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A Review of the Concept of Autonomy in the Context of the Safety Regulation of Civil Unmanned Aircraft Systems

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Abstract

Civil aviation safety regulations and guidance material classify Unmanned Aircraft Systems (UAS) as either Remotely-Piloted Aircraft Systems (RPAS) or Autonomous Aircraft Systems (AAS). This distinction is based on the premise that the effective safety risk management of UAS is dependent on the degree of autonomy of the system being operated. However, it is found that there is no consensus on the concept of autonomy, on how it can be measured, or on the nature of the relationship between Levels of Autonomy (LoA) and the safety-performance of UAS operations.

An objective of this paper is to evaluate existing LoA assessment frameworks for application in aviation safety regulations for UAS. The results from a comprehensive review of existing concepts of autonomy and frameworks for assessing LoA are presented. Six case study UAS were classified using the published LoA frameworks. The implied LoA of UAS for existing modes of operation (e.g., teleoperation, semi-autonomous) were also assessed using the published frameworks.

It was found that the existing LoA assessment frameworks, when applied to the case study UAS, do not provide a consistent basis for distinguishing between the regulatory classes of RPAS and AAS. It was also found that the existing regulatory definition of an autonomous aircraft is too broad, covering UAS of significantly different levels of capability and system complexity. Within the context of aviation safety regulations, a new LoA assessment framework for UAS is required.

Keywords: Autonomy, Unmanned Aircraft Systems, UAS, Regulation

1 Introduction

A classification scheme establishes the foundation for a regulatory framework for civil Unmanned Aircraft Systems (UAS). The components of the International Civil Aviation Organization (ICAO) regulatory classification framework relevant to the regulation of civil UAS are shown in Figure 1. ICAO (2011) defines an UAS as "an aircraft and its associated elements which are operated with no pilot on board." As illustrated by Point A in Figure 1, ICAO further classifies UAS as being either Remotely-Piloted Aircraft Systems (RPAS) or Autonomous Aircraft Systems (AAS)[1]. Where a Remotely-Piloted Aircraft (RPA), a component of the RPAS, is defined as:

> *An aircraft where the flying pilot is not on board the aircraft.*

and, an *Autonomous Aircraft* as:

> *An unmanned aircraft that does not allow pilot intervention in the management of the flight.*

Implicit to this regulatory distinction is the premise that the effective safety risk management of UAS is dependent on the degree of autonomy of the system being operated. However, there is no consensus on the meaning of "autonomy", on how it can be measured, or on the nature of the relationship between levels of autonomy and the safety-performance of UAS operations. Given the foundational role classification plays in the development of a regulatory framework, further clarity on the meaning and definition of autonomy is needed in order to progress the development of regulations and standards for UAS.

This paper presents a review of existing concepts of autonomy with the view to evaluate their use in the refinement of existing regulatory classifications of UAS. A comprehensive review of the literature is undertaken. The review identifies a number of definitions for the general concept of autonomy. The differences between these definitions and those of other related concepts are discussed in Section §2. The literature review also reveals numerous possible frameworks for assessing the degree or Level of Autonomy (LoA) of a system (presented in Section §3). In Section §4, the assessment frameworks are applied to six

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[1] ICAO does not explicitly define Autonomous Aircraft System (AAS). A definition of an *Autonomous Aircraft*, a component of an AAS, is provided implying the existence of the AAS class of UAS.

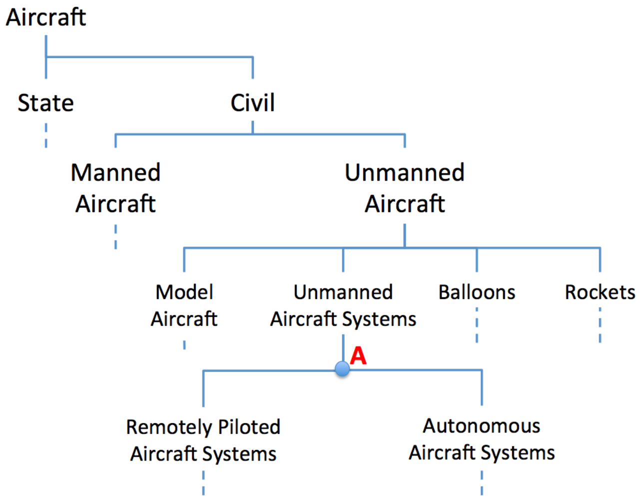

Figure 1: ICAO Regulatory Classification Framework (focused on UAS component) (ICAO 2011)

case study UAS. The LoA determined for the case study UAS are then compared against the LoA corresponding to the ICAO definition of an *Autonomous Aircraft.*

ICAO (2011) also defines an *Autonomous Operation.* A review of the literature reveals numerous definitions of the UAS modes of operation. The modes imply different LoA in the system being operated. The modes of operation and their corresponding LoA are briefly reviewed in Section §4.3.

Section §5 provides discussion and recommendations on a LoA framework for use in the regulation of UAS. A summary of the key outcomes from the study are presented in Section §6.

2 General Concepts of Autonomy

We start by exploring the common meaning of the concepts of *autonomy*, *autonomous* and the related notions of *automatic* and *automated.* The Oxford English Dictionary defines autonomy as being *"the right or condition of self-government; freedom from external control or influence; independence."* and autonomous as *"having the freedom to govern itself or control its own affairs; having the freedom to act independently."* (Stevenson 2012)

On first inspection these definitions convey a simple concept of autonomy/autonomous, that which can be defined entirely by the degree of dependency or interaction between two entities (e.g., the human Remote Pilot (RP) and an UAS).

The higher the LoA of the UAS, the less the human RP is involved in the operation and the more the UAS subsumes the role of the human RP. It is important to recognise that in order to maintain system performance, as the degree of independence increases, so too does the need for the UAS to exhibit the more complex properties that were previously provided by the human RP (e.g., the ability of the UAS to perceive its environment, make decisions, and to modify its behaviour and change its goals accordingly, etc.). Thus, the higher the degree of independence, the higher the implied complexity of the UAS. Ultimately, if the performance of the Human-Machine System (HMS) is to remain the same, then full autonomy would imply that the UAS is capable of performing all of the functions traditionally provided by a RP.

This leads us to the second and more common concept of autonomy, that which makes the relationship between increasing independence and the increasing complexity of the machine explicit (e.g., see definitions summarised in Table 1 of Appendix A). Evident in these definitions of autonomy are the properties of higher-order systems in addition to the degree of freedom or independence from external influence or control. Such properties can only exist in more complex systems; those systems residing in the higher tiers of Boulding's General Hierarchy of Systems (Boulding 1956). Put differently, these definitions have associated the concept of autonomy with complex-system properties such as intelligence, self-awareness, adaptation, and cognition etc., which are properties not present in low-complexity systems (i.e., those classified as belonging to the tiers of frameworks, clockworks, or thermostats in Boulding's Hierarchy).

This provides some explanation for the ongoing difficulties encountered when defining autonomy. There are two camps. The first considers autonomy as being completely described by the property of independence between two entities (e.g., Clough (2002)). This property can be identified in systems residing at any tier in Boulding's General Hierarchy of Systems. The second camp makes explicit the relationship between increasing autonomy (i.e., independence) and the increasing complexity required of the machine in order to maintain a desired level of performance (i.e., the increasing need for the machine to resemble "people"). This second notion of autonomy is not as clearly defined, having been associated with more complex and equally debated system properties (e.g., system intelligence).

Finally, it is worth noting the difference between autonomous and automatic. The Oxford English Dictionary defines automatic as *"(of a device or process) working by itself with little or no direct human control."* (Stevenson 2012) Definitions of automated/automatic identified in the broader literature are summarised in Table 1. There is little distinguishing the notion of automatic from that of the simpler notion of autonomous. A fully autonomous UAS (i.e., one that is entirely independent of human influence or control) could also be identified as automatic, and vice versa. Take, for example, a wristwatch. A wristwatch can be described as automatic. Under the simpler notion of autonomy, the wristwatch can be determined as having a high LoA as it performs its task (measuring and display of time) largely independent of the person wearing it. Whereas, using the more complex notion of autonomy the automatic wristwatch is likely to be assigned a very low LoA (a wristwatch is not intelligent or adaptive, etc.).

The authors agree with Clough (2002) who advocate that the property of autonomy is distinct from other complex properties such as system intelligence. However, the authors recognise that in order to maintain system performance at increasing LoA, the degree of intelligence, adaptability, etc. of the machine must also increase. A pragmatic framework for assessing the LoA of a system may need to take into consideration these additional relationships. This appears to be the (implicit) position adopted by the majority of the assessment frameworks identified in the literature.

3 Assessing Levels of Autonomy

Numerous frameworks for assessing the LoA of a system have been proposed. A summary of the more common frameworks and those that have been previously applied to UAS is provided in Table 2 of Appendix A. Some of the key points of difference between these frameworks include:

1. *Measurement Scales* - LoA have been expressed using ordinal, interval and ratio measurement scales (refer to Stevens (1946) for definitions of scales). The majority of existing frameworks measure a LoA on an ordinal scale. Measures of the difference between LoA defined on an ordinal scale are not meaningful. All that can be ascertained is whether the LoA of one system is less than, equal to, or greater than the LoA of another system. Interval scales permit measures of the magnitude of the difference between differing LoA, however this difference has no 'absolute' reference point. Measurements made on a ratio scale permit assessments of the multiplicative difference between the LoA of different systems (e.g., a system has twice the autonomy of that of another).

2. *Number of Levels* - The number of discrete LoA proposed for ordinal scales ranges from four to twelve (refer to Table 2). The literature provides limited justification for the number of levels proposed.

3. *Component Properties* - The assessment frameworks describe a LoA using a range of properties of the HMS. For example, the degree of human/operator control or interaction with the UAS, the allocation or performance of certain functions or tasks to the human or the machine, or the complexity of the mission or environment in which the HMS operates. Differences in the properties used to assess autonomy arise due to differences in the underlying concepts of autonomy and differences in the context in which the assessment frameworks are used. For example, Clough (2002) defines a LoA assessment framework for military UAS. The proposed LoA assessment framework includes factors such as battle space cognisance, targeting and multi-vehicle coordination. On the other hand, the LoA framework proposed by Billings (1991) was primarily intended for the assessment of cockpit automation and hence the LoA are described in relation to the degree of pilot control and management of a single aircraft.

4. *Measurement* - Two approaches have been used to determine the measure of the LoA:

    (a) A single measure of the LoA of a system is determined from the mathematical 'combination' or 'mapping' of the independent properties used to characterise autonomy. For example, Kendoul (2011) determines a LoA for an UAS by combining independent measures of the guidance, navigation and control capabilities of the UAS. Methods for aggregating the component measures into a single LoA include addition or weighted linear combination.

    (b) The LoA is assessed in relation to independent functions or contexts without aggregation into a single LoA for the system. For example, Parasuraman et al. (2000) measure a LoA in terms of four "broad classes" of functions. The four measures are not aggregated to provide an assessment of the overall LoA of the system.

The above differences make comparisons between the various autonomy assessment frameworks difficult.

4 Evaluation of Assessment Frameworks

Six generic case study UAS are defined. The case study UAS serve as test points for evaluating the existing LoA assessment frameworks. Four of the case study UAS describe systems in use today, with the final two UAS describing systems with capabilities that only currently exist in science fiction[2]. The six generic configurations are:

> **UAS A:** An UAS where the Unmanned Aircraft (UA) is capable of executing a pre-programmed behaviour (e.g., following a series of waypoints) and where it is not possible for the Remote Pilot (RP) to interact with the UA after launch except possibly where to terminate flight. There is significant human interaction in the mission planning phase, but no interaction is possible after launch. An example of this type of UAS are early variants of the Ryan Lightning Bug, a reconnaissance UAS that once launched followed a pre-programmed route without interaction with a RP.
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> **UAS B:** An UAS where the operation of the UAS requires continual input from, or interaction with, a RP. For example, an UA where the flight control surfaces are manipulated by the RP via a data link.
>
> **UAS C:** An UAS where the UA, under normal operating conditions, does not require continual input from, or interaction with, a RP to perform its mission. The RP may or may not interact with the UA during the mission but interaction is possible. The RP continuously monitors the status and performance of the UAS. The behaviour of the UAS can be pre-programmed before the flight or updated by the RP during the flight. RP interactions are predominantly high-level and in the form of deviations to pre-programmed behaviour (e.g., new waypoints) due to changes in the mission objectives, failures in the system or changes in the environment. The behaviour of the UAS is deterministic. The majority of current UAS would be described by this case study system.
>
> **UAS D:** An UAS with all the capabilities of case study type 'C' UAS with the additional capability of the UAS being able to change its behaviour in response to changes in its environment or performance. Given predefined goals the UAS will determine how to achieve those goals within the constraints defined by the RP or system designer. Constraints on the behaviour of the UAS are static and hard (i.e., they cannot be changed or breached by the UAS). Given the goals and constraints the behaviour of the UAS can be non-deterministic, although the bounds on the behaviour are always known. Under normal operating conditions, the RP

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[2] The films identified by the authors are for illustrative assistance in understanding the described configuration and makes no comment in relation to the quality of the film.

has the ability to override decisions made by the UAS. This configuration is in the R&D stage with possible systems in flight test.

UAS E: An UAS analogous to the fictitious "HAL 9000 computer" portrayed in the novel and screenplay "2001: A Space Odyssey" (Clarke 1968). Recall the words from HAL "I'm sorry, Dave. I'm afraid I can't do that." An UAS of this type has all the capabilities of case study 'D' UAS with the additional capability of the UAS being able to override or deny the inputs of the RP. The UAS maintains the initial goals and remains within predefined constraints on its behaviour (as determined by the system designer or programmed before the mission). The ability for the RP to change the goals and/or constraints of the UAS is lost or impaired.

UAS F: An UAS analogous to the fictitious "Extreme Deep Invader (EDI)" portrayed in the Columbia Pictures film "Stealth". For this type of UAS, the UAS performs all of the functions that a RP would and like type 'E' UAS, can operate without the need for interaction with the RP. Interaction between the UAS and the RP is possible but only if the UAS so chooses. The UAS may change its goals and/or constraints independent of the RP.

The autonomy of an UAS can change for different phases of flight (e.g., taxi, take-off, landing, etc), for different functions within its mission (e.g., weapons release) or during emergency situations (e.g., loss of communications between the ground control station and the UA). Systems with such a capability are said to exhibit "adaptive autonomy", which adds another dimension of complexity to the regulation of UAS. For this paper, the case study UAS are assumed to exhibit only one LoA.

4.1 LoA of the Case Study UAS

The LoA is assessed for each of the case study UAS and the ICAO concept of an *Autonomous Aircraft*. Only those frameworks that provided a single measure of the LoA on an ordinal scale were evaluated. In order to explore the consistency of the assessment across different assessors, each author independently assessed the LoA of the case study UAS. The assessment was performed twice by each author to explore the repeatability/consistency of the assessment on an individual assessor basis. The consolidated results from all authors are presented in Table 3 of Appendix A.

The frameworks use different labelling conventions for their scales. For ease of comparison Roman numerals are used for all LoA assessments. The class of lowest LoA is assigned the numeral 'I', the next class of higher LoA assigned the numeral 'II', and so on. A '-' in Table 3 is used to indicate those instances where the LoA of the case study UAS could not be determined using the framework. Where a case study UAS could be assessed as having more than one LoA, all possible levels are indicated. An 'NC' in Table 3 indicates those cases where consensus between the authors on the assessment of the LoA could not be reached.

It should be noted that despite the use of a common labelling scheme, a direct comparison of the LoA determined using different assessment frameworks is not meaningful. For example, a LoA of 'IX' assessed for one framework is not necessarily equivalent to a LoA of 'IX' assessed using another framework. Nor is it meaningful to measure the difference between two LoA on any scale (refer to the Stevens (1946) for further discussion on the limitations of measurements made on ordinal scales). However, meaningful observations can be made in relation to how the different frameworks rank/order the LoA of the case study UAS.

4.2 Analysis of Results

With reference to Table 3, it can be observed that the greatest variation is in the assessment of the LoA of *UAS A*. Under some frameworks *UAS A* is assigned a very low LoA but in others it is assigned a very high LoA (i.e., comparable to the LoA assigned to *UAS E* and *F*). Variability in the LoA assigned for *UAS A* arises due to the different concept of autonomy adopted by each framework. *UAS A* is assigned a high LoA in those frameworks that base their concept of autonomy on the degree of independence between the UAS and the RP. This is because *UAS A* can perform its mission without interaction with a human RP. Conversely, *UAS A* is assigned a low LoA in those frameworks that adopt the more complex notion of autonomy as the UAS is not capable of higher-order functions such as decision making or the ability to change its own behaviour in response to changing conditions.

There are a number of cases where a consensus between the authors on the LoA could not be reached (i.e. the 'NCs' in Table 3). This most commonly occurred in the assessment of the LoA for *UAS C* and *D*. It was found that the majority of the inconsistencies between repeated assessments were due to the limited guidance available on how to make assessments using the proposed LoA schemes. The greatest inconsistency between assessments occurred for LoA frameworks that used independent metrics but provided no guidance as to how the independent measures were to be combined. For example, using the framework proposed by Kendoul (2011), some UAS were assessed as having a high LoA in some functions (e.g., control) but low in others (e.g., guidance and navigation). Limited guidance was provided on how to combine the three independent measures into a single LoA for the system. Kendoul (2011) uses '+' and '-' notation to "distinguish between a system that has accomplished that AL [autonomy level] or TRL [technology readiness level] by satisfying all its requirements, and a system that satisfies some of the requirements only." A description on how the overall LoA assignment is made, e.g., whether the system is a 'VII+' or 'VIII-', is not provided. Often the case study UAS satisfied some of the conditions for assignment to a particular LoA but not all. From the description provided it was unclear as to whether the independent measurement dimensions were necessary or sufficient conditions for the assignment to a particular LoA or if other means should be used to perform the aggregation of independent measurement dimensions (e.g., minimum, maximum, majority, etc.).

Another factor contributing to the inconsistency in the assessments was that there was insufficient information on the case study UAS. Some of the assessment frameworks required detailed information about the UAS (e.g., cognisance of surroundings, % of interaction time with the RP, whether the UAS was reliant on the Global Positioning System or could perform collision avoidance, etc.). Where such information was unavailable an assessor could either indicate that the LoA of the case study UAS could not be determined or make assumptions about the case study UAS. The latter situation contributes to the subjectivity of the assessment process and in turn the potential for inconsistency in the results.

There are many instances in Table 3 where it was not possible to assign a single LoA to the case study UAS. There were also a number of cases where the LoA determined for the different case study UAS overlapped. Overlap in the assessments of LoA was most frequently encountered between *UAS C* and *UAS D*, and between *UAS E*, *UAS F* and *Autonomous Aircraft*. From a regulatory standpoint, a clear distinction between the case study UAS on the basis of their LoA would be required. The higher the LoA of the UAS, the less the human RP is involved in the operation and the more the UAS subsumes the role of the RP. It follows that, as the LoA increases so too does the degree of complexity of the UAS and in turn, greater safety assurance is required of the UAS hardware and software components that perform the safety critical functions previously provided by a human RP. This assurance can be provided through more rigorous standards on the design, implementation, testing and operation of the UAS. The training and licensing requirements on the RP will also depend on the LoA of the UAS, thus, clear distinctions are required.

The ICAO definition of *Autonomous Aircraft* was consistently mapped to the same LoA as that determined for *UAS A*, *UAS E* and *UAS F*. There are significant differences in the capability and complexity of these three case study UAS. Interestingly enough, *UAS A* corresponds to the earliest and most primitive of UAS, whilst *UAS F* corresponds to a much more complex system yet to be fielded in reality. This result is illustrative of the diversity of potential interpretations of the ICAO definition of an *Autonomous Aircraft*. A definition of an *Autonomous Aircraft* that is less open to interpretation is required.

4.3 Assessing UAS Modes of Operation

An *Autonomous Operation* is defined by ICAO as *"an operation during which a remotely-piloted aircraft is operating without pilot intervention in the management of the flight"*. (ICAO 2011) Numerous modes of operation have been defined for UAS (refer to Table 4 of Appendix A). Such modes of operation imply an UAS of a minimum LoA.

The implied LoA for the modes of operation proposed by Huang (2008) and for the ICAO concept of an *Autonomous Operation* are assessed using the same LoA frameworks analysed in Section §4.1. The results are summarised in Table 5 in Appendix A. For convenience, the definitions of the different modes of operation proposed by Huang (2008) can be found in Table 4.

As can be observed in Table 5, the operational mode of *Remote Control* is consistently assigned to the lowest LoA across all assessment frameworks. The LoA associated with the ICAO concept of an *Autonomous Operation* corresponds well with that determined for a *Fully Autonomous* UAS, as defined by Huang (2008). Up to nine LoA could be associated with the concept of a *Semi Autonomous* mode of UAS operation. *Semi Autonomous* would encompass the vast majority of all UAS operations. This class of operations would include UAS of significantly different LoA, and in turn, capability and complexity. It is concluded that the classification provided by Huang (2008) is unlikely to provide a suitable partitioning of the different types of autonomous UAS operations for use within regulations.

5 Discussion on a Regulatory Definition of Autonomy

In this section we briefly explore some of the issues in the development of a LoA framework specifically for use in the safety regulation of UAS. Clothier & Williams (2012) present a set of criteria for the evaluation of classification frameworks used in safety regulations. The same set of criteria can be used to evaluate the LoA assessment frameworks and their suitability for use in the regulation of UAS.

5.1 Context

As stated by Clothier & Williams (2012), all classification frameworks have a purpose and this purpose influences their design. The existing LoA assessment frameworks have been developed for a wide variety of purposes, primarily for analysis of mission or operational capability. Subsequently, the properties used to distinguish one LoA from that of the next reflect differences within the specific context. As an example, the ability to declare enemy ground targets and establish their intent has little relevance in determining the LoA for application in civil aviation safety regulations. Within the context of aviation safety regulation the LoA need to be distinguished on the basis of their impact on the safety of UAS operations. Establishing a relationship between safety and the LoA of a system will require assumptions in relation to the missions and environments in which the UAS are operated (see discussion Section §5.5).

5.2 Scale

An ordinal scale is recommended for a regulatory specification of the LoA of UAS. This would allow regulators to "rank" UAS on the basis of their LoA and would serve to divide the continuum of UAS LoA into a finite number of mutually exclusive classes. Regulations could then be developed and promulgated for each class of autonomy in line with the safety and complexity of the system. As discussed in Clothier & Williams (2012), a regulatory classification should be comprehensive, i.e., capable of providing a complete, contiguous and mutually exclusive partitioning of UAS across all foreseeable types. Therefore, the range of the LoA scale should cover all potential cases, from no autonomy through to systems such as that defined by case study *UAS F*. It is evident that highest LoA of some of the reviewed scales do not consider the possibility of autonomous systems which are *completely* independent of a human operator.

5.3 Number of Levels

The more levels defined on the LoA scale, the higher the resolution and the greater ability to distinguish between differences in the LoA of UAS. Increasing the resolution has the potential to increase the level of flexibility in the regulation of autonomous systems, however, it can increase the regulatory development effort and the complexity of the regulatory classification scheme.

The number of levels defined along the measurement scale can have a significant impact on the effectiveness and practicality of the assessment framework. If too few LoA are defined, then the assessment framework may not be able to distinguish between systems that have a noticeable/significant difference in their respective LoA. In the context of aviation safety regulations, insufficient resolution can result in a failure to distinguish differences in the safety performance of UAS. Conversely, a measurement scale with too many levels would make the framework impracticable to implement. The ideal number of levels is the minimum number needed to distinguish between LoA where there is a significant difference in the safety-performance of the systems. Establishing the relationship between a LoA and the safety performance of the UAS is beyond the scope of this paper. It is important to note that although many of the scales are labelled linearly (e.g., assigned the labels 0, 1, 2...) this does not mean that the relationship between LoA is also linear.

5.4 Component Properties

The set of properties used to determine a LoA should be the simplest and most concise set necessary to distinguish differences in the safety-performance of the systems. The terms concise and simple are included to reflect pragmatic requirements on the regulatory framework for UAS and to simplify the assessment process. For example, the assessment framework proposed by Barber & Martin (1999) requires measurements of how often (% of decisions) and how much (% of time) the RP intervenes in the decision making of the UAS. Such assessments would be sensitive to changes in the mission, task or environment, can be time consuming to evaluate, and are not measures that can be easily verified by a regulatory authority.

5.5 Level of System Complexity

The component properties used to describe autonomy have included properties belonging solely to the machine, properties of the human and the machine, emergent properties of the HMS, or emergent properties of the HMS operation. Thus, autonomy has been assessed at numerous different levels of an hierarchical systems model describing an UAS. This leads to the question as to what level of complexity in the representation of the UAS should the LoA be assessed?

UAS autonomy could be assessed at an operational level, and in so doing take into consideration the complexity of the mission and environment performed by the UAS. An example of this level of representation is the concept of Contextual Autonomous Capability (Huang 2008). A high level requirement for UAS is that they operate seamlessly within the existing airspace system. This high level requirement could be used to establish categories or classes of mission and environment (e.g., UAS operations under visual flight rules and under visual meteorological conditions versus UAS operations in accordance with instrument flight rules), for which "operational" LoA for UAS could be assessed.

UAS LoA could also be assessed in relation to the functions performed by the physical UAS or its component sub-systems. In civil aviation safety regulations flight critical or safety critical functions are determined within the "aircraft system". Safety critical functions can be determined below the operational system level by assuming that the relationships between measures of functional performance and the operational risks are largely independent of a particular mission or environment. For example, a loss of control poses a risk to those people on-board an aircraft irrespective of the mission or environment in which the aircraft is being operated. In such a case, the control function could be classified as having a catastrophic failure condition. From a regulatory perspective, the LoA could be defined in relation to such safety critical functions. Existing function classifications such as those defined in"Part 1309" system safety regulations (FAA 1988, EASA 2012) could be used.

5.6 The Assessment Process

The vast majority of the literature reviewed provided limited or no guidance as to how a LoA scheme could be applied in practice (i.e., the actual measurements required and how they could be aggregated). As described by Clothier & Williams (2012), the LoA measurement scale/scheme and the assessment process are equally important components in any classification framework. If the LoA assessment process is onerous, ambiguous, or overly complex the likely outcome is a miss classification. In the context of aviation safety regulations a miss classification is itself an hazard. An assessment of the LoA of a system must be easily verified by a regulatory authority.

5.7 Adaptive Autonomy

The LoA of an UAS may vary with operating conditions (normal / abnormal / emergency conditions), for particular functions, and/or phases of flight. A methodology will need to be in place to ensure that the safety regulations provide adequate coverage for such systems. This may include the system conditions or process for changing the LoA of the UAS. For example, should the UAS have the ability to change its own LoA *autonomously*? Under some circumstances this may be desirable (e.g., in those situations where the communications link between the UA and the ground control station are lost). If so, what should the safety assurance requirements be for such a capability?

6 Conclusions

Civil aviation safety regulations and guidance material classify Unmanned Aircraft Systems (UAS) as either Remotely-Piloted Aircraft Systems (RPAS) or Autonomous Aircraft Systems (AAS). This distinction is based on the premise that the effective safety risk management of UAS is dependent on the degree of autonomy of the system being operated. However, it is found that there is no consensus on the concept of autonomy, on how it can be measured, or on the nature of the relationship between Levels of Autonomy (LoA) and the safety-performance of UAS operations.

Existing LoA assessment frameworks do not provide a consistent classification of the six generic case study UAS nor of the ICAO concept of an *Autonomous Aircraft*. It was found that the existing LoA assessment frameworks, when applied to the case study UAS, do not provide a consistent basis for distinguishing between the regulatory classes of RPAS and AAS. It was also found that the existing regulatory definition of an *Autonomous Aircraft* is too broad, covering UAS of significantly different levels of capability and system complexity. Within the context of aviation safety regulations, a new LoA assessment framework for UAS is required.

This is not a surprising outcome as none of the existing LoA frameworks were developed for use in a safety or regulatory context. A new LoA assessment framework will require a clear relationship between autonomous system capability/functionality and safety performance to be established. This needs to be first established at the operational level (i.e., taking into consideration the mission and environment).

The higher the LoA of the UAS, the more it subsumes the functions of the human remote pilot. Hence, the more complex the UAS becomes. A wide range of methods for implementing higher LoA in the hardware and software components of an UAS have been successfully demonstrated. Complex high-level decision making is already being achieved through the use of neural networks, agent-based architectures and probabilistic reasoning. This poses a significant challenge to regulators who must certify such implementations as being "safe". The default performance benchmark is that of the human pilot that has been replaced. Not only does this performance benchmark need to be quantified but new tools for use in the certification process need to be developed. These tools must be capable of exercising the behaviour of the system across a wide range of missions and operating conditions (normal/abnormal/emergency).

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A Concepts for UAS Autonomy

Concept	Definition
Automatic / Automated	The execution of a pre-defined process or event that requires UAV pilot initiation and/or intervention e.g. automated take-off/landings, way-point navigation, auto-pilots, pre-programmed manoeuvres etc. (TC 2008) the automatic performance of scripted actions. (ASTM 2007) In the unmanned aircraft context, an automated or automatic system is one that, in response to inputs from one or more sensors, is programmed to logically follow a pre-defined set of rules in order to provide an outcome. Knowing the set of rules under which it is operating means that its output is predictable. (UKMoD 2011) fully preprogrammed and act repeatedly and independently of external influence or control. An automatic system can be described as self-steering or self- regulating and is able to follow an externally given path while compensating for small deviations caused by external disturbances. However, the automatic system is not able to define the path according to some given goal or to choose the goal dictating its path. (USDoD 2011)
Autonomy	the ability of the machine to interpret its environment and make decisions that result in unscripted actions. (ASTM 2007) A UMS's [Unmanned System] own ability of integrated sensing, perceiving, analyzing, communicating, planning, decision-making, and acting/executing, to achieve its goals as assigned by its human operator(s) through designed Human-Robot Interface (HRI) or by another system that the UMS communicates with. UMS's Autonomy is characterized into levels from the perspective of Human Independence (HI), the inverse of HRI. (Huang 2008) The ability to execute processes or missions using on-board decision making capabilities. No intervention by UAV [Unmanned Aerial Vehicle] crew members is required. An autonomous UAV would be capable of dynamic mission management that is not scripted. It would depend on intelligent reasoning and deliberate behaviour for the ability to cope with uncertainty i.e. self-governance. (TC 2008) the quality of being autonomous; self-determination. (FAA 2011) the condition or quality of being self governing. When applied to UAS, autonomy can be defined as UASs own[1] ability of integrated sensing, perceiving, analyzing, communicating, planning, decision-making, and acting/executing, to achieve its goals as assigned by its human operator(s) through designed Human-Robot Interface (HRI) or by another system that the UAS communicates with. (Kendoul 2011) the capability of the system to make decisions based upon an evaluation of the current situation (often referred to as situation awareness). (CAA-UK 2012)
Autonomous	An autonomous system is capable of understanding higher level intent and direction. From this understanding and its perception of its environment, such a system is able to take appropriate action to bring about a desired state. It is capable of deciding a course of action, from a number of alternatives, without depending on human oversight and control, although these may still be present. Although the overall activity of an autonomous unmanned aircraft will be predictable, individual actions may not be. (UKMoD 2011) not controlled by others or by outside forces; independent judgment. (FAA 2011) A UAS is defined to be autonomous relative to a given mission (relational notion) wherein it accomplishes its assigned mission successfully, within a defined scope, with or without further interaction with human or other external systems. A UAS is fully autonomous if it accomplishes its assigned mission successfully without any intervention from human or any other external system while adapting to operational and environmental conditions. (Kendoul 2011) self-directed toward a goal in that they do not require outside control, but rather are governed by laws and strategies that direct their behavior. ...An autonomous system is self- directed by choosing the behavior it follows to reach a human-directed goal. ...autonomous systems may even optimize behavior in a goal-directed manner in unforeseen situations (i.e., in a given situation, the autonomous system finds the optimal solution). (USDoD 2011) that perceives its environment and determines if this affects its goals, and it takes action to ensure as far as practicable (and safe) that its goals will be achieved. It reasons about its course of action from a number of alternatives, to achieve these goals without recourse to human oversight and control. (CAA-UK 2012)

Table 1: Autonomy and related concepts defined in the context of UAS

[1] *own* implies independence from human or any other external system. (Kendoul 2011)

Reference	Number of Levels	Scale	Basis for Scale
Sheridan & Verplank (1978)	10	Ordinal	Autonomy scale based on human-machine role in decision making.
Riley (1989)	12	Ordinal	Autonomy scale is based on the degree of control/authority the machine has over the world (inclusive of the operator).
Billings (1991)	7	Ordinal	Autonomy scale is based on the pilot role in the control and management of system. The control and management continuum is described in terms of "the degree of direct or immediate involvement of the pilot." Olson & Wuennenberg (2001) use the scale to specify requirements on the pilot-aircraft interface for UAS.
Hasslacher & Tilden (1994)	N/A	Interval	A level of autonomy is measured in terms of a Survival Signature Space which is the weighted linear combination of measurements made with respect to the three independent capability vectors of mobility, acquisition, and protection.
Endsley & Kaber (1999)	10	Ordinal	LoA 'taxonomy' is based on the assignment of tasks/functions to a human operator and/or computer. The tasks/functions were defined as monitoring, generating, selecting, and implementing.
Barber & Martin (1999)	N/A	Ratio	Classification based on how often (% of decisions) and how much (% of time) an agent intervenes in the decision making of the robot.
Parasuraman et al. (2000)	N/A	Interval	Level of automation based on the scheme proposed by Sheridan & Verplank (1978) but expressed in relation to the four independent functions of information acquisition, information analysis, decision selection, and action implementation.
Clough (2002)	11	Ordinal	Level of autonomy defined in relation to the combination of three independent functions of perception/situational awareness, analysis/decision making, and communication/cooperation. The framework is used by Sholes (2007) to assess the autonomy of UAS.
Taylor et al. (2002)	6	Ordinal	Level of autonomy defined based on the combined dimensions of pilot authority and contractual authority. A modified version of this scheme is presented by Hill et al. (2007) for describing UAS human-system interaction.
Proud et al. (2003)	8	Ordinal	Level of autonomy defined in relation to four independent dimensions reflecting the decision making processes of Observe, Orient, Decide and Act (OODA). Scheme is based on that developed by Parasuraman et al. (2000), Clough (2002)
Huang, Messina & Albus (2007)	11	Ordinal	LoA relates to the Human Interaction (HI) axis of the ALFUS Contextual Autonomous Capability framework. This axis is described as "the ability for the UMS to identify and communicate and/or negotiate with humans and/or other entities." A consistent measurement framework for the HI axis is difficult to identify from within the various published works. Five levels of HI are defined in (Huang, Pavek, Ragon, Jones, Messina & Albus 2007). Table 1 of (Huang, Messina & Albus 2007) describes the measurement of HI in terms of the % of interaction time and defines eleven "reference levels" of HI.
Galster et al. (2007)	8	Ordinal	Classification is based on the degree of operator control over the UAS.
Kendoul (2011)	11	Ordinal	Similar to the concept of Contextual Autonomy presented in the ALFUS framework, where the LoA of UAS is "characterised by the missions that the UAS is capable of performing (Mission Complexity or MC), the environments within which the missions are performed (Environment Complexity or EC), and independence from any external system including human element (External System Independence or ESI)". The LoA is determined from the ability of the UAS to perform the independent functions of guidance, navigation and control for a specified mission and environment.
USDoD (2011)	4	Ordinal	Autonomy scale is defined in relation to the degree of interaction between human control and the machine motions.
Insaurralde & Lane (2012)	N/A	Interval	Autonomy scale is defined in relation to the five independent contexts of: itself, system, user, environment, and norm. The five contexts are measured in terms of the ability of the system to perform the functions of Observe-Orient-Decide-Act-Check (OODAC). The level of autonomy for each context is determined by the weighted average of the measures for each of the OODAC functions.

Table 2: Autonomy scales identified in the Literature

Autonomy Scale	Case Study UAS UAS A	 UAS B	 UAS C	 UAS D	 UAS E	 UAS F	Autonomous Aircraft[2]
Sheridan & Verplank (1978)	I	I	I	VIII	IX	X	VII, VIII, IX, X
Riley (1989)	XII	I	VII, VIII	IX	XI	XII	XII
Billings (1991)	VII	I, II	III, IV, V	V, VI	VII	VII	VII
Endsley & Kaber (1999)	III	I, II	II, III	NC	IX, X	X	X
Clough (2002)	II	I	III	NC	NC	X, XI	X, XI
Taylor et al. (2002)	-	I	NC	IV, V, VI	-	-	-
Huang, Messina & Albus (2007)[3]	NC	I	NC	X	XI	-	-
Galster et al. (2007)	VIII	I	V	VI, VII	VIII	VIII	VIII
Kendoul (2011)	II	I	NC	NC	NC	XI	XI
USDoD (2011)	-	I	III	III, IV	-	-	-

Table 3: Assessment of the LoA of the case-study UAS

[2] Defined by ICAO (2011)

[3] Human Interaction (HI) as defined in Table 1 of Huang, Messina & Albus (2007)

Reference	Term	Definition
Clough (2002)	Remotely piloted	The UAV [unmanned aerial vehicle] is simply a remotely piloted aircraft with the human operator making all decisions.
	Remotely operated	The human allows the UAV to do the piloting, but outer loop decisions are made by the human (like where to go and what to do once there). The UAV is a "mother-may-I" system, asking the human permission to do tasks.
	Remotely supervised	The human allows the UAV to execute its own tasks, only taking command if the UAV fails to properly execute them.
	Fully autonomous	The UAV receives goals from the humans and translates that into tasks which it does without human intervention. The UAV has authority to make all decisions.
ASTM (2007)	Semi autonomous	... mode of control[4] of a UAS where the pilot executes changes and conducts the mission through a flight management system interface. Without this input, the UAS will perform pre-programmed automatic operations. This can, but might not, include some fully autonomous functions (like takeoff, landing, and collision avoidance).
	Fully autonomous	... mode of control of a UAS where the UAS is expected to execute its mission, within the pre- programmed scope, with only monitoring from the pilot-in- command. As a descriptor for mode of control, this term includes: (1) fully automatic operation, (2) autonomous functions (like takeoff, landing, or collision avoidance), and (3) "intelligent" fully autonomous operation.
Huang (2008)	Remote control	A mode of UMS [Unmanned System] operation[5] wherein the human operator controls the UMS on a continuous basis, from a location off the UMS via only her/his direct observation. In this mode, the UMS takes no initiative and relies on continuous or nearly continuous input from the human operator.
	Teleoperation	A mode of UMS operation wherein the human operator, using sensory feedback, either directly controls the actuators or assigns incremental goals on a continuous basis, from a location off the UMS.
	Semi-autonomous	A mode of UMS operation wherein the human operator and/or the UMS plan(s) and conduct(s) a mission and requires various levels of HRI. The UMS is capable of autonomous operation in between the human interactions.
	Fully autonomous	A mode of UMS operation wherein the UMS accomplishes its assigned mission, within a defined scope, without human intervention while adapting to operational and environmental conditions.
ICAO (2011)	Autonomous operation	An operation during which a remotely-piloted aircraft is operating without pilot intervention in the management of the flight.

Table 4: UAS modes of operation

[4] *mode of control* is defined as the means the pilot uses to direct the activity of the UAS. Modes include remote control, semi autonomous and fully autonomous. The remote control mode of operations is not explicitly defined.(ASTM 2007)

[5] *mode of operation* defined as the human operator's ability to interact with a UMS to perform the operator assigned missions.(Huang 2008)

Autonomy Scale	UAS Modes of Operation[6] Remote Cont	 Teleop	 Semi Auto	 Fully Auto	Autonomous Operation[7]
Sheridan & Verplank (1978)	I	I, II, III	II, III, IV, V, VI	VII, VIII, IX, X	VII, VIII, IX, X
Riley (1989)	I	II, III, IV, V, VI, VII	VIII, IX, X, XI	XII	XII
Billings (1991)	I	II, III, IV	IV, V, VI, VII	VII	VII
Endsley & Kaber (1999)	I	II	III, IV, V, VI, VII, VIII, IX	X	X
Clough (2002)	I	II, III	II, III, IV, V, VI, VII, VIII, IX, X	XI	X, XI
Taylor et al. (2002)	I	I	III, IV, V	NC	-
Huang, Messina & Albus (2007)[8]	I	NC	II, III, IV, V, VI, VII, VIII, IX, X	XI	XI
Galster et al. (2007)	I , II	II, III	III, IV, V, VI, VII	VII, VIII	VIII
Kendoul (2011)	I	I, II	II, III, IV, V, VI, VII, VIII, IX, X	XI	XI
USDoD (2011)	I	I	II, III, IV	-	-

Table 5: Assessment of the LoA of UAS for different modes of operation

[6] Defined by Huang (2008)

[7] Defined by ICAO (2011)

[8] Human Interaction (HI) from Table 1 Huang, Messina & Albus (2007)