DEFINITION OF AIRWORTHINESS CATEGORIES FOR CIVIL UNMANNED AIRCRAFT SYSTEMS (UAS)

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Keywords: *UAS, UAV, Airworthiness, Civil Regulations, Certification*

Abstract

This paper introduces a novel strategy for the specification of airworthiness certification categories for civil unmanned aircraft systems (UAS).

The risk-based approach acknowledges the fundamental differences between the risk paradigms of manned and unmanned aviation. The proposed airworthiness certification matrix provides a systematic and objective structure for regulating the airworthiness of a diverse range of UAS types and operations.

An approach for specifying UAS type categories is then discussed. An example of the approach, which includes the novel application of data-clustering algorithms, is presented to illustrate the discussion.

1 Introduction

The requirement for regulations governing the airworthiness of a civil aircraft stems from the Chicago Convention of 1944 [1]. Article 31 of the Convention requires aircraft to be certificated as airworthy, and Article 8 stipulates the extension of these requirements to UAS. As described in Annex 8 to the Convention, the objective of these regulations is to achieve, “among other things, protection of other aircraft, third parties and property” [2].

Airworthiness, according to Australian Defence Force (ADF) instructions [3], is: “…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.”

For civil conventionally piloted aviation (CPA), airworthiness is assured through the issuance of a Certification of Airworthiness (CoA) to an individual aircraft or through special certificates. A CoA is a formal statement that the aircraft is verified as being compliant with a prescriptive body of standards and regulations that are defined based on its type. The foundation of the CPA airworthiness regulatory framework is established in Part 21 regulations [4, 5], which prescribe the applicability of different codes of requirements to the different types of aircraft and their intended operation.

International consensus on a prescriptive framework of airworthiness regulations for civil unmanned aircraft systems (UAS) has yet to be reached. Currently, there are no specific standards and regulations for the type certification of civil UAS.

In Australia, assurances of the safety of other airspace users and people and property on the ground are instead provided by the placement of restrictions on where UAS operations may take place. These restrictions are mandated under Civil Aviation Safety Regulations (CASR) Part 101 [6], which specifies that a UAS must be certificated as airworthy: if the unmanned aircraft[1] (UA) has a maximum takeoff weight (MTOW) above 150

[1] The term unmanned aircraft refers only to the airborne component of a UAS.

kg, if the UAS is to be operated over a 'populated' area or in controlled airspace, or for commercial reward. UAS may be certificated in the experimental designation (*e.g.*, as described in AC 21-43(0) [7]), for specific applications and not for commercial reward, but remain subject to operational restrictions. Operational regulations such as CASR Part 101 [6] prescribe the requirement for certification (primarily based on the nature of the intended operation), but not the specific type categories or categories of airworthiness against which a CoA may be issued.

The absence of a prescriptive airworthiness certification framework and the subsequent operational limitations imposed come at significant expense to the UAS industry. A prerequisite to the realisation of a viable civil UAS industry is the definition of an appropriate airworthiness certification framework for UAS. This framework must take into consideration the unique aspects of the technology, their operations, the market drivers, and the broader socio-political issues associated with the integration of a new aviation technology into society.

2 The Airworthiness Framework

The basis for an airworthiness framework for civil UAS is established by acknowledging that the primary entities of value (EoV) are external to the UAS. The primary hazard of concern is that of a UAS impacting a region on the ground and the subsequent losses that could be registered against different EoV in the region. UAS may be operated over a diverse range of areas, and hence the associated degree of risk varies. Illustrations of the nature of this dependency are provided in Refs. [8-10]. Conversely, for CPA, the primary risks are to those people onboard the aircraft and hence CPA airworthiness regulations are defined "as far as is practicable" [11] independent of: the nature of the operational environment and the purpose for which the aircraft will be used in service [11]. McGeer and Vagners [12] aptly encapsulates the differences between the two airworthiness paradigms:

> *…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.* [12]

A new concept for the structuring of airworthiness regulations for civil UAS that acknowledges this fundamental difference between paradigms is required. One such framework is proposed by Clothier *et al.* [13] and illustrated in Fig.1. The framework is based on the principles of a risk matrix and advocated as being a suitable structure for the definition of Part 21-equivalent regulations for civil UAS [13]. The framework is briefly described in the following sections.

2.1 Operational Environments

The set of *m* rows of the proposed airworthiness certification matrix represent the different environments that a UAS may be operated over, ranked in order of increasing 'susceptibility' of an area to experience loss given a UAS mishap (*i.e.*, a categorisation of operational areas ranging from the high seas through to large open-air gatherings). These categories are defined independent of the type of UAS impacting the area. The set of categories of operational environments must be disjoint, and provide complete and contiguous coverage of the range of operational environments potentially over-flown (*i.e.*, provide an unambiguous classification of all potential areas over which a UAS operation could occur).

2.2 Type Categories

The set of ***n*** columns of the matrix represent the different type categories of UAS. Each type category 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. Or more generally, UAS are grouped based on the question: *given the occurrence of an unrecoverable flight critical failure, what is the*

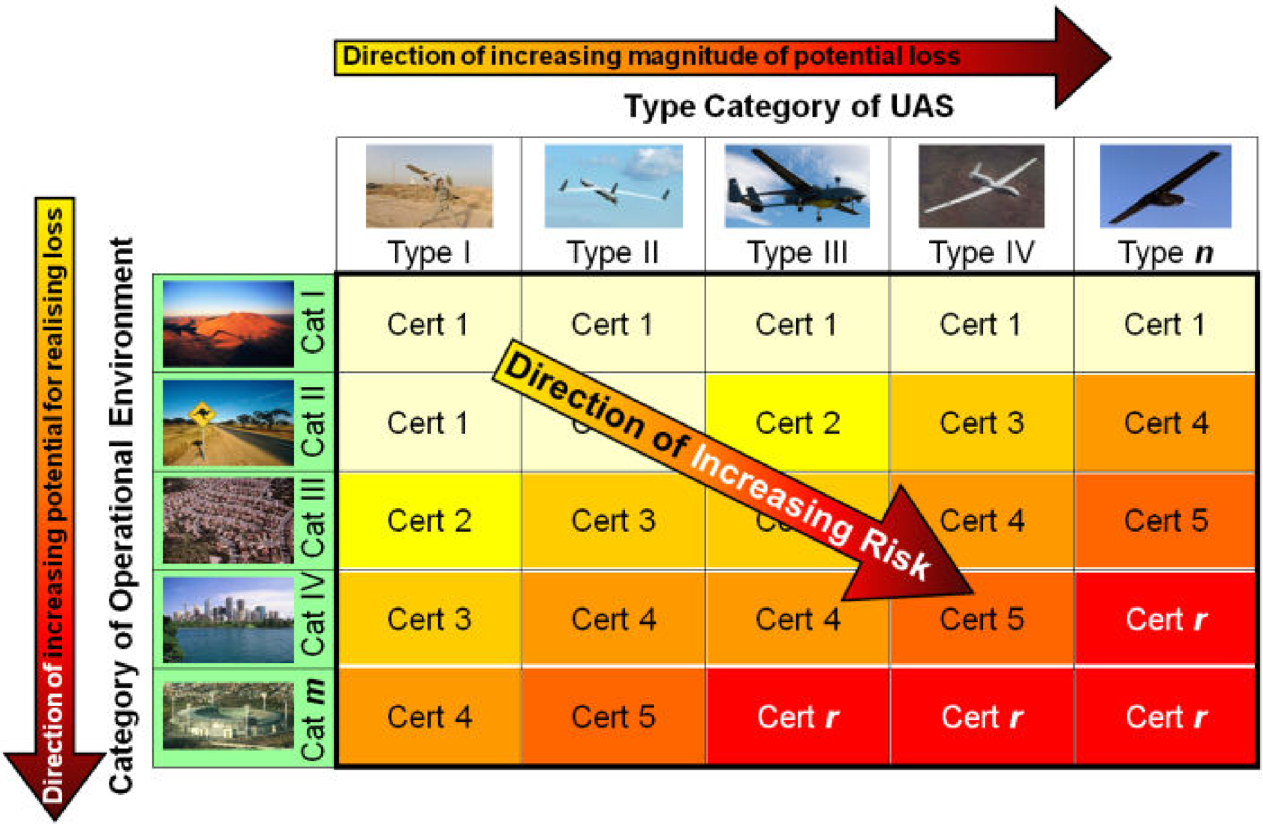

Fig. 1 Proposed structure of an airworthiness certification framework for civil UAS [13]

maximum degree of loss the UAS could cause, irrespective of where it crashed?

The set of type categories must be disjoint (*i.e.*, provide an unambiguous classification of the diverse range of UAS) and provide complete and contiguous coverage of the range of plausible magnitude of potential loss.

2.3 Operational Scenarios

Each of the $m \times n$ cells of the matrix represents a unique operational scenario, defined by the combination of a specific UAS type category with a specific category of operational environment. For each operational scenario formed, an assessment of the level of risk is then made.

2.4 Airworthiness Categories

Illustratively, the assignment of the r airworthiness categories is the process of assigning colours to each of the cells of the matrix illustrated in Fig. 1.

The airworthiness categorisation scheme is representative of a discrete, contiguous and increasing ranking of risk (*e.g.*, MIL-STD-882D defines the risk-ranking scheme of low, medium, serious, and high [14]). Each operational scenario may then be mapped to one of the airworthiness certification categories based on the levels of risk assessed for the operational scenario. Operational scenarios with 'similar' levels of risk may logically be assigned to the same airworthiness certification category.

In general, the operational scenarios (and subsequently the certification categories assigned to them) in the lower-right quadrant of the matrix present higher levels of risk than are associated with the scenarios in the upper-left quadrant.

Unlike the CPA airworthiness framework, the aircraft-type category does not directly define the airworthiness category. A UAS of a specific type may be certificated in one or more airworthiness categories dependent on the category of operational area over which it is intended to be flown. The approach permits UAS manufacturers to develop and certify a UAS-type for a specific application, operational environment or price-point in the market.

A significant challenge is the determination of an appropriate number of airworthiness certification categories. The minimum number of categories is one. This represents the undesirable case where all UAS operational scenarios are regulated under the same standards irrespective of the differences in the associated levels of risk.

The maximum number of airworthiness categories is equal to the number of rows, m, multiplied by the number of columns, n. This represents the case where a separate body of airworthiness regulations is defined for each of the operational scenarios. This case offers the maximum possible degree of tailoring of regulations. However, Clothier *et al.* [13] identify several disadvantages to a large number of airworthiness categories. A determination of the optimum number of airworthiness categories requires subjective trade-offs to be made, for example, determining the number of airworthiness categories necessary to:

1. minimise the relative differences between the levels of risk associated with each operational scenario assigned to a particular certification category (*i.e.*, ensure operational scenarios assigned to a given certification category are indeed comparable in their risks);
2. ensure sufficient resolution in the certification categories to permit niche or unique operational scenarios; and
3. ensure a practical and workable categorisation from the perspective of the authority charged with promulgation of the regulation (*e.g.*, not unmanageable in number).

Given an appropriate assignment of certification categories to operational scenarios, regulations may then be developed (or existing CPA regulations tailored and adopted) to each scenario. An example of this process, for civil UAS Part 1309 regulations, is described in [13].

2.5 Summary

The airworthiness certification matrix provides a flexible, yet systematic and defensible framework for regulating the airworthiness of civil UAS. The matrix provides a suitable structure for simplifying the classification of the diversity of systems and operations. A systematic and transparent process for assigning airworthiness categories is described based on assessments of risk. This assignment considers both the system and the environment, hence the proposed airworthiness certification matrix acknowledges the fundamental differences between the CPA and the UAS risk paradigms.

It is for these reasons, and others, that Clothier *et al.* [13] advocate the proposed airworthiness certification matrix as a suitable basis for defining a Part 21-equivalent regulation for civil UAS.

The remainder of this paper describes a possible strategy for the specification of a principal component of the proposed airworthiness certification matrix, that of UAS type categories (*i.e.*, the columns of Fig. 1).

3 Specification of UAS Type Categories

For a comprehensive review of existing UAS type categorisation schemes refer to the forthcoming work of Nas [15].

Currently, there is no consensus on the definition of type categories for UAS [16, 17], with many of the existing schemes having not been defined for the purpose of certification. In addition, there is no consensus on the process for defining a suitable scheme when such consensus is fundamental to the progress of regulations [16]. The specification of type categories could have a significant influence on the future 'shape' of the civil UAS industry, hence a more objective and systematic process for defining UAS type categories is needed. The following sub-section describes one possible approach that could be used to define type categories for UAS.

3.1 A Risk-Based Approach

A type category is a grouping of UAS that are similar in some relevant way. In accordance with the structure of the proposed airworthiness matrix (Fig. 1), the measure of similarity used to define UAS type categories is the theoretical magnitude of potential loss due to a mishap (§2.2). A measurement of loss may be made for a range of different types of EoV (*e.g.*, people, property, and environment) and entity attributes (*e.g.*, for people: physical, psychological, and financial). Within the context of defining airworthiness regulations for civil UAS, the primary loss of concern is the magnitude of physical harm to third parties on the ground. Proceeding on this premise, a generalised two-dimensional (2D) space describing the magnitude of potential loss to people on the ground is defined in Fig. 2. The two component-dimensions are defined as:

X (or horizontal axis): the types of potential harm to people exposed to a mishap; and
Y (or vertical axis): the maximum number of people that could be harmed given a mishap.

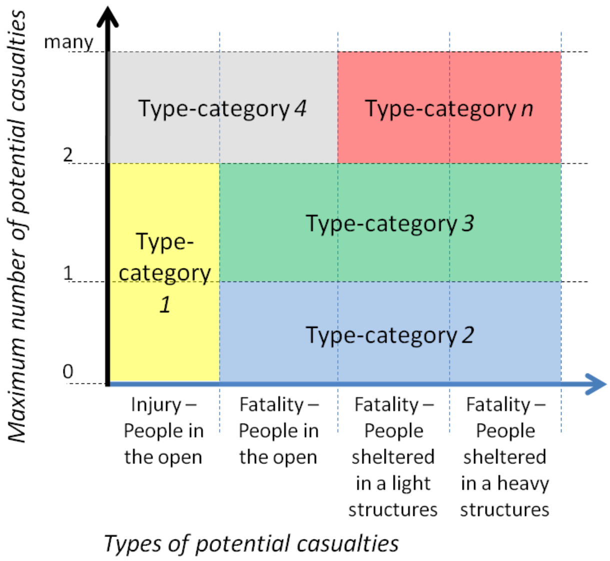

Fig. 2 Illustration of the assignment of UAS type categories within a 2D space describing the magnitude of potential loss to people on the ground due to a UAS mishap

The first component-dimension aims to distinguish between UAS types based on their ability to cause levels of physical harm to people exposed to a UAS mishap. For example, the physical and aerodynamic properties of some UAS make them very unlikely to cause a fatal injury to a person struck in the open. On the other hand, some UAS are capable of penetrating the strongest of structures and consequently have the potential to cause harm to the people sheltered within buildings.

A range of different hazards must be considered to adequately characterise the ability of a UAS to cause harm to people on the ground, including:

1. primary hazards – *e.g.*, the transfer of energy through a direct strike, flying debris, heat from an explosion, and incident pressure waves; and
2. secondary hazards – *e.g.*, the ensuing collapse of a building, bush fires, and on-going contamination by hazardous substances.

To simplify this example, for this paper, the UA is assumed to be in-frangible, and the UA and any object that it strikes (*e.g.*, a building or vehicle) are inert (*e.g.*, no secondary explosions or collapsing walls are assumed possible); however, a more comprehensive approach would include a broader range of hazards. Based on these assumptions, the primary hazard may be considered as the transfer of kinetic energy from the UA to people and structures on the ground directly struck by the UA. The measure used to characterise this component-dimension is the maximum possible kinetic energy of the UA on impact with the ground (KE_{max}), given by:

$$KE_{\max} = \frac{1}{2} MV_{\max}^2 \qquad (1)$$

where M is the MTOW of the UA and V_{max} is its maximum speed.

The second component-dimension aims to distinguish amongst UAS types based on the maximum number of potential casualties due to mishap. Such a distinction is necessary to reflect society's heightened apprehension towards mishaps with a large magnitude of potential loss, irrespective of the associated likelihood of occurrence [18].

Assuming independence of the particular region over-flown (*i.e.*, assuming an exposed population of uniform distribution and of uniform susceptibility or response to an incident stress), the potential number of casualties is a complex function of the spatial-temporal distribution of the effects of a mishap. This spatial-temporal region is referred to as the hazard area.

Within the context of the simplified example, the hazard area is the impact area of the crashing UA. A range of models describing the impact area of a crashing aircraft are described in Refs. [19-24]. In this example, the impact area, I_{area}, is modelled as a simplified glide area for a fixed-wing UA [21, 24], given by:

$$I_{area} = (W_{span} + 2R_p) \times (L + D_{glide} + 2R_p), \qquad (2)$$

where W_{span} is the wingspan, R_p is the average radius of a person (the shoulder width of an average person), L is the length of the aircraft, and D_{glide} is the distance along the ground travelled by the UA at glide path angle, γ, from the height of an average person, H_p, given by:

$$D_{glide} = \frac{H_p}{\tan \gamma}. \qquad (3)$$

3.1.1 Defining the Type Categories

The process of defining type categories is one of determining mutually exclusive regions within the 2D space where the magnitude of potential loss due to a UAS mishap is similar (Fig. 2). Two approaches for guiding the specification of these regions are investigated in this paper:

1. definition of limits with respect to one or both of the component-dimensions (*i.e.*, specification of loss criteria); and
2. application of a data-clustering algorithm to 'learn' type categories from a UAS dataset.

To ensure an unambiguous classification of UAS types, the specification of type categories must also satisfy:

$$P_{Loss}(i) < P_{Loss}(i+1), \text{ for } 1 \le i < r, \qquad (4)$$

where $P_{Loss}(i)$ is the potential magnitude of loss associated with the i^{th} type category. Satisfying this relationship requires subjective judgements on the relative significance of the two components used to represent the magnitude of potential loss (*i.e.*, the ranking of different loss outcomes).

3.1.2 Categorisation Using Limits

The first approach to defining UAS type categories is to specify boundaries with respect to one or both axes of the 2D space describing the magnitude of potential loss due to a UAS mishap.

To illustrate, four high-level type categories are defined based on the energy required to cause a particular level of harm to a person exposed to a UAS mishap (*i.e.*, along the impact-energy component-dimension). The type categories and associated impact-energy boundaries are summarised in Table 1. The first category describes UAS that have sufficient impact energy to cause injury (but not a fatal injury) to one or more people exposed in the open. A range of different injury scales could be used to further describe this category (*e.g.*, the Abbreviated Injury Scale in Ref. [25]). The second category describes UAS with impact energy greater than 42 J but less than 1,356 J, which are capable of causing fatal injuries to one or more unsheltered people. The third category describes UAS with sufficient impact energy to penetrate a typical residential structure (*i.e.*, a corrugated-iron roof). The final category describes UAS that are capable of penetrating the highest level of protection afforded to the general public (*i.e.*, a reinforced concrete structure).

A database[2] comprised of over 500 rotary and fixed-wing UAS types is used to illustrate the outcome type categories. Three-hundred and eighty-three fixed-wing UAS types are mapped to the 2D space by use of Eqs. 1–3. These UA are then colour coded based on the type-classification scheme described above. Fig. 3 shows the classification of the fixed-wing UAS dataset based on the categories defined in Table 1. Fig. 4 shows the same classification mapped

[2] Database of UAS compiled and maintained by Defence Science and Technology Organisation (DSTO) personnel. Database includes military UAS.

Category	Description of loss outcome	Energy Limit* (J)	Description of Energy Limit
1	UAS capable of causing a non-fatal injury to one or more exposed people	$KE_{max} < 42$	< 5% probability of causing a fatal injury to an individual standing in the open [26]
2	UAS capable of causing a fatal injury to one or more exposed people	$42 \leq KE_{max} < 1{,}356$	≥ 5% probability of causing a fatal injury to an individual standing in the open [26]
3	UAS capable of causing a fatal† injury to one or more people within a typical residential structure	$1{,}356 \leq KE_{max} < 13{,}560$	Capable of penetrating a corrugated-iron roof house [27]
4	UAS capable of causing a fatal† injury to one or more people within a typical commercial structure	$KE_{max} \geq 13{,}560$	Capable of penetrating a reinforced concrete structure [27]

*Energy limits are based on the conservative assumption that each UA may be represented as an in-frangible piece of inert debris.

†It is assumed that any individual inside a structure is fatally injured if the UA has sufficient energy to penetrate the structure.

Table 1 Type categories based on the ability of the UAS to cause harm

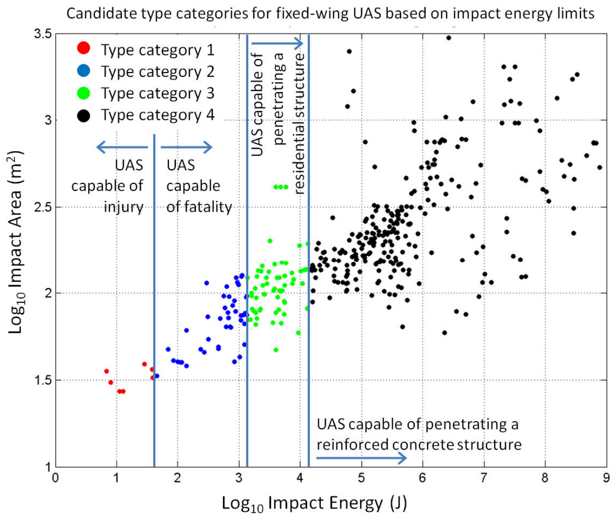

Fig. 3 Type categorisation of fixed-wing UAS based on impact energy limits

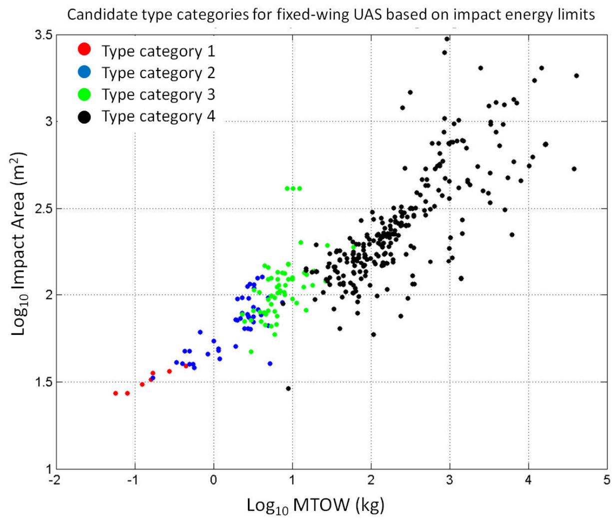

Fig. 4 Type categorisation displayed using UA MTOW

against the MTOW of the UA, a common metric used in existing type categorisation schemes.

The mapping of the categories with respect to the MTOW of each UA type, shown in Fig. 4, results in an ambiguous classification. This highlights that a measure of the MTOW of a UA, on its own, may not provide a good discriminator with respect to the potential harm it may cause. One must also consider the maximum potential speed of the UA upon impact. From Fig. 3 and 4, it may be observed most UAS of MTOW greater than 200 g are capable of inflicting a fatal injury to one or more people exposed in the open. In addition, nearly all UAS with a MTOW greater than ~20 kg have sufficient maximum impact energy to penetrate the highest level of protection typically available to a member of the general public. Consequently, type category 4 covers a disproportionately large range of UAS types. Greater resolution within the type categories may be required. This may be obtained by defining additional categories of harm along the impact-energy axis (*e.g.*, types of sheltering, levels of injury, or a combination of both) or by defining limits with respect to the second component-dimension (*i.e.*, the impact area).

Classifying with respect to the maximum impact area of the UA attempts to distinguish UAS type categories based on the number of people potentially harmed. The larger the impact area, the more people potentially exposed to harm given a UAS mishap. Relating the impact area to a number of potential casualties (*i.e.*, through the specification of a population distribution) and the specification of category boundaries in terms of a number of casualties is a subjective process. A more objective approach is to use a data-clustering algorithm to objectively 'learn' type categories from the UAS dataset.

3.1.3 Categorisation by Use of Data Clustering

Data clustering or data segmentation [28] is a process of unsupervised learning [29] that attempts to organise a collection of objects into a finite number of meaningful groupings, or clusters, based on some measure of similarity [30]. In this example, the objects are individual UAS types and the measure of similarity is the impact area of the UA, given by Eq. 2.

Data-clustering techniques have been widely applied, particularly in the field of image processing, with clustering algorithms being used for image compression, segmentation, and pattern recognition for machine vision. It is not the objective of this paper to provide a thorough overview of data-clustering techniques. For this, the reader is referred to the introductory paper of Jain and Dubes [31]. Instead, the aim here is to emphasise that an alternative and more objective approach to the definition of UAS type-certification categories may lie in the application of data clustering techniques.

In this example, the widely applied [32] k-means algorithm [33] is used to determine sub-type categories within the fourth type category illustrated in Fig. 3. The k-means algorithm is a partitioning relocation algorithm [32] that determines a finite number of k clusters/groups directly from the data by iteratively relocating points until a minimum in an objective distance measure is obtained. k is an integer value less than or equal to the number of unique UAS types in the dataset (K).

The k-means algorithm has the advantages of being extensively used, simple to interpret and implement, and computationally efficient. One of the significant disadvantages is that the convergence of the algorithm is highly dependent on its initialisation state [28-30]. Dependent on the initial conditions, the algorithm may converge to a local optimum [28] and consequently may not find a globally optimal partitioning of UAS types into categories. Another significant disadvantage of the algorithm is that the number of clusters (k) must be known *a priori*.

To address these disadvantages, the k-means algorithm was run for values of k ranging from 2 to 7. The algorithm was run fifty times for each value of k, with randomly selected initial conditions. The solution with the lowest sum of intra-cluster distances was then selected from the set of fifty possible solutions. As advocated by Kaufman and Rousseeuw [32], the silhouette coefficient (SC) may be used to objectively compare the performance of the clustering algorithm for each value of k. SC is the maximum of the average silhouette width for the entire dataset, a dimensionless measure of how well each object within a dataset has been classified [32] (refer to p.83 of Ref. [32] for a description of its calculation). SC ranges between –1 and +1, with the values of –1, 0 and +1 indicative of a poor, an indifferent, and an appropriate classification of UAS into type categories, respectively. SC for each value of k is presented in Table 2.

No. of type sub-categories, *k*	**Maximum average SC**	**Qualitative assessment* of how well the classification represents the structure of the dataset**
2	0.822	strong
3	0.705	strong
4	0.706	strong
5	0.692	reasonable
6	0.710	strong
7	0.720	strong

*Based on the qualitative assessment table presented in Kaufman and Rousseeuw [32].

Table 2 Results obtained from clustering approach for different numbers of type categories

Based on the results presented in Table 2, the mathematically optimal solution is to sub-divide the fourth UAS type category into two sub-categories (k = 2, Table 2). This results in a total of five UAS type categories.

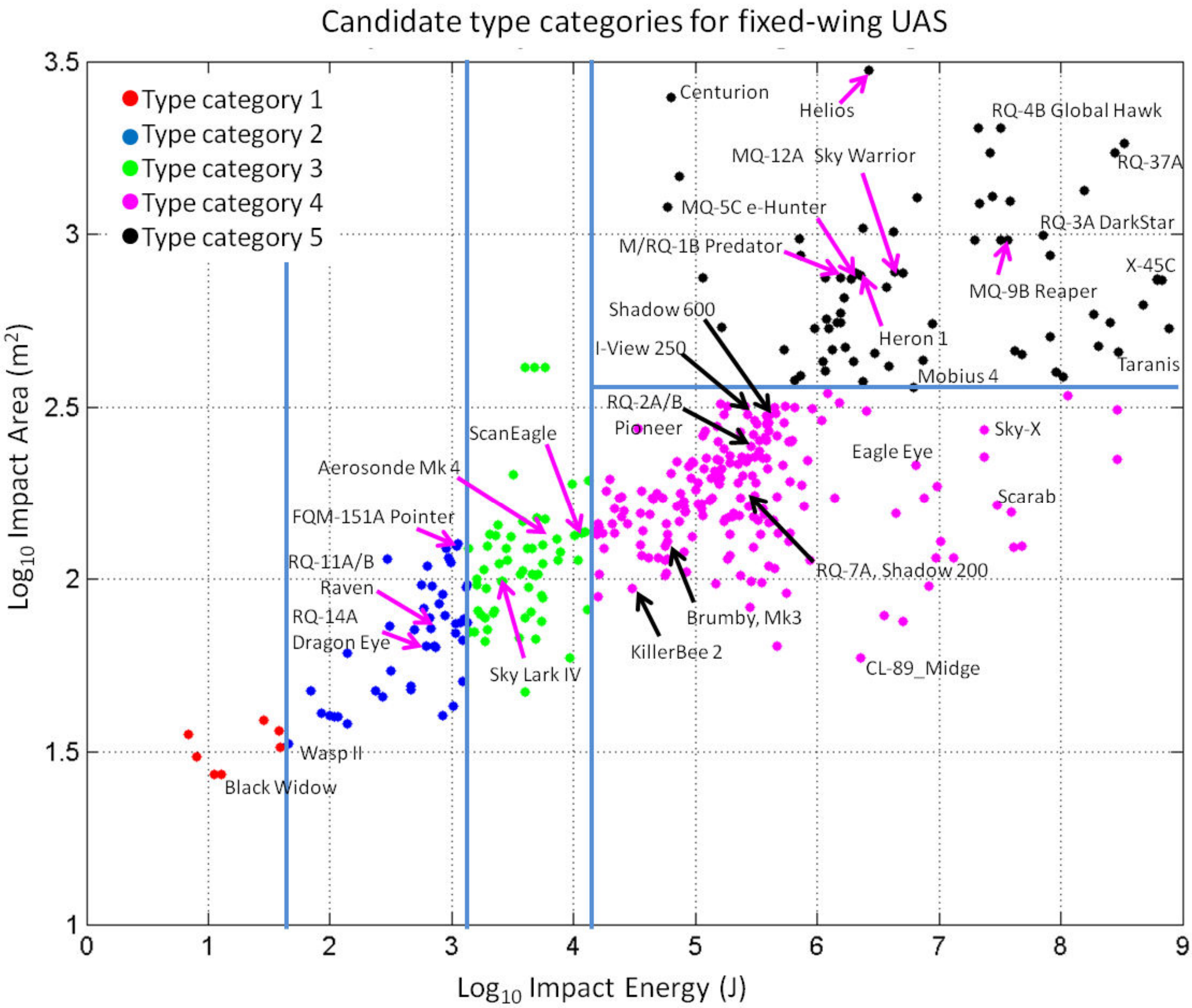

Fig. 5 Classification of UAS into five type categories

Type category	Boundary conditions	Example UAS
1	$KE_{max} < 42$ J	Black Widow, Hornet
2	42 J $\leq KE_{max} <$ 1,356 J	Pointer, Raven
3	1,356 J $\leq KE_{max} <$ 13,560 J	ScanEagle, Aerosonde Mk4
4	13,560 J $\leq KE_{max}$ $I_{area} < 347$ m^2	Shadow 600
5	347 m$^2 \leq I_{area}$	Heron 1, Taranis, Global Hawk

Table 3 Example output UAS type categorisation scheme

A visualisation of the candidate five-category UAS type categorisation scheme is illustrated in Fig. 5; and Table 3 summarises the boundaries of the example type categorisation scheme.

It may be observed in Table 2 that the SC determined for each value of *k* varies little, and hence the ideal number of type categories is more likely to be determined by the context of the problem (*i.e.*, broader subjective trade-offs, as described in §2.4), rather than by the mathematically optimal solution. Thus, the results presented in Fig. 5 and Table 3 are illustrative only.

3.4 Discussion

The assumptions and simplified model used in the previous example place limitations on the usability of the results; however, the intention here is to illustrate an objective approach for specifying UAS type categories. The basis for classification is the magnitude of potential loss a UAS may cause given a mishap, independent of where it is flown. Two techniques for specifying the boundaries of the type categories have been described. However, it is unlikely that this process will ever be reduced to a purely mathematical approach. The specification of type categories will heavily influence the nature of the future civil/commercial UAS industry; hence, it is likely the decision-making process will involve multiple, competing stakeholders and be a predominantly discursive process. The approaches presented in this paper provide a focus for a risk-informed basis to help guide this higher-order decision-making process.

4 Summary and Conclusions

This paper summarises a novel strategy for the specification of airworthiness certification categories for civil UAS. The proposed framework, outlined in §2, comprises two orthogonal dimensions (representative of the potential magnitude of loss and the potential for realising loss, given a UAS impacting the ground). The Cartesian product of the two dimensions defines a finite set of operational scenarios, to which airworthiness categories are then assigned based on an assessment of the risks. In §3, the specification of the columns of the matrix (a type-categorisation scheme for UAS) was discussed and presented in simplified form. As discussed in §2.4, an appropriate system of certification categories for the purpose of regulating civil UAS may be based on such a risk matrix.

The risk matrix approach permits a tailoring of airworthiness regulation in line with the risks. For example, small UAS, which present lower levels of risk, are subject to lower standards of airworthiness and hence may be permitted a higher mishap rate. Larger UAS, which present risks comparable to CPA, attract a level of airworthiness regulation comparable to CPA.

The airworthiness matrix approach provides a systematic and justifiable (through traceability in risk) framework for the regulation of the diverse range of UAS and their operations. The matrix affords a greater degree of flexibility in the regulation of UAS allowing UAS manufacturers to develop and certify a UAS-type for a specific application, operational environment or price-point in the market.

Broader social, political, technical, and practical considerations will ultimately determine the refinement of any airworthiness certification scheme adopted for civil UAS; however, the approach presented in this paper provides the risk-informed foundations from which to guide these discussions. The comprehensive specification of the airworthiness certification matrix, including the specification of UAS type categories and operational environments, will be the subject of a future paper.

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Acknowledgement

The authors would like to thank Mr. Michael Nas, from Murdoch University, Perth, Australia, and members from the Australian Aerospace Industry Forum, Certification and Regulation Working Group, Unmanned Aircraft System Sub-Committee for their input to this paper. The authors would also like to thank Dr XunGuo Lin for his comments made in reviewing this paper. This research is supported by a Queensland State Government Smart State PhD Scholarship.

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