). For example: a mishap of catastrophic severity that is probable is assessed as a high risk (DoD 2000). Each operational scenario within the ACM with a comparable risk assessment (*e.g.*, all those cells assigned as being low risk) could then be assigned to the same certification category (*e.g.*, Cert 1), and so forth for all other levels defined by the qualitative scale describing the risk-assessment value (DoD 2000). For quantitative risk assessments presented on a continuous scale, one approach is to try to observe natural breakpoints within the assessments of risk and to use these breakpoints to delineate the airworthiness categories (*e.g.*, mathematical clustering approaches). The process is complete when all operational scenarios (*i.e.*, cells) within the matrix have been assigned to one of the ***r*** airworthiness categories.

Given the mapping of each cell of the matrix to a particular airworthiness category, the final step is to tailor regulations to each category.

3.7 Tailoring of Regulations

The primary purpose of safety regulations is to mandate controls that ensure that risk is managed to an acceptable level. Under the ELOS objective, the tailoring of UAS airworthiness regulations is the process of specifying standards particular to each airworthiness category that provide assurance that levels of risk are, at a minimum, equivalent to those of CPA operations. Thus, assessments of the *de facto* risk levels for CPA should be used to define the *de manifestis* risk criteria for UAS (*i.e.*, the existing CPA risk levels define the limit on what is considered tolerable for UAS). As discussed in §3.6, the UAS risk criteria should be specified in terms of measures of the IR, CR and SR for each loss outcome of concern (*i.e.*, human casualty, damage to buildings, *etc.*).

The primary focus of airworthiness regulations is to control the potential occurrence of flight-critical failures. In this paper, a failure is used to describe any state within the UAS-airworthiness system (*e.g.*, people, processes, and equipment that are components of the design, manufacture, maintenance, and operation of the UAS) that, when realised, can lead to the primary hazard of a UAS impacting the ground during flight. Examples include a failure of the navigation system, a latent error in flight-control software, incorrect maintenance procedures leading to a structural or propulsion failure in flight, or incorrect operator commands that lead to a controlled flight into terrain. All UAS assigned to the same airworthiness certification category are ultimately subject to the same body of airworthiness regulations and hence should exhibit a comparable rate of flight-critical failure. The tailoring of regulations is the process of ensuring the potential for a flight-critical failure for a given certification category, ***X***, satisfies the following relationships:

$$\begin{aligned} IR_{CPA} &\geq IR_X \\ CR_{CPA} &\geq CR_X \\ SR_{CPA}(i) &\geq SR_X(i) \quad \forall\, \boldsymbol{i} \geq 0, \end{aligned} \qquad \text{Equation 1}$$

where IR_{CPA}, $CR_{CPA,}$ and SR_{CPA} are the measures of individual, collective and societal risk based on the safety performance of CPA, respectively. IR_X, $CR_{X,}$ and SR_X are the measures of individual, collective and societal risk determined for the given airworthiness category ***X***, respectively, and ***i*** is the plausible domain of a spectrum of loss outcomes.

The particular method for solving the relationships given in Equation 1 depends on the measure used to describe each risk criterion and the model used to relate the potential for a flight-critical failure to each risk criterion. A description of this process specific to the definition of Part 1309 regulations for civil UAS is provided in the next section. However, it is important to note that the same fundamental process can be used to tailor regulations relating to any aspect of UAS regulation, including maintenance, personnel training and licensing, and software-assurance levels [*e.g.*, the tailoring of software-assurance levels defined in DO-178B (RTCA 1992)].

3.7.1 Example – Tailoring of Part 1309 Regulations

Part 1309[7] regulations [*e.g.*, FAR Part 23.1309 or FAR Part 25.1309 (FAR 2009)] define "average failure probability objectives" to guide the design of a system or the modification or installation of parts to existing systems. These objectives are expressed as allowable qualitative/quantitative probabilities assigned to individual failure conditions (FAA 1988, 2009).

With the exception of a draft kinetic energy-based approach proposed by the Joint Authorities for Rulemaking on UAS (JARUS 2009), the default approach for the definition of Part 1309 regulations for UAS is to assign the same system-failure-probability objectives as used for CPA [*c.f.*, NATO (2009)]. This approach is based on the premise that an equivalency in the average probability of failure will lead to an equivalency in safety. Reliability does not directly equate to safety and thus these approaches fail to recognise the fundamental distinction that the primary EOV at risk are no longer onboard the aircraft, but rather are external to the UA. In contrast, this paper advocates the tailoring of Part 1309 regulations through the use of a simple risk model that relates safety criteria (measures of potential loss determined for CPA) to measures of the potential for a flight-critical-failure event. In Equation 2, this relationship is expressed as the potential of a loss event ($\boldsymbol{ELOS_{CPA}}$), which is measured with respect to each of the ELOS criteria specified in Equation 1, the potential occurrence of a flight-critical failure (***FAILURE***), and the potential for loss given the occurrence of a flight-critical-failure (***LOSS | FAILURE***).

$$ELOS_{CPA} = FAILURE \times LOSS | FAILURE \qquad \text{Equation 2}$$

Examples of a model-based approach are presented by McGeer *et al.* (1999), Grimsley (2004), Weibel and Hansman (2004), Clothier and Walker (2006), Clothier *et al.* (2007), and Dalamagkidis *et al.* (2008a, 2009). These existing models relate the expected number of casualties per flight hour (a measure of CR) to the expected number of failures per flight hour. It is recommended that similar models relating measures of the IR, CR and SR to measures of system reliability also be developed. Irrespective of the particular measure, the general process for tailoring average failure probability objectives, as described in the following sections, is the same.

3.7.1.1 Specifying the ELOS Objective ($ELOS_{CPA}$)

In accordance with the ELOS objective, the Part 1309-equivalent regulations for UAS must ensure a minimum level of safety equivalent to that exhibited by CPA. This equivalency may be described in terms of the specification of a loss outcome and a measure of the potential of realising that outcome for CPA operations (*i.e.*, a measure of risk). For example, McGeer *et al.* (1999), Grimsley (2004), Weibel and Hansman (2004), Clothier *et al.* (2006, 2007), and Dalamagkidis *et al.* (2008a, 2009), specify equivalency in terms of a single measure of the expected number of casualties per flight hour, CE_{CPA}.

One approach to specifying this benchmark is to conduct an analysis of CPA accident databases, *e.g.*, as presented by Weibel and Hansman (2004) and Clothier and Walker (2006). These figures represent criteria aggregated across the entire fleet of CPA. As described in paragraph *13.c* of AC-23.1309-1D (FAA 2009), processes are needed to disaggregate these criteria to individual aircraft and then to a finite number of failure conditions. The outcome of these processes is a set of measures of IR, CR and SR, normalised to individual aircraft-failure conditions.

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[7] Although most commonly referred to as "Part 1309", these regulations are actually *sections* of the regulations contained in *Parts* 23, 25, 27 and 29 (*e.g.*, FAR Part 23.1309, FAR Part 25.1309). To save confusion with other usage of the term "section", in this paper these regulations are referred to as "Part 1309".

3.7.1.2 Modelling the Occurrence of a Flight-Critical Failure (*FAILURE*)

A model for describing the occurrence of flight-critical failures is needed. The most common approach (Grimsley 2004; Weibel and Hansman 2004; Clothier *et al.* 2007; Clothier *et al.* 2008; Dalamagkidis *et al.* 2008a, 2009) is to assume that the occurrence of failure events may be modelled by an exponential distribution with a constant rate parameter, λ (usually expressed as the expected number of failures per flight hour or per mission). A large number of complex factors challenge the assumption of a constant failure rate. For example, the rate of failure will change with increased experience in the operation of a given UAS type [*e.g.*, the burn-in or infant-mortality period evident in *Figure A-2* of OSD (2009)] and will depend on the type of system component being modelled (*e.g.*, crew are more likely to fail if fatigued or stressed) and on aspects specific to an operation (*e.g.*, manoeuvring flight or weather conditions). However, within the context of Part 1309 regulations, the output needs to be the average failure rate (referred to as an average failure probability), which is equal to λ, for small values of λ.

3.7.1.3 Potential for Loss Given a Flight-Critical Failure (*LOSS* | *FAILURE*)

The second component of a model-based approach is the specification of the potential for loss given the occurrence of a flight-critical failure. This is a complex model that may be broken into sub-models describing: the potential location of impact, the conditions on impact for a given type of flight-critical failure, the exposure and distribution of EOV, the stress incident on EOV, and the strength-response of EOV to an incident stress.

McGeer *et al.* (1999), Grimsley (2004), Weibel and Hansman (2004), Clothier *et al.* (2007, 2008), and Dalamagkidis *et al.* (2008a, 2009) present simplified models for determining measures of the casualty expectation associated with the operation of UAS over populated areas. Similar models need to be determined for each of the ELOS criteria that relate the occurrence of a flight-critical failure to measures of the IR, CR, and profiles describing SR. These models must be developed for each type of loss outcome of concern (*e.g.*, fatal injury of people, damage to property, and damage to the environment).

The evaluation of these models should be specific to each operational scenario. For example, the parameters input to the casualty-expectation model presented in Clothier *et al.* (2007) include the population density and the dimensions of the UA. The values of these input parameters may depend on the particular row (*i.e.*, the operating environment over-flown) and column (*i.e.*, type category of UAS).

3.7.1.4 Solving for the Average Failure-Probability Objectives

The average failure-probability objectives for UAS may be determined by combining Equation 1 and 2. Specifically, the average failure-probability objectives may be determined by rearranging and solving Equation 2 for the average flight-critical-failure rate against each of the measures used to describe the ELOS objective (*i.e.*, IR, CR, and the profile characterising SR, Equation 1).

A conservative management approach would then select the most stringent of the average failure-probability objectives determined for each certification category. This defines the upper limit of the average probability per flight hour for failure conditions that result in the worst loss outcome (*e.g.*, defined as “catastrophic” conditions in Part 1309 regulations). Based on this value, average probability objectives may then be further apportioned to failure conditions that would result in loss outcomes of lower concern. Existing definitions of failure conditions may require revision. It is recommended the categories of failure conditions be defined based on the degree of controllability of the UA given the failure and hence the ability of the system to avoid an impact in an inhabited area.

3.7.1.5 Summary

The outcome of the generalised process described in the previous sections is a tailoring of the Part 1309-equivalent regulations to each of the certification categories defined in the certification matrix. The approach is flexible in that regulations may be defined in consideration of the diversity of systems and operational environments. The approach is systematic in that the structure of the risk matrix and the models used ensure a consistent specification of regulations in accordance with the degree of risk associated with each operational scenario. Finally, the approach is defensible in that the resultant regulations can be objectively verified against the overarching requirement for an ELOS to CPA.

3.8 Accommodating Mitigation Approaches

As the primary risks from UAS operations are to EOV external to the system, it is possible for UAS to employ a range of mitigation strategies, both operational and technical, to reduce the levels of risk. Examples include parachute recovery systems, frangible systems, autonomous recovery and autonomous flight-termination guidance systems [*e.g.*, Mejias *et al.* (2009)]. Within the airworthiness framework for CPA, such mitigation systems are addressed on a case-by-case basis (*e.g.*, the parachute flight-termination system used onboard Cirrus aircraft). However, for UAS, mitigation systems are common; hence, a systematic method of incorporating them into the airworthiness certification framework is desirable.

Weibel and Hansman (2005) use an event-tree model to describe the effectiveness of mitigation measures. In this model, mitigations influence the probability of:

1. entering a hazardous state (in terms of formal causal-hazard analysis this is a flight-critical-failure state),
2. recovering from the chain of failure states and hence prevention of the immediate realisation of the hazard state,
3. reducing the effects of the mishap, or
4. combinations of the above.

Using this framework, the effectiveness of different mitigation strategies may be systematically defined in terms of permissible movements within the certification matrix. A mitigation strategy may be assessed as to whether it contributes to:

1. a reduction in the plausible level of loss (*i.e.*, representative of a horizontal movement within the matrix – *e.g.*, frangible systems),
2. a reduction in the susceptibility and hence potential of a given operational area to register loss (*i.e.*, representative of a vertical movement within the matrix – *e.g.*, operating only at night when most people are indoors and sheltered), or
3. a combination of both (*i.e.*, representative of a diagonal movement within the matrix – *e.g.*, a controlled parachute flight-termination system that reduces kinetic energy and may be used to control where the UAS comes to earth).

Mitigation systems may permit certification in a lower airworthiness category, greater operational freedom for a given certification category, or a combination of both. It is important to note that technical mitigation systems only address a subset of the possible failure conditions leading to an occurrence of the primary hazard and may introduce new failure conditions into the system. Hence, standards and regulations are required for the certification of technical mitigation systems. A mechanism for the certification of mitigation systems could be provided by the issuing of a supplementary type certificate (STC) to a UAS. The STC could also include details of any permissible operational dispensations.

3.9 Summary

Unlike in the CPA certification framework, in the proposed ACM, the type category alone does not define the airworthiness category. Instead, the framework may be defined so as to prescribe airworthiness standards and regulations through consideration of both the system (type) and its intended operation (environment). A single UAS type may therefore be certificated in one or more airworthiness categories. Similarly, a single airworthiness category may be applicable to more than one type category of UAS. The objective tailoring of standards and regulations to the airworthiness categories is based on the level of risk and the need to satisfy the ELOS objective.

It is likely that existing CPA prescriptive codes of airworthiness standards and regulations (*e.g.*, Part 23, Part 25, and Part 27) will be mandated for higher categories of airworthiness (*i.e.*, airworthiness categories assigned to cells in the lower-right corner of the ACM illustrated in Figure 3). However, airworthiness categories that present lower relative risk (*i.e.*, airworthiness categories assigned to cells closer to the upper-left corner of the matrix illustrated in Figure 3) would necessitate less stringent regulation (*e.g.*, regulation under a safety-target approach).

Finally, the ACM has some added practical advantages. Firstly, the structure is easily visualised, thus providing a simple tool for conveying airworthiness requirements. In addition, the compartmentalised structure facilitates the phased development and introduction of airworthiness regulations. Regulatory development efforts could therefore be prioritised according to industry needs and those areas of immediate risk or to capitalise on the availability of existing standards and regulations.

3.10 Challenges to the ACM Approach

Cox (2008) identifies a number of limitations in the use of risk matrices. Although the mathematical analysis provided by Cox is based on the more restrictive position that risk is measured through an arithmetic multiplication of its components, general issues may be identified from the discussion provided.

As with any assessment of risk, there is the difficulty of incorporating events with uncertain outcomes. As described in Section §3.2, the concept of uncertainty has dimensions that are not captured in a typical risk matrix. These include the aleatory uncertainties associated with the measure, as well as the complex epistemic uncertainties associated with the model, process and data used in an assessment, regardless of whether it is qualitative or quantitative. An additional dimension of the matrix providing a mapping of the broader concept of uncertainty in the assessment could be envisaged [insight into how this could be structured is provided by Stirling *et al.* (1998), Figure 3].

Cox (2008) also states that personal judgements and the potential for inconsistencies "…implies that there may be no objectively correct way to fill out a risk matrix." All assessments of risk are inherently and inescapably subjective. Such subjectivities are not specific to the assessment structure provided by a risk matrix. On the contrary, risk matrices may assist in distinguishing between the sources of subjectivity within a risk assessment and hence reduce potential stakeholder conflicts. For example, if stakeholders could reach agreement on the specification of the dimensions of the matrix then the subjectivities lie in the assessments of the subsequent quantification of the loss and its associated measure of likelihood or probability. An encompassing component of any assessment is the perspective of the stakeholder. Thus, a likely input to any decision-making process is a set of matrices, with each matrix representing a particular stakeholder's assessment of the risks. The mapping of all matrices to a single ACM is the output of a deliberative and subjective process involving all stakeholders.

Throughout the previous section, the specification of a matrix structure necessitated that a number of trade-offs be made. These primarily relate to the scope of assessment and the resolution of the dimensions. In addition to these trade-offs, there is the final practical issue of international harmonisation in standards and regulations. The proposed framework facilitates a tailoring of regulations to the industry, operational environment, regulatory needs, and the political and social demands of a specific nation. For example, Australia has a unique operating environment, unique applications, and a unique social and cultural attitude towards aviation technologies (and hence risk acceptance). Although the matrix approach offers flexibility in the tailoring of airworthiness regulations to a specific nation, incompatibilities may arise between airworthiness frameworks developed for different nations and hence hinder UAS operations in international airspace. To address this, regulators could either seek international consensus on the specification of the matrix or could define compliance matrices that provide a mapping between the different airworthiness categorisation schemes.

4 Application to Airspace Integration

The risk matrix-approach could also be used to structure regulations governing the integration of UAS operations within civil airspace.

The primary hazard governing airspace integration is that of a midair collision with another aircraft carrying people. A sense-and-act capability equivalent to, or better than, the see-and-avoid functionality provided by a human pilot is viewed as one the most significant challenges facing the non-segregated operation of UAS within the NAS. Despite the known performance limitations of a pilot's see-and-avoid capability [see ATSB (1991)], the default position mandates the need for an equivalent functionality. Equivalent functionality may not equate to equivalence in safety. Requirements on the operation and equipage of UAS within the airspace system should be defined in consideration of the entire safety case [all "layers" (ARC 2009)] and not solely based on the last layer of defence provided by a human pilot.

A range of technologies could be used to establish a safety case for UAS operations in the civil airspace system. It is proposed that the fundamental risk-matrix approach could provide a systematic structure for the assessment of such safety cases and the development of operational regulations commensurate with the levels of risk presented by the different operations. A distinct risk matrix could be structured in a similar fashion to that illustrated in Figure 3 or, if the UAS-type categories used were the same as those defined for airworthiness regulations, then the application of the risk-matrix approach could be visualised as an extension of the existing ACM into a third dimension (Figure 5). The extra dimension would correspond to the categorisation of airspace environments based on the potential for a mid-air collision. It is important to note that the airspace categories illustrated in Figure 5 may not be the same as the current classes of airspace defined by ICAO (*e.g.*, Classes A-G, ICAO 2001). The level of service provided by air-traffic services is but one of many factors that will need to be considered in the definition of this dimension of the matrix. These factors may include: radar coverage; the distribution and number of aircraft; the level of pilot-proficiency; equipage and type of other airspace users; density of airspace users; and typical meteorological conditions. For example, "Cat A" illustrated in Figure 5 could represent segregated airspace (*e.g.*, a prohibited area); "Cat B" could represent a "managed" and "known" airspace environment with a low number and density of airspace users. At the other end of the spectrum of airspace environments, "Cat Z" could represent airspace that is completely unmanaged, has a high number and complex mix of airspace users, and includes airspace users with no additional situational awareness other than that provided by an onboard pilot. This would represent airspace of greatest potential for mid-air collision.

The existing UAS-type categories could also be grouped into those considered capable of causing flight-critical damage to another aircraft and those that are unlikely to cause substantial damage to other aircraft (*i.e.*, micro or highly frangible UAS). This partitioning, if desired, could be based on the energy limits used for certifying the resilience of an aircraft empennage or propeller to a bird-strike (defined in FAR 25.631 and FAR 35.36, respectively).

Within Figure 5 each three-dimensional cell would prescribe the airworthiness and operational requirements proportionate to the degree of risk that a given UAS type presents to EOV over-flown and to other airspace users, respectively. A COA could then be issued inclusive of the systems necessary for operations in the given airspace environment. For example, radios, transponders, sense-and-act systems, and navigation systems can be considered part of the airworthiness certification baseline.

Airspace integration is a highly politicised issue, and hence there are likely to be many external factors influencing the setting of regulations on UAS integration into the civil airspace system. However, the application of the proposed risk-matrix structure may aid the resolution of such discussions by providing risk-informed and justifiable boundaries, within which further rational and risk-informed discussion may take place. The further application of the risk-matrix approach to the issue of UAS airspace integration is the subject of a future paper.

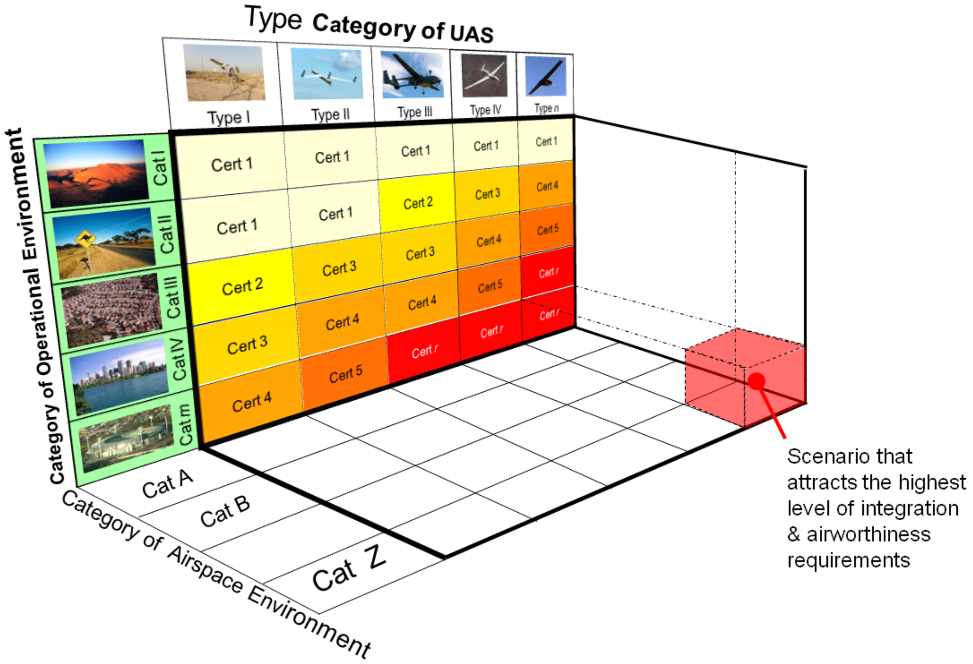

Figure 5 – Illustration of a combined airspace-integration and airworthiness certification strategy for UAS

5 Conclusion

UAS are a fundamentally new aviation technology that promises many benefits to society; however, they also represent a fundamentally new risk paradigm that must be appropriately managed. A number of limitations associated with the direct adoption of the existing civil CPA airworthiness framework to UAS have been described. These limitations justify the need to explore possible alternatives. The objective of this paper was to describe an approach that could be adopted to assist in the structuring of the airworthiness requirements for UAS. For civil UAS, this approach could be used to structure a Part 21-equivalent regulation.

The proposed airworthiness certification matrix (ACM) offers flexibility by allowing regulations to be tailored in consideration of the levels of risk, the practical and commercial limits of the technology, and the social and political environment in which the regulatory decisions are made. In addition, through the quantified specification of the framework it is possible to establish a transparent and justifiable basis in terms of the overarching requirement for an ELOS. It is acknowledged that the approach is not without its challenges, however, as stated by Bruce Tarbert, recently retired head of national airspace integration FAA, AIR-160 Program Office, in an interview regarding the certification of small UAS:

> … *SUAS* (Small UAS) *cannot be effectively certified for airworthiness like other aircraft types can… We need to think differently, well outside the box…*
>
> (La Franchi 2009)

The basis of the proposed ACM approach does not venture far beyond the boundaries of the existing "box", with the fundamental principles being clearly visible in existing regulations for civil CPA (albeit in a less explicit and structured manner). The systematic structuring of the problem space as proposed in this paper, at a minimum, will aid further discussions on the development of regulations for civil or commercially operated UAS.

The practical specification of the ACM for the regulation of civil UAS in Australia is being explored by the Australian Aerospace Industry Forum (AAIF) Certification and Regulation Working Group Sub-committee on UAS Regulations. In May 2010 the AAIF Sub-committee provided CASA with formal recommendations on the development of regulations for civil UAS. The first recommendation was that the ACM approach be adopted as a suitable structure for the airworthiness certification of civil UAS in Australia.

Acknowledgements

The authors would like to acknowledge the feedback provided by Mr Michael Nas (Murdoch University, Western Australia), Mr Nicholas Brewer (CAA-UK) and the representatives from CASA, the UAS industry and the Australian Department of Defence participating in the AAIF Certification and Regulation Working Group Sub-committee on UAS Regulations. All photographs used in figures are in the public domain. This research is supported, in part, by a Queensland State Government Smart State PhD Scholarship, the Australian Research Council's Linkage Projects funding scheme (project number LP100100302) and the Smart Skies Project, which is funded, in part, by the Queensland State Government Smart State Funding Scheme.

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Glossary

AAIF	Australian Aerospace Industry Forum
ACM	Airworthiness certification matrix
ADF	Australian Defence Force
CASA	Civil Aviation Safety Authority (Australia)
COA	Certificate of Airworthiness
CONOPS	CONcept of OPerationS
CPA	Conventionally piloted aircraft
CR	Collective risk
DSTO	Defence Science and Technology Organisation
ELOS	Equivalent level of safety
EOV	Entities of value
FAA	Federal Aviation Administration
ICAO	International Civil Aviation Organization
IR	Individual risk
NAS	National Airspace System
SR	Societal risk
STC	Supplementary type certificate
SUAS	Small unmanned aircraft system/s
UA	Unmanned aircraft
UAS	Unmanned aircraft system/s