EXPANDING THE ENVELOPE OF UAS CERTIFICATION: WHAT IT TAKES TO TYPE CERTIFY A UAS FOR PRECISION AGRICULTURAL SPRAYING

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One of the key challenges to the development of a commercial Unmanned Aircraft System (UAS) market is the lack of explicit consideration of UAS in the current regulatory framework. Despite recent progress, additional steps are needed to enable broad UAS types and operational models. This paper discusses recent research that examines how a risk-based approach for safety might change the process and substance of airworthiness requirements for UAS. The project proposed risk-centric airworthiness requirements for a midsize unmanned rotorcraft used for agricultural spraying and also identified factors that may contribute to distinguishing safety risk among different UAS types and operational concepts. Lessons learned regarding how a risk-based approach can expand the envelope of UAS certification are discussed.

INTRODUCTION

To spur the emerging commercial market for Unmanned Aircraft Systems (UAS), the United States (U.S.) Congress has directed the Federal Aviation Administration (FAA) to take steps toward "safe and routine operation" of commercial UAS in the national airspace system (NAS).[1] Regulatory progress has been made for smaller UAS (< 55 lb) operating in visual conditions;[2] however, those efforts do not include type design and airworthiness requirements for larger and more capable UAS operating in non-segregated airspace and beyond the visual line-of-sight of the remote pilot. Those requirements are critical for safe and routine access of all UAS to the NAS and are the focus of this paper.

For conventional aircraft (those with pilots onboard), the risk to people and property on the ground from poor vehicle design or maintenance is addressed through airworthiness regulations.[3,4] Airworthiness can be broadly defined as the suitability for flight of an aircraft. In civil aviation regulations, an aircraft is considered airworthy if the aircraft is compliant with relevant technical requirements governing its design and manufacture, and is in a condition for safe flight. Airworthiness regulations cover all aspects of the design, manufacture, and maintenance of aircraft systems and components. International consensus on airworthiness regulations for the broad spectrum of UAS types has yet to be reached. An initial approach proposed by some regulators was to apply the existing airworthiness framework for conventional aircraft to UAS, with the intent of minimizing change to aviation regulations.[5] However, it is now broadly recognized that

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the "off-the-shelf approach"[6] is unlikely to lead to an acceptable regulatory outcome for all UAS types.[4]

More recently, researchers and regulators have begun exploring risk-based approaches to UAS certification.[3,7,8] As stated by the European Aviation Safety Agency (EASA), "the regulatory framework should not simply transpose the system put in place for manned aviation but must be proportionate, progressive, risk based... Only [in] this way can we address the challenges posed by the wide variety of drones and their operation..."[7] Ideally, a risk-based approach ensures safety regulations have a foundation in, and traceability to, the underlying safety-related hazards that need to be managed. The adoption of a risk-based approach "marks a significant change in the way aviation safety regulations are developed, becoming proportionate to the risks they aim to address."[9]

This paper presents some observations about risk-based certification based on a recent research study of type design requirements for commercial UAS. The study was undertaken by the National Aeronautics and Space Administration (NASA) with the objective of proposing design criteria for a midsize unmanned rotorcraft (~1000 lb maximum takeoff weight) used for commercial precision agricultural spraying operations. The research effort produced prototypes of documentation needed to support airworthiness certification, including a proposed (or mock) type certification basis with design standards for the unmanned rotorcraft.[10] A type certificate provides both airworthiness standards and operating limits for a specific model of aircraft.

This paper summarizes the study's findings relevant to pushing forward with a risk-based certification approach to airworthiness. The next section provides additional background information on the relationship between risk and certification. The subsequent section covers foundational elements essential to a risk-based approach, starting with revised definitions of hazard severity. The discussion continues by summarizing the hazards identified for the unmanned agricultural concept of operations (ConOps), and provides examples from the mock certification basis. The next section looks at the set of factors that influence safety risk. These factors may be useful in distinguishing the risk of one UAS operation from another. The final section summarizes the observations and lessons learned.

RISK-BASED CERTIFICATION

Risk-based certification is an approach in which the requirements from the certification process are proportional to the risk (combining likelihood and severity of consequence) of an aviation operation. Public safety interests associated with commercial UAS operations are the same as those for commercial operations of conventional aircraft. However, the primary risks managed through airworthiness regulations are different.[3,4] For UAS that could endanger the public, airworthiness requirements are needed to manage the risk to persons on the ground and in other aircraft. Whereas for conventional aircraft used for commerce or hire, airworthiness regulations serve to protect people onboard the aircraft, with the protection of persons and property on the ground being another benefit. This subtle, yet significant, difference changes the hazard space, which permits unique trade-offs in the setting of airworthiness requirements for UAS.[4] In addition, current regulations for airworthiness certification are based on decades of experience and extensive historical data on aircraft and system designs, performance, and limitations. Based on this data, hazards that require regulation are reasonably well understood. UAS do not have this long history and unmanned aircraft designs are proliferating. Although the current airworthiness standards are based on the likelihood and severity of consequence, these standards rely on assumptions about the hazards of aircraft and its operation. Alternately, a risk-based approach relies on an explicit identification of hazards for a particular aircraft and operation. Table 1 contrasts some characteristics of airworthiness standards for conventional aircraft with those being proposed for risk-based certification of UAS. The challenge in moving to an explicitly risk-based approach is in realizing differences in risks and finding ways to mitigate those risks without unduly restricting designs.

Table 1. Characteristics of Airworthiness Standards for Commercial Operations

General Characteristics of Existing Airworthiness Standards for Conventional Commercial Aircraft	**Expected Characteristics of Risk-based Airworthiness Standards for UAS**
Originate from experience with system designs, performance, and limitations	Will originate from *a priori* functional and operational hazard analysis for an aircraft and operation
Operation agnostic	Will be operationally driven
Based on aircraft designs from 1950's and 1960's[22]	Will not presuppose a reference aircraft
Focus on protection of people onboard	Will focus on protection of people on the ground and in other aircraft
Both performance-based safety objectives and prescriptive (technology-centric) requirements	Will primarily be performance-based safety objectives

The next section describes the NASA study and the risk-based approach used to propose airworthiness criteria for an agricultural rotary wing UAS. The approach included identification of the hazards inherent to the UAS and its operation. Explicitly capturing hazards allowed novel aspects of the UAS to be addressed with more flexible thinking about meeting public safety requirements. The research effort produced generalized, over-arching design and performance requirements to manage the risks to acceptable levels (commensurate with the excellent safety record of conventional aircraft), while also providing design flexibility needed to allow for innovation and industry growth. This risk-based approach adapts the system safety processes used in the certification of the avionics in conventional aircraft to the whole UAS.

USING RISK TO EVALUATE NOVEL FEATURES

The airworthiness requirements proposed in the mock type certification basis were largely determined by the hazards and risks that need to be managed for the precision spraying operation. Hazard and risk assessment processes are, by their nature, subjective and are dependent on hazard severity definitions. The first step in developing the mock certification basis was to consider those definitions.

Hazard Severity Definitions

In conventional civil aircraft safety assessment, failure conditions that pose a hazard are identified and then classified according to the severity of the potential consequence: catastrophic, hazardous, major, minor, or no safety effect.[11] Definitions of these categories establish what vehicle conditions are to be avoided, making the definitions a keystone to a risk-based certification approach. Hazards that could prevent safe flight and landing and those that can injure or kill passengers or crew are always considered catastrophic. Regulatory guidance for conventional aircraft aims to reduce the likelihood of those events to acceptable levels.

Protection of crew and passengers is central to the existing definitions for hazard categories.[12] In a conventional aircraft, hull loss is inextricably tied to catastrophe because loss of life is a realistic expectation. In contrast, hull loss of an unmanned aircraft (UA) may pose no hazard to life, depending on the operational context. UAS operations over water or unpopulated areas (e.g., farmland or wilderness) would present little risk to human life because the likelihood of an unfortunate encounter with a human is extremely low. This fundamental difference in risk has motivated some regulators to use an operation-centric approach to categorizing UAS.[2,13]

The difference in risk between conventional aircraft and UAS motivates some degree of tailoring of severity definitions. To do that tailoring, a number of proposed definitions were reviewed, yielding three major premises: protection of people, preservation of aircraft safety margins and functional capabilities, and protection of the crew's ability to perform their safety role.[14-16] Protecting any person from harm, including third parties on the ground and people in other aircraft, is obvious and necessary. Maintaining safety margins is a fundamental engineering concept to allow safe operation during emergency situations and unexpected conditions (e.g., a fly away event). Lastly, any condition that could interfere with the pilot and crew's ability to perform their safety roles must be avoided. These safety roles can be quite different for UAS because the degree to which a UAS pilot and crew can directly affect safety varies significantly across the spectrum of UAS types. A formal ConOps is needed to characterize the specifics of both safety margins and safety roles for a UAS and its operation.

The most significant differences between existing hazard severity definitions for UAS and those used in the study can be seen in the definition of catastrophic:

> From the Joint Authorities for Rulemaking on Unmanned Systems (JARUS)[14]: "Catastrophic: Failure conditions that could result in one or more fatalities"
>
> From the NASA study[10]: Catastrophic: Failure conditions that are expected to result in: (1) fatality or fatal injury to any person; (2) complete loss of safety margins (e.g., fly away for a UA); or (3) complete loss of the UAS crew's ability to perform their safety role (e.g., from incapacitation).

The tailored definitions retain the protection of people, but also emphasize the safety role of the crew and allow flexibility in setting safety margins commensurate with the UAS and its operation, making the definitions broadly applicable to UAS.

UAS for Precision Agriculture Case Study

The ConOps for the NASA study[10] focused on a midsize rotary wing UAS intended to spot treat crops in a precision agriculture operation, as shown in Figure 1.

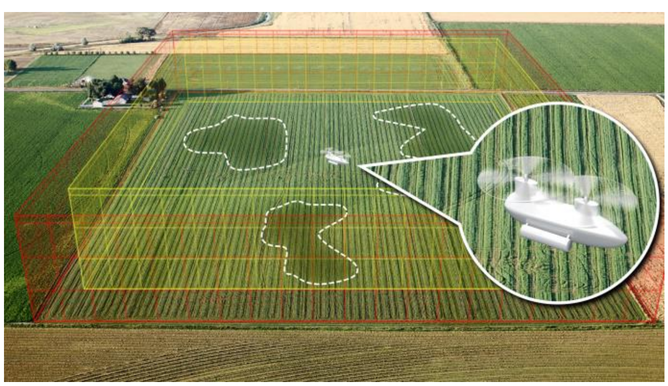

Figure 1. Concept for Precision Agricultural Application with Unmanned Rotorcraft

In the ConOps, one UAS is operating with one remote ground control station (GCS) within radio line-of-sight (RLOS). The pilot may be within visual line-of-sight (VLOS) or beyond

VLOS (BVLOS). Spray operations are limited to a designated *operational boundary* (Figure 1, yellow lines) and an absolute *containment boundary* (Figure 1, red lines) just beyond the operational boundary. *A priori* knowledge about crop health is used to identify treatment areas (Figure 1, dashed white lines). The unmanned rotorcraft is expected to operate a few feet above crop height, with a maximum altitude of 400 ft. Constraining the operation to a well-defined volume, restricted in altitude and inhabitants, is key to limiting operational risk.

Using the hazard severity definitions, a functional and operational hazard assessment was conducted[11, 17] with the goal of evaluating whether the potential consequences of a hazard necessitate mitigation in the form of a design or performance standard. Only those hazards whose severity was considered major or worse were targeted for requirements to be included in the mock certification basis.[21] Table 2 lists the primary hazards considered for that purpose.

Table 2. Primary Hazards for the Unmanned Precision Agriculture Spraying Operation

Hazards affecting the crew's ability to perform their safety role	Hazards that pose harm to any person	Hazards that affect aircraft safety margins and functional capabilities
• Loss of command and control (C2) link used for contingency management (e.g., flight termination) • Loss of or degraded electrical power in the ground control station for contingency and emergency functions • Loss of or degraded electrical power subsystems on the UA for contingency and emergency functions • Loss or degradation of ground control station capability (e.g., loss of displays) required for contingency and emergency functions	• Loss of or inadequate structural integrity, especially of the rotor system (that could lead to release of high energy parts) • Failure to detect, alert or warn, and avoid intruder aircraft • Failure to detect, alert or warn, and avoid dynamic or other obstacles on the ground • Explosion in the powerplant or fuel system	• Failure to recognize and avoid adverse environmental conditions • Failure to stay within authorized operational area • Loss of pilot situational awareness • Loss of or degraded communication between pilot and crew • Failure to maintain adequate controllability, maneuverability, and stability • Loss of UAS position and anti-collision lights (loss of means to be seen by other aircraft and observers) • Interference of spray system with required UAS function

Many of the hazards in Table 2 are the same as those for conventional aircraft; e.g., loss of situational awareness and failure to maintain adequate control. Other hazards are either new functional hazards posed by unique physical attributes of a UAS (e.g., C2 links) or are new functional hazards for systems and equipment related to traditionally human-centric functions (e.g., detect and avoid (DAA) of other aircraft). New design requirements were proposed in the mock type certification basis to mitigate risks posed by these hazards.

Addressing Hazards through Requirements

Once the hazards were classified, the next step was to specify design requirements to mitigate the hazards. Each paragraph in current standards for normal category rotorcraft (i.e., Part 27 of the Federal Aviation Regulations)[18] and the UAS-tailored version JARUS[19] was evaluated for applicability to the hazards in Table 2. Of the 260 regulations in Part 27, only 11 were included as written in the certification basis; 119 regulations were excluded outright; 56 were slightly modified; and 74 were abstracted by intent into three special issue papers on controllability/stability/maneuverability, structural integrity, and powerplant. Those three issue papers reinterpreted existing requirements into less prescriptive guidance more suitable for UAS. The certification basis also included four additional special issue papers that propose requirements for hazards not covered in Part 27: (1) vehicle containment within authorized boundaries, (2) DAA of other aircraft, (3) DAA of ground-based obstacles, and (4) C2 links.

The aim of all of the special issue papers was to draft safety-centric requirements that were sufficiently abstract and technology-agnostic, while still providing adequate information to objectively describe the desired system behavior. This style of requirements is called *performance-based safety objectives*.[20] This style is in contrast to *prescriptive* requirements, where a specific technology or method is specified to mitigate a hazard. Performance-based safety objectives are generally preferred since they offer increased design flexibility and tradeoffs between design and operational limitations.

Examples of Hazard Mitigations

To help illustrate the difference between performance-based and prescriptive requirements consider two examples from the mock type certification basis. The first example deals with loss of the C2 link. If the C2 link does not effectively and consistently pass data between the UA and the GCS, then the pilot cannot take emergency action when needed: the pilot cannot perform his safety role. The mock certification basis includes an issue paper with proposed performance-based requirements to mitigate this hazard. One of those requirements is, "The C2 link shall … be available in all vehicle attitudes under all foreseeable operating conditions throughout the containment volume…" The requirement does not specify how the link must work, but rather specifies the desired outcome, namely that the UA can continue to receive commands from the pilot regardless of where it is in the operational area, and independent of its attitude.

The second example is the loss of (or inadequate) structural integrity, especially of the rotor hub and drive system. This hazard affects normal rotorcraft as well as UA; however, the hazard changes in nature. Rotor integrity is usually a hazard to people onboard a conventional rotorcraft, whereas the hazard for a UAS in this agricultural ConOps is the release of high-energy parts that could injure flight crew or bystanders. There is an existing requirement in Part 27.917 to provide a unit to disengage the engine from the rest of the rotor system: "Each rotor drive system must incorporate a unit for each engine to automatically disengage that engine from the main and auxiliary rotors if that engine fails."[18] This is an example of a prescriptive requirement. Typically this requirement is satisfied in normal rotorcraft with the addition of a clutch that disconnects if the engine were to seize. Instead of a prescriptive requirement, an associated performance-based requirement on the powerplant (i.e., engine and rotor drive system) would establish that high-energy parts would not be ejected. Compliance with this requirement could entail a series of requirements on the engine, gearing mechanisms, rotor hubs, shafts, bearings, etc. However, the pattern of conventional rotorcraft indicates that most applicants would use a clutch or similar device. Therefore, simply mandating that the UAS have a means to disconnect the engine from the rotors was preferable.

RISK ASSESSMENT THROUGH FACTORS

Various characteristics (or factors) such as kinetic energy[8] have been proposed to distinguish between the risks inherent in the operation of different types of UAS. As the NASA study progressed, it became clear that some characteristics of the UAS and its operation affected overall safety risk more than others. This section examines those factors as a potentially useful way of grouping platform-operation pairs that pose a similar system safety risk and for comparing risk profiles of different platform-operation pairs. The factors described here are not comprehensive, but provide a preliminary list of characteristics that may facilitate risk assessment.

Factors Influencing Safety Risk

Several factors linked to the UAS and its ConOps were notable in their influence over the requirements in the mock type certification basis. These factors were found to sufficiently embody the pertinent characteristics of the vehicle under the specified ConOps, and directly impact the set of requirements. This led to the observation that these factors could potentially be used to span the design space of UAS under a variety of operations—not limited to a precision agriculture rotorcraft. For ease of reference, the factors were divided into two categories: design characteristics and operational characteristics. A plausible range of each factor was determined, and then an abstract scale was postulated over that range, to best characterize the factor's impact on the derived type certification requirements. Finally, each factor was assessed to determine which hazard was foremost in its sphere of influence.

The design factors primarily concern aspects related to the UAS. Characteristics such as the *mass* and *speed* relate to intrinsic physical qualities of the UA. *Pilot remote control authority*, where the pilot has inner-loop control or outer-loop control, or the operation is autonomous, and *GCS to UA ratio* that allows for multiple GCSs and multiple UAS in the same operation influence the disposition of human-machine control authority in the system.

The operational factors are predominantly derived from the ConOps. The factor *pilot locality* refers to the how close, both visually and by radio, the pilot or crew is to the UAS. The pilot can be within VLOS or BVLOS, and within RLOS or beyond RLOS (BRLOS). The VLOS-BRLOS value of the locality factor describes an operation that is constrained to VLOS of the observers, but may have operational areas where the UA is BRLOS of the GCS. Factors such as *population density*, *operational altitude*, and *air traffic density* are fixed by the geospatial location of the operation. The *mission duration* and *visual conditions* under which the operation takes place are temporal aspects of the type of operation being performed, including both day and night Visual Meteorological Conditions (VMC), and Instrument Meteorological Conditions (IMC). The *operational volume*, *access to overflown area* and *pilot locality* factors are fundamental properties of the operation, but also function as constraints. The *operational volume* factor describes the airspace volume that the UA may legitimately occupy; that is, whether the operation requires the aircraft to remain in a contained (bounded) volume of airspace. If the vehicle were allowed to access its entire operational space (e.g., full physical range and altitude limits for its mission duration), the operation would be characterized as "uncontained." The *access to the overflown area* factor captures whether ground-based access is allowed. For example, if access to the operational area (e.g., by persons or ground-based vehicles) is under the control of the operation, then access is "controlled".

These factors are not necessarily independent; for example, *air traffic density* is often dependent on *operational altitude*. Furthermore, the list is not comprehensive; it is a set of factors from the NASA study deemed to have a significant impact on the overall system safety risk. Table 3 provides a summary of the factors that emerged as dominant influences on system hazards.

Visualization of the Risk Space

To appreciate the difference in the safety risk inherent in diverse UA platforms performing a variety of operations, a graphical means of displaying the factors can be useful. Dissimilar platforms performing distinct operations could then be seen to possess similar risk profiles, as the coarse discretization of the factors allowed for visual patterns to emerge. Figure 2 shows the visualization for the ConOps for the precision agriculture spray operation, indicated in blue and purple. The pink blocks are described later.

These factors help visualize why, for this operation, hull loss of the vehicle, within the operational volume, is not a safety hazard. When population density is 'sparse', the operational volume is 'contained', and the access to overflown area is 'controlled', it is reasonable to assume

Table 3. List of Dominant Safety Risk Factors

Design Factors	Range	Primary Hazard
Mass	Micro (<4.4 lb), Small (<55 lb), Medium (<7000 lb), Large (>7000 lb)	Harm to people
Operational Speed	Low Speed, Medium Speed, Subsonic, Supersonic	Harm to people
Pilot Remote Control Authority	Inner Loop, Outer Loop, Autonomous	Interference with crew safety role
GCS to UA Ratio	0:1, 1:1, 1:n, m:1, m:n	Interference with crew safety role
Operational Factors		
Population Density	None, Sparse, Medium, Dense	Harm to people
Operational Altitude	<500 ft, <18000 ft, <60000 ft, >60000 ft	Degradation of safety margin
Air Traffic Density	None, Light, Moderate, Heavy	Degradation of safety margin
Mission Duration/ Range	Minutes, Hours, Days, Weeks	Harm to people
Visual Conditions	Day VMC, Night VMC, IMC	Interference with crew safety role
Operational Volume	Contained, Uncontained	Degradation of safety margin
Access to Overflown Area	Controlled, Uncontrolled	Harm to people
Pilot locality	VLOS-RLOS, BVLOS-RLOS, VLOS-BRLOS, BVLOS-BRLOS	Interference with crew safety role

that no people are in the operational volume during operations. Additionally, when the speed factor is 'low' and the operational altitude is '<500 ft', the impact footprint can be operationally specified to always be within the containment volume (with a judicious choice of containment volume). Thus, hull loss (due to ground impact) within the contained operational volume does not present a hazard, as no harm is posed to ground based humans. Note that a hull loss due to impact outside the containment volume is accounted for in the "Failure to stay within authorized operational area" hazard (see Table 2). Similarly, hull loss due to impact with another aircraft within the containment volume is also considered in the "Failure to detect, alert or warn, and avoid intruder aircraft" hazard (see Table 2).

To see how comparisons are possible, consider a variation of the agricultural ConOps, where a midsize unmanned rotorcraft delivers cargo and the aircraft's route is confined to corridors over uncontrolled rural areas. This sort of operation would likely have a longer duration, a higher operational altitude, and require the vehicle to venture BRLOS. However, if the population density of the overflown area is 'sparse', the change in risk could be less substantial. For few people in the operational area, the risk of hitting someone on impact is somewhat naturally mitigated, despite the control or lack of control of the overflown area. Thus, a corridor operation with an uncontrolled overflown area would subsume many of the requirements of a contained operational volume and a controlled overflown area operation; though additional attention would have to be paid to the fly-away risk if populated areas exist within the possible range of the aircraft. Such an operation is visualized in pink and purple cells in Figure 2.

CONCLUSION AND FUTURE WORK

The NASA study investigated airworthiness requirements for a midsize UAS used for precision spraying applications and provided some insights on both UAS certification and risk-based certification. The first is that current airworthiness certification processes can be used, with some tailoring, as a basis for larger commercial UAS operations, particularly for low-risk use cases.

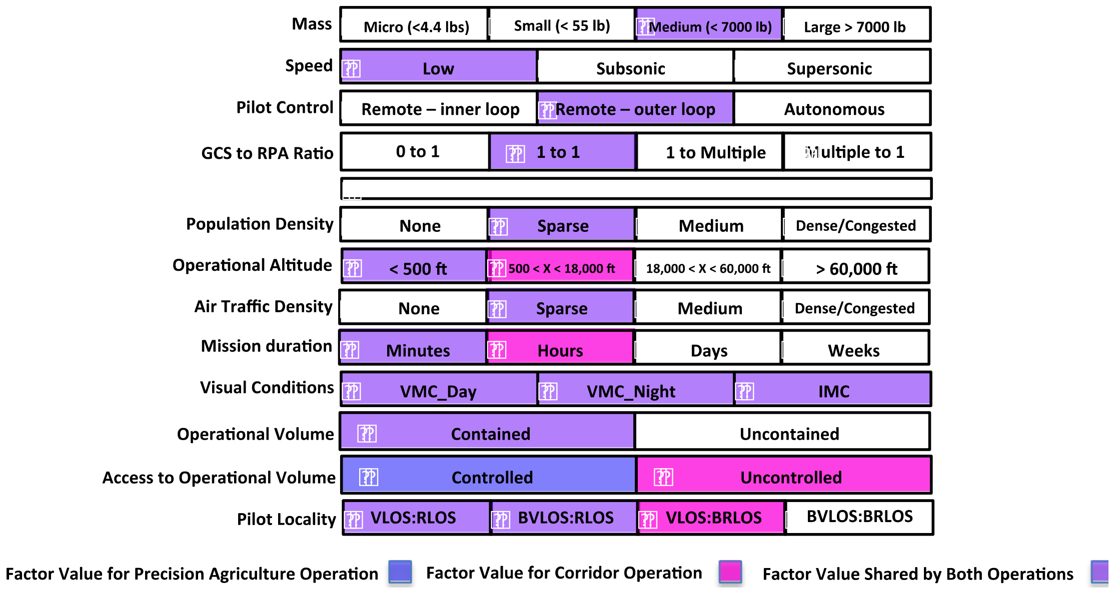

Figure 2. Visualization of Precision Agriculture Application with Rotorcraft

This can be accomplished without requiring compliance with *all* of the existing (prescriptive) airworthiness regulations applicable to similar conventional aircraft. The end result is that UAS could be certified without compromising the innovative and novel features that make them financially and operationally attractive.

Moving toward risk-based certification seems feasible, but will necessitate some fundamental changes. These changes include redefining hazardous conditions for a UAS and explicitly evaluating the hazards associated with the ConOps, instead of relying on the implicit hazards captured in the existing regulatory standards. Performing operational hazard analysis early in a risk-based airworthiness process allows airworthiness standards to be tailored to simultaneously maintain public safety and not unduly burden the proposed UAS operation. Basing airworthiness standards on a hazard analysis for the designated ConOps allows maintenance of public safety without undue burden on the proposed UAS operation. Performance-based safety objectives will be needed for novel systems and equipment including C2 links, containment systems, and systems that can DAA situations that pose harm to people, property, or other aircraft. The NASA study provided an initial attempt to draft requirements in that style. Finally, risk factors will need to be established that can distinguish risk profiles among different UAS types and their operations to help define the envelope of safe UAS operations.

Further work is needed to validate the conclusions of the paper especially with regard to the applicability of risk factors to other UAS and operations. Establishing a means to comply with the certification requirements would greatly enhance the viability of this approach to risk-based certification advocated in this paper. Work is also needed to develop the system architectures, requirements, and means of compliance when autonomous capabilities, responsible for safety critical functions, are added to the UAS.

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