An operability framework for unmanned aircraft systems

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ABSTRACT

In the current absence of comprehensive and generic UAS airworthiness regulations, the development of UAS and their introduction into non-segregated airspace pose significant challenges to the UAS industry and regulators. This paper reports on a research study that considered the problem, from an engineering perspective, beyond the limits of the airworthiness of the aircraft and remote control station. The study introduces the concept of UAS operability, which includes the safe and reliable functioning of the UAS as a system, the airworthiness of its airborne sub-systems, and the safe and reliable functioning of its non-airborne sub-systems and functional payloads. The regulatory domain for UAS operability is described and the study establishes a generic and comprehensive UAS operability framework. The framework was validated by populating its elements with engineering criteria that can be used by the UAS engineering domain for the development of engineering specifications and as guidance towards achieving the safe and reliable functioning of UAS.

NOMENCLATURE

AIAA	American Institute of Aeronautics and Astronautics
ANNEX 8	Annex 8, Airworthiness of Aircraft, of the Chicago Convention
ASTM	American Society for Testing and Materials
CAA	Civil Aviation Authority
CARCOM	(South African) Civil Aviation Regulations Committee
CASA	Australian Civil Aviation Safety Authority
CASR	Australian Civil Aviation Safety Regulations
CS	(European Aviation Safety Agency) Certification Specifications
DGA	(French) Délégation Générale des Armements
EASA	European Aviation Safety Agency
EC	European Community
EMAAG	European Military Aviation Authorities Group
EUROCAE	European Organisation for Civil Aviation Equipment
EU	European Union
EUROCONTROL	European Organisation for the Safety of Air Navigation
FAA	(United States of America) Federal Aviation Administration
FAR	(United States of America) Federal Aviation Regulations
FLYGI	Swedish Military Flight Safety Inspectorate
ICAO	International Civil Aviation Organisation
IEEE	Institute of Electrical and Electronic Engineers
IMAAC	International Military Aviation Authorities Conference
JAA	Joint Aviation Authorities
JAR	European Joint Airworthiness Requirements
kg	kilogrammes
NAEW&CFC	NATO Airborne Early Warning and Control Force Command
NASA	National Aeronautics and Space Administration
NATO	North Atlantic Treaty Organisation

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RLV	Reusable Launch Vehicle
RLVs	Reusable Launch Vehicles
RML	Swedish Rules of Military Aviation
RTCA	Radio Technical Commission for Aeronautics
RTI	(United States of America) Research Triangle Institute
SA	South Africa
SA CAA	South African Civil Aviation Authority
SA-CAR	South African Civil Aviation Regulations
UAS	Unmanned Aircraft System/s
UASSG	(ICAO) UAS Study Group
UAV	Unmanned Aerial Vehicle
UK	United Kingdom
UK CAA	United Kingdom Civil Aviation Authority
USA	United States of America
USAR	(French DGA) UAV Systems Airworthiness Requirements

1.0 INTRODUCTION

1.1 General

For unmanned aircraft systems (UAS) to operate in non-segregated airspace, relevant airworthiness and operational safety requirements must be determined by means of safety regulation[1-8]. From an engineering perspective it is equally important to ensure that UAS can operate as and when required. A research study[9] was carried out to determine the existing status regarding regulatory and engineering requirements for UAS airworthiness, and to address specific shortcomings in the UAS engineering domain.

1.2 Study background

In response to the implementation of 'interim' UAS regulating policies in various countries[2-4,10,11] the International Civil Aviation Organisation (ICAO) established a UAS Study Group (UASSG)[12-15] to oversee the development of international regulations for civil UAS, including airworthiness requirements. A military equivalent of ICAO does not exist[16] and the development of airworthiness requirements for military UAS is typically done by defence departments[17,18], armed forces[10,19-21] or organisations such as the North Atlantic Treaty Organisation (NATO)[22].

A survey of the existing airworthiness requirements[9,10] indicated that:

- a generic and comprehensive set of airworthiness requirements for UAS does not yet exist[23];
- a more general term to describe a wider concept of 'airworthiness' for all the sub-systems of a UAS is not used, and requirements in terms of such a general term have therefore not been developed for UAS[23];
- airworthiness requirements derived from manned aircraft regulations primarily address only the aircraft and remote control station elements of a UAS, and requirements at system level and for other airborne and non-airborne sub-systems and functional payloads are usually not included[2,23];
- a limited number of industry standards for UAS have been developed or are being developed[9,10]; and
- the similarities between UAS and reusable launch vehicles (RLVs) warrant that regulations for RLVs should be studied for useful reference criteria in the development of airworthiness requirements[9,10] for UAS.

The survey also indicated that the direct application of manned aircraft airworthiness requirements to UAS is not desirable[23], but that the selective tailoring of such requirements is currently applied as an interim arrangement[5,10,11,23]. It was further established that where a specific type of UAS will not be subject to regulation, the responsibility for ensuring the safety and reliability of that type of UAS will revert to the developing and operating organisations of the UAS[11,24].

Therefore, to enable consistency and accountability in at least the development phases of UAS, this study focused on:

- introducing the concept of 'UAS operability' to address the safety and reliability of a UAS[9];
- investigating and describing the regulatory domain that applies to UAS[9]; and
- the development of a generic 'UAS Operability Framework' within the scope of the UAS regulatory domain, but populated with operability criteria for UAS, their airborne sub-systems, their non-airborne sub-systems and their payloads, specifically for use in the UAS engineering domain[9].

The primary milestones of the study are shown in Fig. 1[9].

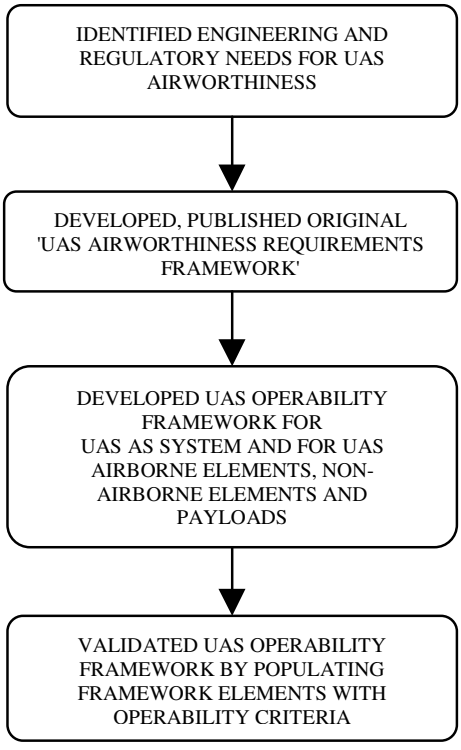


Figure 1. Primary milestones of the study.

1.3 Research methodology

The study was primarily a qualitative study and was based on the development type research approach in order to make both scientific and practical contributions[9]. Scientifically, engineering analysis and development methods were applied to both legislative and technical reference material in developing the UAS operability framework and criteria as tools for the engineering domain, rather than the regulatory domain. The practical contribution of this study is found in the resulting UAS operability framework, as well as in the operability criteria with which the framework was validated.

An extensive literature study was conducted to identify, collect and disseminate appropriate airworthiness-related material. Initially, the literature study focused on manned aircraft and UAS regulatory requirements for airworthiness, but it was soon found that the USA

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FAA reusable (space) launch vehicle (RLV) regulations and technical reports contain additional airworthiness — or flightworthiness in space terms — material that could and should be adopted for UAS applications[9]. The RLV literature was analysed and compared with existing manned and unmanned aircraft airworthiness regulations and requirements, and appropriate RLV flightworthiness criteria were identified and applied in the UAS operability framework and criteria[9].

Data collected during the literature survey were evaluated, analysed, consolidated and structured into an appropriate framework format. The first result of this process was the original UAS airworthiness requirements framework which was published[10] as a peer-reviewed paper. Further research and analysis of related engineering and regulatory material, and an analysis of potential future UAS utilisation scenarios, identified numerous UAS-specific additional airworthiness and operability issues that were addressed in the development of the final UAS operability framework[9].

A critical evaluation of the UAS operability framework was done by means of the validation of the framework structure[9]. The framework was populated with operability criteria that were developed to address all operability-significant issues of a UAS as a system, as well as of its airborne, non-airborne and payload sub-systems[9].

The development of the UAS operability criteria was based, in part, on the analaysis and adaptation of existing manned aircraft, UAS and RLV material. Where such material did not exist, the author applied sound engineering innovation, extrapolation and judgement to create the required criteria. All the criteria were, however, compiled to be generic and applicable to the engineering domain, while conforming to the general intent of the regulating domain[9].

This evaluation and validation process confirmed that the UAS operability framework structure is appropriately generic and has sufficient scope to be relevant for UAS[9].

1.4 Limitations of study

This study focused on the development of a UAS operability framework, with UAS operability criteria, appropriate for use in the engineering domain. The objective of the study was not to develop detail engineering requirements for UAS. The study also did not develop regulatory requirements for UAS, although its results could be used as guidance material for the development of such regulations.

Since UAS utilisation is not yet on the same level as that of manned aircraft, the study had to consider the results of a future scenario study and the results of the research study will need to be continuously monitored and revised to reflect future changes in UAS operability requirements and criteria.

2.0 UAS OPERABILITY

2.1 Introduction

Generally, the airworthiness of an aircraft is regulated (civil aviation) or managed (military aviation) in an appropriate manner to ensure its safe and reliable functioning[5,10,16,25]. The 'flightworthiness' of spacecraft is also regulated to ensure their safe operation[26,27], where flightworthiness is defined as an aircraft, missile or spacecraft that 'is ready and sufficiently sound in all respects to meet and endure the stresses and strains of flight'[28].

Although airworthiness is central to the regulation of aviation safety at international and national levels, the term 'airworthiness' is not defined in the following:

- the Chicago Convention and its Annexes[1]1;
- the USA Federal Aviation Regulations (FAR)[29];
- the European Joint Airworthiness Requirements (JAR)[30]; and
- EASA's Certification Specifications (CS)[31].

For the purposes of this study, therefore, the following definition for airworthiness from the United Kingdom (UK) Military Airworthiness Regulations[32] was used:

Airworthiness is "the ability of an aircraft or other airborne equipment or system to operate without significant hazard to aircrew, ground crew, passengers (where relevant) or to the general public over which such airborne systems are flown"[32].

Since an unmanned aircraft system consists of various sub-systems that are both airborne and non-airborne[2], the 'airworthiness' of the UAS should be considered in terms of the following[9]:

- the safe and reliable functioning of the UAS as a system;
- the airworthiness of the airborne sub-systems of the UAS;
- the safe and reliable functioning of the non-airborne sub-systems of the UAS;
- the safety of cargo payloads carried by the UAS; and
- the safe and reliable functioning of functional payloads carried by the UAS.

It is therefore not sufficient to only consider the airworthiness of the airborne sub-systems of the UAS, and an alternative term is needed to describe the safety and reliability status of a UAS and its sub-systems in such a manner that it can be applied generally in both the engineering and the regulating domains[9].

2.2 Introducing the concept of UAS operability

In order to effectively address the safety and reliability status of a UAS and its sub-systems, a different approach is necessary which would require:

- a change in at least the interpretation of the term 'airworthiness';
- the use of a different, but related term, such as 'flightworthiness'; or
- the introduction of a specific and generic term to address all airworthiness, safety and reliability issues of a UAS[9].

A change in the interpretation and meaning of the term 'airworthiness' is not recommended, as this could result in mis-interpretations, particularly in aviation regulations[9].

'Flightworthiness' is typically associated with RLVs and its scope does not include all RLV sub-systems[26,28]. Again, its use for UAS is not recommended as it could result in mis-interpretations in both the UAS and spacecraft domains[9].

These considerations, and a thorough survey of related terms, resulted in the selection of an alternative term to address the functional status of a UAS. Hence, 'UAS operability' was conceptualised, where 'UAS operability' is defined to include:

- the safe and reliable functioning of the UAS as a system;
- the airworthiness of the airborne sub-systems of the UAS;
- the safe and reliable functioning of the non-airborne sub-systems of the UAS; and
- the safe and reliable functioning of relevant payloads to be carried by the UAS[9].

This definition of 'UAS operability' does not limit the concept of UAS operability to a particular category or type of UAS, nor does it limit the application of the concept to individual sub-systems of a UAS. In addition, the format of the definition allows the application of the 'UAS operability' concept to all UAS, military and civilian, and whether regulated or not.

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3.0 REGULATORY DOMAIN FOR UAS OPERABILITY

3.1 Introduction

Most UAS will eventually need to comply with relevant UAS regulations and aligning the UAS engineering development process with at least the philosophy of aviation regulation should largely eliminate the need to re-engineer a UAS to comply with the regulatory requirements[9].

Although this type of engineering investigation should not be bound by regulatory constraints, defining the UAS regulatory domain will enable the development of the UAS operability framework to satisfy engineering requirements for safe and reliable UAS functioning within the regulatory scope.

An overview of regulatory principles in general, and international and national approaches in the regulation of aviation and UAS airworthiness, enabled the anticipated UAS regulating domain in terms of existing legal bases to be determined.

3.2 UAS regulation in civil aviation

3.2.1 General regulation of civil aviation

The Convention for the Regulation of Aerial Navigation (Paris Convention) of 1919 established a legal basis for rights in international civil aviation[33]. The principle that 'every nation has absolute and exclusive sovereignty over the airspace above its defined territory'[33] remained the cornerstone for the Convention on International Civil Aviation (Chicago Convention)[1] in 1944. Annexes to this Convention focus on categorised regulatory requirements[33], and the International Civil Aviation Organisation (ICAO) was established to enforce the Convention through national legislation in ICAO contracting states.

The Chicago Convention and its Annexes therefore represent the international legal basis for the regulation of civil aviation.

3.2.2 Regulation of airworthiness in civil aviation

Airworthiness standards and recommended practices were established by ICAO in 1949 in accordance with Article 37 of the Chicago Convention[1]. These standards and practices are included in Annex 8, Airworthiness of Aircraft[25], to the Convention.

In 1956, Annex 8 was supplemented with mandatory 'Acceptable Means of Compliance'. However, the Acceptable Means of Compliance were abandoned in 1972 in favour of technical guidance material with no mandatory obligations and a review of ICAO's airworthiness policy confirmed that 'each Contracting State should either establish its own comprehensive and detailed code of airworthiness or select a comprehensive and detailed code established by another Contracting State'[25].

Annex 8 is therefore the legal basis for the regulation of airworthiness, although it is limited in its scope and only provides for:

- the administration of airworthiness and continued airworthiness;
- airworthiness requirements for fixed wing aircraft with a maximum certified take-off mass of more than 5,700kg which are to be used for transporting passengers and cargo[25]; and
- airworthiness requirements for helicopters that are to be used for passenger and cargo transportation[25].

3.2.3 Current approaches to regulating the airworthiness of civil UAS

Article 8 of the Chicago Convention applies to 'pilotless aircraft'[1] and as it is recognised that significant differences exist between manned and unmanned aircraft[5,10], ICAO initiated a process to establish guidelines for regulating UAS in 2006[12].

In 2007, it was decided that ICAO should develop a regulatory concept and co-ordinate the development of ICAO standards and recommended practices for civil UAS[13]. This process was initiated with the establishing of the ICAO UAS Study Group in 2007[15]. It was also confirmed that the Annexes of the Chicago Convention would need to be revised to provide for UAS[13], and it is accepted that the Chicago Convention will remain the international legal basis for the regulation of manned and unmanned civil aviation[9]. This also implies that Annex 825 of the Convention will remain the legal basis for the regulation of the airworthiness of civil UAS.

The current approach of most ICAO contracting states is to regulate civil UAS against the same, or tailored, requirements that apply to manned aircraft[2,23,34-36], or in terms of regulations for radio controlled model aircraft for smaller unmanned aircraft[10,24,34].

Examples of current UAS regulatory approaches at national level include:

- **FAA Interim Policy**. The legal basis for civil UAS regulation in the USA is the Federal Aviation Regulations (FAR), and the Federal Aviation Administration (FAA) developed an interim UAS policy[3]. With regard to airworthiness, the interim policy requires that all UAS must be airworthy and must conform to the same FAR airworthiness standards that apply to manned aircraft[3,9].
- **EASA Policy Proposal**. Under European Community (EC) Regulation 1592/2002, the European Aviation Safety Agency (EASA) is responsible for the regulation of civil UAS with a maximum take-off mass of 150kg or more. In 2005, EASA developed a UAS airworthiness certification policy[2] which resulted from a joint JAA/Eurocontrol initiative[23]23, and which is based on existing EASA procedures for manned aircraft[2,9]. In addition, it is indicated that airworthiness requirements for UAS under EASA regulation will typically be based on appropriate manned aircraft requirements (EASA 'CS' requirements)[2,9].
- **UK CAA CAP722 and Light UAS Policies**. As a European Union (EU) member state, the UK is responsible for the regulation of UAS of less than 150kg maximum take-off mass, and other UAS that are not included under the jurisdiction of EASA. The UK Civil Aviation Authority (CAA) developed two UAS policies, CAP 7224 and the UK-CAA Policy for Light UAV Systems[24], covering general UAS certification and operating procedures[4], and light visual range UAS[24] respectively. As is the case in most other UAS regulating models, UAS operating under CAP722 must meet at least the same safety and operational standards that apply to manned aircraft[4].
- **Australian CASA Regulations**. The Australian Civil Aviation Safety Authority (CASA) applies Part 101, Unmanned Aircraft and Rocket Operations, of the Civil Aviation Safety Regulations (CASR) to regulate unmanned aircraft and rocket operations[37].
- **SA CAA Interim UAS Policy**. The regulation of civil aviation in South Africa is performed by the South African Civil Aviation Authority (SA CAA) under the Civil Aviation Act[38,39] and the South African Civil Aviation Regulations (SA-CAR)[40] An interim policy[11] for the approval of civil UAS airworthiness and operations in South African airspace was approved by the South African Civil Aviation Regulations Committee (CARCOM) in 2008 and is awaiting implementation by the SA

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CAA. This interim policy is a composition of best practices derived from similar international policies, and from knowledge and experience gained from previous UAS operations in South Africa.

3.3 UAS regulation in military aviation

3.3.1 Regulation of military aviation

A legal basis for the regulation of international military aviation, similar to the Chicago Convention[1], does not currently exist[10,16] and it is generally accepted that the responsibility for assuring military aviation safety is vested in the relevant armed forces at national level[9].

3.3.2 Regulation of airworthiness in military aviation

In most countries, military airworthiness is regulated or managed under a defence department safety programme[16,41]. A Safety Target Model is often used in such safety programmes, in which the aircraft is considered in terms of its intended missions and operating environments and an overall safety target[23] is set[9]. Critical safety issues are identified in a top-down analysis and potential risks are deduced in terms of design and operational requirements[41]. This approach allows the focus to be on reducing or eliminating critical safety risks, rather than on the development and application of detailed airworthiness requirements, particularly when only a limited number of a particular type of aircraft are to be put into operation[9].

A process of initial airworthiness certification and subsequent continued airworthiness assurance of an aircraft system is employed by the NATO Airborne Early Warning and Control Force Command (NAEW&CFC) to ensure that its aircraft systems are supplied and maintained in airworthy conditions[42]. This process is similar to the type and airworthiness certification process in civil aviation. However, instead of being based in legislation, the initial certification is mandated in an airworthiness policy and the continued airworthiness process follows best practices that are derived from both the military and civil aviation domains[9,42].

Although military type certification of aircraft is applied in some countries, its use is not mandated and discrepancies and airworthiness assurance issues often arise as a result of using either the type certification model or the safety target approach. To mitigate these concerns, an industry study[43] proposes a hybrid certification approach. The hybrid approach utilises the type certification process for those elements of a military aircraft for which airworthiness requirements are prescribed in regulations and industry standards[9,43]. The safety target approach is used for the remainder of the aircraft's elements for which airworthiness requirements do not exist[9,43]. The combined safety target and type certification process therefore allows for rapid introduction of modifications and new technologies into operational aircraft and new aircraft designs[43].

3.3.3 Current approaches to regulating the airworthiness of military UAS

Military UAS are used increasingly on a global scale with operations often crossing several international borders. It is therefore becoming increasingly necessary to consider at least the international regulation of military UAS[20,34].

At national level, however, various military UAS regulation and safety oversight programmes have been implemented. The USA Department of the Army Regulation 95–23[21], for example, includes procedures for both national and international Army UAS operations, the UK CAP 722[4] applies equally to civil and military systems, and the UK DEFSTAN 00-970 Part 9[17] describes airworthiness requirements for the design, development and testing of UAS.

France developed military UAV Systems Airworthiness Requirements (USAR)[18], based on the EASA CS-23[44] civil airworthiness requirements, and NATO followed with UAS airworthiness requirements in Draft STANAG 4671[22], which were approved for ratification by NATO nations in 2007. In Sweden, the scope of the Rules for Military Aviation (RML)[45] is to be expanded to also include requirements for UAS[20].

3.4 Industry standards

Regulatory systems often prescribe industry standards to achieve airworthiness objectives. Although industry standards have no legally enforceable status on their own[10], organisations such as the American Institute of Aeronautics and Astronautics (AIAA), the American Society for Testing and Materials (ASTM), the European Organisation for Civil Aviation Equipment (EUROCAE), the Institute of Electrical and Electronic Engineers (IEEE), and the Radio Technical Commission for Aeronautics (RTCA), amongst others, are developing airworthiness and operating standards for unmanned aircraft, onboard systems and supporting systems[10,11,34].

3.5 Regulatory domain for UAS operability

From the above discussions, it was deduced that the Chicago Convention1 will remain the international legal basis for UAS regulation in general, with Annex 8[25] of the Convention continuing to be the international legal basis for at least the airworthiness of UAS. At national level, safety in civil aviation is based on the national legislation and regulations of each ICAO contracting state[9].

Although an international legal basis for regulating military UAS airworthiness does not exist, the regulation and/or oversight of safety in military aviation is achieved at national level in most armed forces on the basis of national military legislation and defence policies[9]. The national legislation and policies will therefore also, for now, remain the basis for the regulation and safety oversight of military UAS airworthiness and operations.

Since the term had not been previously defined as such in aviation legislation and regulations, a legal basis for the regulation of 'UAS operability', rather than just airworthiness, does not exist in either the civil or military aviation regulating domains[9]. For the purposes of this study, therefore, it was decided to use Annex 8[25] of the Chicago Convention as the regulatory basis for developing the UAS operability framework, based on the following considerations[9]:

- The international legal basis for the regulation of airworthiness in civil aviation is Annex 8.
- The international legal basis for the regulation of civil UAS operability can be expected also to be Annex 8, subject to appropriate expansion to accommodate the wider scope of UAS operability requirements.
- There is currently no international legal basis for the regulation of military aviation, and at national level the formal regulation of military airworthiness in particular is only gradually being introduced. The regulation of the airworthiness of military UAS is done similarly to the regulation of military manned aircraft, and cognisance is also taken of civil aviation requirements for UAS to assure authorisation of UAS operations in civil airspace, when required.

In addition to the regulatory basis, it was also necessary to define the technical scope of the regulatory basis in as far as it would be applicable to UAS operability, and the study identified the following[9]:

- Although Annex 8[25] of the Chicago Convention provides guidance for developing UAS operability criteria, it does not adequately address the total scope of UAS operability.

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- UAS operability should not be based on manned aircraft requirements or currently perceived UAS-unique requirements only, but must also provide for new and novel technologies.
- The regulation of military UAS operability should be co-ordinated, but not necessarily harmonised, with civil regulations.
- Both civil and military aviation regulators should consider the application of a hybrid airworthiness/operability certification approach to enable rapid introduction of new technologies.
- Although the regulation of UAS operability will continue to be performed mostly manually for the foreseeable future, the concept of developing a degree of automated UAS operability regulation should be considered.

From these considerations, it was concluded that the regulatory domain for the UAS operability framework should be based on Annex 8[25] of the Chicago Convention and that its technical scope should apply to both civil and military UAS. Finally, the modernising of the process of regulating UAS should be given consideration to ensure effective and optimal regulation of UAS operability in the future.

4.0 DEVELOPMENT OF THE UAS OPERABILITY FRAMEWORK

4.1 Introduction

The development of the UAS operability framework was divided into three phases. The first phase included the development and evaluation of the UAS airworthiness requirements framework developed originally as part of this study. During the second phase the UAS operability framework was developed and in the final phase, this framework was validated.

4.2 Phase 1: The original UAS airworthiness requirements framework

The original objective of this study was to focus on regulatory aspects of UAS airworthiness. Therefore, during an in-depth survey, the regulation of manned aircraft airworthiness was investigated and existing UAS policies and regulations, both for airworthiness and operations, were studied. It was also established that the regulation of the flightworthiness of RLVs[26,27] provided significant additional material that could be reviewed and applied in the development of airworthiness requirements for UAS.

Based on the results of the survey, the original UAS airworthiness requirements framework was developed. The framework was primarily based on Annex 8[25] of the Chicago Convention1, the French DGA's USAR[18] requirements for military UAS, and other appropriate regulatory and policy references[2-4,23,24,37] for airworthiness and flightworthiness. The framework is generic in scope and is not limited to a particular type or category of UAS. It was also anticipated that the framework would be used for civil and military UAS, and for establishing engineering and regulatory requirements for UAS airworthiness.

This original framework was published for peer review[10] and was also subsequently evaluated in terms of the operability objectives of this study[9].

Although the original framework represented the best practices in the regulation of manned aircraft airworthiness, UAS airworthiness and RLV flightworthiness, its evaluation indicated numerous aspects that required additional research. The most significant of these was the need to expand the scope of the framework to more than just the airworthiness of the aircraft and the 'airworthiness' of the remote control station[10].

Thus, although the original framework was a significant contribution towards defining UAS airworthiness requirements10, its limitations required a review of the objectives of this study, and the second phase of developing the UAS operability framework was initiated[9].

4.3 Phase 2: The UAS operability framework

The development of the UAS operability framework commenced with a detailed analysis and critical evaluation of the original UAS airworthiness requirements framework[10] to identify its critical shortcomings. In addition, the definition of the concept of UAS operability was analysed to determine which additional aspects of a UAS had to be addressed to achieve the objectives of this study.

Based on the results of this work, it was confirmed that the operability framework should address the UAS as a system of systems, and it should address the airborne and non-airborne sub-systems of the UAS, as well as its payloads.

4.3.1 Evaluation of the original UAS airworthiness requirements framework

In evaluating the original framework[10] in respect of operability objectives from an engineering perspective, the following issues were identified[9]:

- Only criteria to achieve the airworthiness of the aircraft, and the 'airworthiness' of the remote control station, are included in the framework.
- The structure of the framework effectively mirrors the structure used in manned aircraft regulations and does not reflect engineering domain requirements for the complete UAS.
- Part I, Definitions and Classifications, of the framework addresses UAS-specific terminology and UAS classifications as used in regulations, and would need to be revised to be relevant in the UAS engineering domain.
- Part II, Procedural Requirements, includes regulatory procedures for the administration of UAS airworthiness approvals. For the purposes of this study, however, this Part should prescribe administrative processes that are aligned with regulatory requirements, but which can be applied by the engineering domain to ensure that UAS operability is achieved in an accountable and traceable manner.
- Part III, Unmanned Aerial Vehicle and System Airworthiness Requirements, of the framework includes airworthiness criteria that primarily address typical regulatory requirements only, and which are limited to the aircraft and remote control station. For the purposes of this study, this part should address UAS operability from an engineering perspective and should include operability requirements for the UAS as a system, for its airborne sub-systems, for its non-airborne sub-systems and for its payloads.

The evaluation of the original UAS airworthiness requirements framework[9] indicated that a significant revision of the framework would be required if the operability of a UAS and its sub-systems were to be addressed comprehensively in the contemplated UAS operability framework.

4.3.2 Conceptualising the UAS operability framework

The UAS operability framework was conceptualised to be an effective UAS engineering development tool, while reflecting the intent of safety regulation in aviation. Based on the following considerations, this was achieved by using the original UAS airworthiness requirements framework[10] as a basis for a new, improved and expanded framework:

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- Because the UAS operability framework is primarily intended for use by the engineering domain, it should include the necessary generic and comprehensive engineering criteria that would ensure the safe and reliable functioning of a UAS, whether regulated or not. These criteria should, however, recognise the scope of the UAS regulatory domain[9].
- In practice, the operability framework would be used to identify the applicable operability elements that would apply in the engineering development of a particular UAS. The operability criteria associated with those elements would then be used to develop appropriate engineering processes, procedures and requirements for the UAS. The operability framework should therefore be usable in the engineering of UAS.
- The operability framework should guide the UAS engineering domain to produce engineering work that would be accepted in terms of regulatory requirements, whether the UAS is regulated or not9. However, although the framework is intended to guide the engineering of safe and reliable UAS, regulatory compliance may become an operational requirement or objective for a particular UAS. In this case, the engineering development foundation derived for the particular UAS from the framework should be sufficiently sound to enable the showing of compliance with relevant regulations without the need to re-develop the UAS.

4.3.3 Developing the UAS operability framework

Based on the evaluation of the original UAS airworthiness framework and the concept considerations for the new operability framework, the UAS operability framework was developed as follows[9]:

- Relevant engineering elements in the original UAS airworthiness framework were identified for use and regulatory elements were discarded.
- The structure of the original framework was revised, refined and expanded to three hierarchical levels to make provision for UAS definitions and classifications, procedural requirements for UAS engineering development processes, and operability criteria for UAS, their sub-systems and their payloads.
- The new operability framework structure was defined and validated to ensure that the objective of establishing a generic and comprehensive engineering framework was achieved.
- Subsequent to the validation of the new operability framework, its structure was further refined to reflect improvements required as a result of the validation process.

The UAS operability framework that resulted from this development process achieved the study objectives and has the following properties:

- The framework is a UAS engineering development tool, intended for use primarily in the engineering domain. However, the framework is sufficiently generic to be useful as a reference source for developing UAS regulations.
- The operability elements and criteria are generic and comprehensive, and are not limited to a specific type, class or category of UAS.
- Part I, Definitions and Classifications, of the framework provides for the definition and classification of specific engineering terms, requirements, specifications and documentation for a particular UAS. For reference purposes, Part I is presented in Appendix A1, Table A1.
- Part II, Procedural Criteria, includes administrative procedures that should be applied to ensure accountability and traceability in the relevant engineering processes, and to ensure compliance with regulatory requirements when required. Part II is presented in Appendix A2, Table B1.
- Part III, UAS Operability Criteria, includes the operability criteria for UAS in three sub-parts. Part III is included in Appendix A3.
- Part IIIA, System of Systems Operability Criteria, addresses the operability of the UAS as a system of systems. A systems engineering approach was applied to develop appropriate UAS-specific criteria from reference material used by the United States Department of Defense[46] and NASA[47]. Part IIIA of the operability framework is presented in Appendix A3, Table C1.
- Part IIIB, Airborne Sub-Systems Operability Criteria, includes operability and airworthiness criteria for the aircraft, as well as for any other critical airborne sub-systems of the UAS that are necessary to ensure the safe and reliable functioning of the UAS as a system. This part is included in Appendix A3, Table C2.
- Part IIIC, Non-Airborne Sub-Systems Operability Criteria, includes operability criteria for all non-airborne sub-systems of the UAS, including remote control stations and any other required support sub-systems. These non-airborne sub-systems could typically be ground-based, water-based, based on seafaring vessels, submarine based, building based, or man-carried. Part IIIC is included in Appendix A3, Table C3.
- Part IIID, Payload Operability Criteria, covers the payloads that are to be carried by UAS. This sub-part includes operability criteria for functional and cargo payloads, and makes provision for internal and external payloads. Human passengers and live animals are, however, excluded from this sub-part for the purposes of this study. Part IIID is included in Appendix A3, Table C4.
- To ensure consistency in the structure of the framework, the topical layouts of Parts IIIB, C and D were kept substantially similar.

4.4 Phase 3: Validating the UAS operability framework

Being the result of a research study, it was necessary to validate the UAS operability framework against the research objectives. However, it was also important to show that the framework was more than just an engineering index of UAS operability criteria. Therefore, in addition to an appropriate validation process, it was necessary to evaluate the framework as an engineering tool in terms of its relevance, comprehensiveness and generalised character[xx]9.

The framework validation was achieved by expanding the structure of the framework to a fourth hierarchical level and by populating the framework with operability criteria that were specifically developed for each sub-part, section and sub-section[9].

The operability criteria were newly developed by applying sound engineering judgement and experience, or were based on best industry practices where such practices were identified in regulatory and engineering literature[9]. The operability criteria are not engineering specifications, but are guidelines that should be used to identify the relevant operability requirements and develop the associated engineering specifications for a particular UAS, in addition to any other client-specified requirements.

The structural elements of the framework, as well as the operability criteria with which the elements were populated, were evaluated by applying engineering judgement to determine whether:

- the framework and criteria were sufficiently generic and comprehensive to be applied to any type of UAS;
- the framework and criteria could be applied in the engineering development of both regulated and non-regulated UAS;

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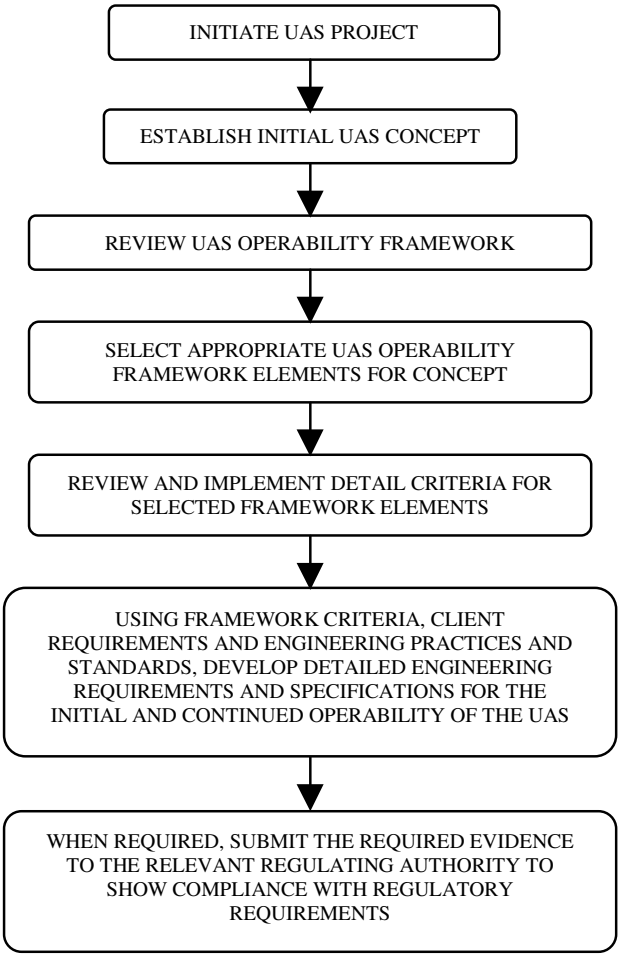


Figure 2. Utilising the UAS operability framework in the UAS engineering domain.

- the framework and criteria could be applied to a UAS as a system, as well as independently to any UAS sub-system (airborne, non-airborne or payload); and
- whether the criteria could be applied to develop specification-level UAS engineering development requirements.

The operability framework, as well as the operability criteria with which it is populated, were found to be relevant, comprehensive and generic, and were also found to contain sufficient detail from which appropriate engineering requirements and specifications for the development of UAS can be developed and implemented to achieve the safe and reliable functioning of UAS.

5.0 FRAMEWORK UTILISATION

The UAS operability framework can be utilised for the selection of appropriate operability and airworthiness criteria for the engineering development of a UAS. The framework complements the standard technical specification for the UAS, as supplied by the client, by guiding the development process towards a system that can be operated safely and reliably within the scope of the currently developing and maturing UAS regulatory domain. In addition, the framework provides a basis for achieving consistency in the process of engineering UAS.

The intended process for utilising the framework in the UAS engineering domain is illustrated in Fig. 2.

Beyond the UAS engineering domain, the framework and its operability content criteria can be utilised as reference material in the development of regulatory requirements for UAS, while other airspace users can use the framework as an example for developing similar frameworks in their own domains.

6.0 CONCLUSIONS AND RECOMMENDATIONS

In order to guide the engineering development of UAS that are safe and reliable, the UAS operability framework was established and populated with engineering criteria specifically intended to be applicable to the UAS engineering domain.

This was achieved by:

- defining the operability of a UAS to include the safe and reliable functioning of the UAS as a system, the airworthiness of its airborne sub-systems, and the safe and reliable functioning of its non-airborne systems and payloads;
- defining the regulating domain within which the engineering criteria were developed;
- developing the framework structure; and
- validating the framework by populating it with appropriate operability criteria.

It is recommended that:

- the framework and criteria be applied to actual UAS projects for further evaluation and improvement of the framework;
- the framework be evaluated for use as a reference tool in the development of UAS regulations;
- the framework be reviewed and updated regularly to maintain its relevance; and
- the framework development process be considered to develop similar operability and/or airworthiness frameworks for other aerospace products.

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APPENDIX A1

Table A1
The UAS Operability Framework: Part I

PART	SUB-PART	SECTION	SUB-SECTION
UAS OPERABILITY FRAMEWORK PART I — DEFINITIONS AND CLASSIFICATIONS			
	General		
	Definitions		
	Classifications		

APPENDIX A2

Table B1
The UAS Operability Framework: Part II

PART	SUB-PART	SECTION	SUB-SECTION
UAS OPERABILITY FRAMEWORK PART II —PROCEDURAL CRITERIA			
	Introduction		
	General Criteria	Applicability	
		Types of Approvals and Certifications	Engineering Approvals; Regulatory Approvals and Certifications
		Administration	Engineering Processes
		Safety Assurance	General
		Safety Assurance	General
		Training	General
		Licensing	General
	Procedures for Approvals and Certifications Associated with UAS Operability	General	Applicability; Eligibility; Designated Authorisations; Application for Approvals and Certificates; Applicable Requirements; Special Conditions; Issuing of Approvals and Certificates; Approval/Certificate Holder Responsibilities; Deviations; Non-compliance; Changes Requiring New Approvals and Certificates; Inspections by Authority; Suspension/Cancellation of Approvals/ Certificates
	Criteria for Initial and Continued Compliance with Operability Requirements	Introduction	
		Initial Compliance	Qualification; Design Type Certification; Engineering Process
		Continued Compliance	Continued Compliance Process and Procedures
	Risk Management	Introduction	
		Risk Management Criteria	Hazard Identification; Risk Assessment; Risk Control Plan; Risk Acceptance; Risk Tracking

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APPENDIX A3

Table C1
The UAS Operability Framework: Part IIIA

PART	SUB-PART	SECTION	SUB-SECTION
UAS OPERABILITY FRAMEWORK PART III — UAS OPERABILITY CRITERIA			
UAS OPERABILITY FRAMEWORK PART IIIA — SYSTEM OF SYSTEMS OPERABILITY CRITERIA			
	Introduction	Engineering Approach Criteria; Engineering Process Criteria	
	System Operability	Achieving Initial System-level Operability	Define Missions and System Requirements; Conceptualise System and Constituent Sub-Systems; Systems and Finalise System of Sub-system Designs, Integrate System of Systems Sub-systems; Test and Evaluate System of Systems; Acceptance of System of Systems; Confirm System of Systems Operability
		Maintaining Continued System-level Operability	Acceptance of System of Systems; Confirm System of Systems Operability; Monitor and Maintain System of Systems Continued Operability; Monitor and Maintain Sub-system Continued Operability; Confirm Post-maintenance System of Systems Operability; System of Systems Termination, Decommissioning and Disposal

Table C2
The UAS Operability Framework: Part IIIB

PART	SUB-PART	SECTION	SUB-SECTION
UAS OPERABILITY FRAMEWORK PART III — UAS OPERABILITY CRITERIA			
UAS OPERABILITY FRAMEWORK PART IIIB — AIRBORNE SUB-SYSTEMS OPERABILITY CRITERIA			
	Introduction		
	General	Applicability	
		Operations and Missions of the UAS Airborne Sub-systems	
	Flight and Ground Handling	General	Verification and Validation; Aircraft Principles of Flight; Aircraft Weights; Centre of Gravity Range and Limits; Removable Ballast; Payload and Payload Distribution; Load Distribution Limits; Airborne Sub-systems other than the Aircraft
		Aircraft Performance	General; Minimum Flight Speed; Stall Speed; Take-off/ Launch Performance; Climb Performance; Glide Performance; Landing/Recovery Performance; Cruise Performance; Manoeuvring Performance and Limitations;

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		Loitering Performance; Combat Performance and Limitations; Maximum Speed; Endurance; Range; Performance of Airborne Sub-systems other than the Aircraft
	Flight Characteristics	General; Aircraft Aerodynamics; Aircraft Flight Characteristics; Flight Characteristics of Airborne Sub-systems other than the Aircraft
	Controllability and Manoeuvrability	General; Flight Control System; Minimum Control Speed; Trim
	Stability	Stability Characteristics
	Stalls	Stalls; Stall Protection
	Spinning	Spinning
	Characteristics	Surface Handling; Stability and Control; Operation from Unprepared Surfaces
	Miscellaneous Requirements	Vibration and Buffeting; High Speed Characteristics; Other Novel Characteristics
	Assisted Take-Off/Launch	Take-off/Launch Safety; Take-off/Launch System Interfacing; Take-off/Launch Performance; Transition to Normal Flight; Control of Aircraft During Take-off/Launch
	Assisted Landing/Recovery	Landing/Recovery Safety; Aircraft Performance before Landing/Recovery; Landing/Recovery System Interfacing; Control of Aircraft During Landing/Recovery
	Emergency Landing/ Recovery	Emergency Landing/Recovery Safety; Emergency Landing/Recovery System Interfacing; Control of Aircraft during Emergency Landing/Recovery
Flight and Surface Operation Load Considerations	Flight Loads	General; Flight Loads and Flight Load Considerations
	Control System Loads	General; Primary Control System Loads; Secondary Control System Loads; Limit Control Forces and Torques; Surface Gust Conditions
	Pitch Control Device Loads	General; Pitch Control Device Loads; Balancing Loads; Unsymmetrical Loads; Trim Device Loads; Trim Device Effects; Surface Gust Loads
	Yaw Control Device Loads	General; Yaw Control Device Loads; Balancing Loads; Unsymmetrical Loads; Outboard Fins and Winglets; Trim Device Loads; Trim Device Effects; Surface Gust Loads
	Roll Control Device Loads	General; Roll Control Device Loads; Balancing Loads; Unsymmetrical Loads; Trim Device Loads; Trim Device Effects; Surface Gust Loads
	Surface Operation Loads	General; Surface Operation Loads and Surface Operation Load Considerations
	Emergency Conditions	General
	Catapult Assisted and Rocket Assisted Take-Off Loads	Launch Loads; Trolley or Shuttle Loads; Rocket Assisted Take-off Loads
	Parachute Recovery System Loads	Parachute Recovery Loads; Extracting Devices; Sacrificial Elements; Aircraft Dragging on the Surface
Design and Construction	General	Factors of Safety; Strength and Deformation; Materials; Fatigue Strength and Evaluation; Flutter; Fabrication Methods and Workmanship; Protection of Structure; Accessibility Provisions; Health Monitors and Data Recorders; Icing, Lightning and Other Environmental Protection; Human Factors
	Flight Management System	Flight Management System; Flight Safety System; Flight Control System; Autonomy; Health Monitors and Data Recorders

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	Structures	Primary Structural Elements; Other Structural Elements; Flight Controls; Onboard Launch System Elements; Onboard Recovery System Elements
	Rotors	General
	Flight Control Devices	General; Surface Gust Conditions
	Control Systems	General
	Landing Gear	General
	Payload and Equipment Accommodations – Internal and External	Internal Compartments; External Equipment Installations; External Payload Hardpoints
	Pressurisation and Environmental Control Systems	Pressurised Compartments; Environmental Control Systems
	Fire Protection	General; Fire Extinguishing Systems
	Miscellaneous	Levelling Means; Ballast Provisions
	Floats and Hulls	General
	Emergency Systems	Emergency Recovery Systems; Flight Termination Systems
	Electrical Systems	General
	Software	General; Software Maintenance
	Navigation and Communication Systems	General
	Mechanical Systems	General
Powerplant and Powerplant Installation	General	Powerplant Type; Rotor and Power Transmission Systems
	Powerplant Systems	General; Transmissions and Gearboxes
	Fuel Systems	General; In-flight Refuelling Systems
	Energy Storage Systems	General
	Powerplant Fire Protection	General
	Powerplant Controls and Accessories	Powerplant Controls; Powerplant Accessories
Hazard and Collision Avoidance	Hazard Avoidance Systems	General
	Collision Avoidance Systems	General
Avionics, Instruments and Equipment	General	Software; Software Maintenance
	Communication and Navigation Equipment	Communication Equipment; Command and Control Data Link; Navigation Equipment
	Instruments and Sensors	General
	Automatic Take-off and Landing Systems	General; Manual and Automatic Abort Functions
	Electrical Equipment	General; Batteries; Circuit Protection Devices; Switches; Lights and Lighting Systems
	Safety Equipment and Emergency Capabilities	Safety Equipment; Emergency Capabilities
	Miscellaneous Equipment	General
Operating Limitations, Safety Information and System Manual	Operating Limitations	General
	Markings and Placards	General
	Aircraft/Airborne Sub-system Manual	General
Continued Operability and Airworthiness	Continued Operability and Airworthiness Requirements	General
Security	Aircraft/Airborne Sub-system Security	General

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Table C3
The UAS Operability Framework: Part IIIC

PART	SUB-PART	SECTION	SUB-SECTION
UAS OPERABILITY FRAMEWORK PART III — UAS OPERABILITY CRITERIA			
UAS OPERABILITY FRAMEWORK PART IIIC — NON-AIRBORNE SUB-SYSTEMS OPERABILITY CRITERIA			
	Introduction		
	General	Applicability Functions of Non-Airborne Sub-systems	
		General	Verification and Validation
		Take-off/Launch System	General; Take-off/Launch System Safety
	Operating and Functional Characteristics	Landing/Recovery System	General; Landing/Recovery System Safety; Emergency Landing/Recovery Safety
		Remote Control Station	General; Remote Control Station Safety
		Other Non-Airborne Support Systems	General; Support System Safety
	Load Considerations	Take-off/Launch System Loads	General
		Landing/Recovery System Loads	General
		Remote Control Station Loads	General
		Other Non-Airborne Support System Loads	General
		Emergency Conditions	General
	Design and Construction	General	Factors of Safety; Strength and Deformation; Materials; Fatigue Strength and Evaluation; Fabrication Methods and Workmanship; Protection of Structure; Accessibility Provisions; Health Monitors and Data Recorders; Icing, Lightning and Other Environmental Protection; Human Factors; Transportability; Storage Provisions
		Structures	Primary Structural Elements; Other Structural Elements
		Controls and Equipment	General
		Internal Environment Control Systems	General
		Fire Protection	General; Fire Extinguishing Systems
		Environmental Hazards Protection	General
		Emergency Systems	General
		Electrical Systems	General
		Software	General; Software Maintenance
		Mechanical Systems	General
		Powerplants	General

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Instruments and Equipment	General	Software; Software Maintenance
	Communication Equipment	Communication Equipment; Command and Control Data Link
	Instruments and Sensors	General
	Electrical Equipment	General; Batteries; Circuit Protection Devices; Switches; Lights and Lighting Systems
	Safety Equipment and Emergency Capabilities	Safety Equipment
	Miscellaneous Equipment	General
Operating Limitations, Safety Information and System Manuals	Operating Limitations	General
	Markings and Placards	General
	System Manuals	General
Continued Operability	Continued Operability Requirements	General
Security	Non-Airborne Sub-system	General

Table C4
The UAS Operability Framework: Part IIID

PART	SUB-PART	SECTION	SUB-SECTION
UAS OPERABILITY FRAMEWORK PART III — UAS OPERABILITY CRITERIA			
UAS OPERABILITY FRAMEWORK PART IIID — PAYLOAD OPERABILITY CRITERIA			
	Introduction		
	General	Applicability	
	General and Functional	General	Verification and Validation
	Characteristics	Cargo Payloads	General; Payload Safety
		Functional Payloads	General; Payload Safety; Safety during UAS Emergency
	Load Considerations	Cargo Payloads	General
		Functional Payloads	General
		Emergency Conditions	General
	Design and Construction	General	Factors of Safety; Strength and Deformation; Materials; Fatigue Strength and Evaluation; Fabrication Methods and Workmanship; Protection of Structure; Accessibility Provisions; Health Monitors and Data Recorders; Icing, Lightning and Other Environmental Protection; Human Factors; Transportability; Storage Provisions
		Structures	Primary Structural Elements; Other Structural Elements
		Controls and Equipment	General
		Fire Protection	General
		Environmental Hazards Protection	General
		Emergency Systems	General
		Electrical Systems	General
		Software	General; Software Maintenance

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	Mechanical Systems	General
Instruments and Equipment	General	Software; Software Maintenance
	Communication Equipment	Communication Equipment; Data Link
	Instruments and Sensors	General
	Electrical Equipment	General; Batteries; Circuit Protection Devices; Switches; Lights and Lighting Systems
	Miscellaneous Equipment	General
Operating Limitations, Safety Information and System Manuals	Operating Limitations	General
	Markings and Placards	General
	System Manuals	General
Continued Operability	Continued Operability Requirements	General
Security	Payload Security	General

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