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Safety and Certification Considerations for Expanding the Use of UAS in Precision Agriculture

Kelly J. Hayhurst*, Jeffrey M. Maddalon*, Natasha A. Neogi*, Harry A. Verstynen**

*NASA Langley Research Center, Hampton, Virginia

**Whirlwind Engineering, LLC, Poquoson, Virginia

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Abstract. *The agricultural community is actively engaged in adopting new technologies such as unmanned aircraft systems (UAS) to help assess the condition of crops and develop appropriate treatment plans. In the United States, agricultural use of UAS has largely been limited to small UAS, generally weighing less than 55 lb and operating within the line of sight of a remote pilot. A variety of small UAS are being used to monitor and map crops, while only a few are being used to apply agricultural inputs based on the results of remote sensing. Larger UAS with substantial payload capacity could provide an option for site-specific application of agricultural inputs in a timely fashion, without substantive damage to the crops or soil. A recent study by the National Aeronautics and Space Administration (NASA) investigated certification requirements needed to enable the use of larger UAS to support the precision agriculture industry.*

This paper provides a brief introduction to aircraft certification relevant to agricultural UAS, an overview of and results from the NASA study, and a discussion of how those results might affect the precision agriculture community. Specific topics of interest include business model considerations for unmanned aerial applicators and a comparison with current means of variable rate application. The intent of the paper is to inform the precision agriculture community of evolving technologies that will enable broader use of unmanned vehicles to reduce costs, reduce environmental impacts, and enhance yield, especially for specialty crops that are grown on small to medium size farms.

Keywords. *Unmanned Aircraft System (UAS), unmanned aerial applicator, certification, airworthiness requirements, precision agriculture*

Introduction

Civil use of unmanned aircraft systems (UAS)[1] represents a major transformation in today's commercial aviation industry. Interest in civil applications for unmanned aircraft, such as their use in agriculture, is not novel. A 1976 study by the National Aeronautics and Space Administration (NASA) assessed the state of civil use of unmanned aircraft "to determine whether or not the potential market is real and economically practical, the technologies are within reach, the operational problems are manageable, and the benefits are worth the cost" (Aderhold et al., 1976). That study found a "promising potential demand" for civil unmanned aircraft and identified agricultural spraying and crop dusting as one of the most promising uses. In the early 1980's the Yamaha Motor Company of Japan began developing industrial-use unmanned rotorcraft "that would be able to spray paddy fields near residential quarters efficiently and precisely and reduce necessary labor" (Sato, 2003). Today, 40% or more of Japan's rice crops are treated by UAS (Anderson, 2016). The potential of UAS is also being realized in the United States (US), but slowly and incrementally. Last year the Federal Aviation Administration (FAA) authorized limited commercial use of Yamaha's RMAX system, based on its history of extensive and safe use in Japan (DOT-11448T, 2003).

Modern agricultural technology plays a vital role in increasing productivity to meet rising food demands for a growing global population, and in the conservation and management of agricultural resources (Abdullahi et al., 2015). UAS support that role by providing a convenient platform for advanced remote sensing technologies and effective dispersion of agricultural inputs (Ehsani et al., 2012; Peña et al., 2014; Jannoura et al., 2015). Since early 2015, the FAA has granted over 5000 petitions for some limited commercial operation of UAS (FAA-333, 2016). Many of those petitions are for small UAS (sUAS), generally less than 55 lb, operating under visual conditions to provide surveillance, monitoring, and imagery data. This data is more accurate and can be refreshed in a more timely and efficient manner, as compared with current means of data collection for agricultural crop conditions. UAS can collect data "at high spatial resolutions enabling differences in crops to be compared by the centimetre rather than the metre, as in the case of satellites" (Abdullahi et al., 2015). Furthermore, most sUAS are easily deployed, making on-demand data collection feasible. With the increased availability and accuracy of data comes a desire to act on it more efficiently.

By many accounts, routine operation of agricultural UAS, including both small and large UAS, has been hampered by a lack of certification standards (Nonami, 2007; Turner et al., 2016; Zhang and Kovacs, 2012). According to the FAA, airworthiness certification will be required for commercial operation of UAS in the national airspace system (NAS), except for certain special cases where a UAS is exempted (FAA-RM, 2013). For example, last year the FAA implemented a Section 333 exemption process to authorize some limited commercial use of UAS (FAA-333, 2016). This process effectively serves as a stopgap measure to allow case-by-case approvals of UAS until UAS-specific regulations and standards can be put in place. The FAA also issued a Notice of Proposed Rulemaking specifically for sUAS with proposed criteria for their operation, but those rules have yet to be finalized (DOT-NPRM, 2015). A 2015 NASA study investigated safety and certification considerations associated with commercial use of UAS larger than sUAS (Hayhurst et al., 2015). A summary of the results of that study are presented here.

The 2015 study investigated some of the certification requirements for UAS needed to support operations that take place in environments with a relatively low safety risk, such as precision agriculture. The objective of the study was to propose design criteria for a midsize unmanned

[1] In this paper, *UAS* will be used to refer to a remotely-piloted aircraft system (RPAS), and *conventional aircraft* will be used to refer to an aircraft with an onboard pilot. At the present time, regulatory authorities will only consider approval of UAS with remote pilots. Fully autonomous aircraft, that do not allow any pilot intervention in the management of the flight, are currently prohibited (ICAO, 2011).

rotorcraft (about 1000-lb maximum takeoff weight) hypothesized for commercial precision aerial application. In this paper, precision aerial application refers to variable rate application of direct agricultural inputs (e.g., water, fertilizers, herbicides, pesticides, etc.) by an aircraft. Application may take place on a field within visual line-of-sight (VLOS) of the remote pilot or beyond visual line-of-sight (BVLOS). The research effort produced a candidate set of design and performance requirements needed to support airworthiness certification of an unmanned rotorcraft for aerial application.

This paper summarizes the 2015 study's findings and the impacts of those findings on early adopters of UAS technology for precision agriculture. The next section discusses some possible incentives for using a midsize UAS for precision agriculture, especially for aerial application. The discussion includes observations on how unmanned aerial applicators might provide benefit to precision agriculture beyond that already provided by conventional aerial applicators and ground equipment. The following section provides a brief overview of aircraft certification relevant to using UAS for precision aerial application. The subsequent section describes the 2015 NASA research study, focusing on the precision agriculture concept of operations. The discussion continues by summarizing some of the remaining challenges for research and development for the precision agriculture and aviation industries. The final section summarizes the observations and lessons learned.

Motivation

The challenge in deploying a midsize UAS for precision aerial application is not limited to determining whether or not it is designed and built to operate safely (i.e., compliance with aviation regulations and standards). A significant challenge also lies in establishing the benefits of using a midsize UAS for precision aerial application—in terms of when and how to best deploy a UAS to reduce input costs (e.g., product applied and deployment expense) and increase yields or economic or environmental benefit. This section briefly examines some of the potential benefits of using UAS in precision aerial application.

Business Case Considerations

Variable rate application of agricultural chemicals at the right time, in the right place, is known to have both economic and environmental benefits (Plant, 2001; Bongiovanni, 2004; McBratney et al., 2005). Aerial application can further increase these benefits by (1) limiting physical damage to crops during the application process, (2) reducing soil compaction, and (3) providing a more optimal mix of dispersed product through rotor-wash action (Lan et al., 2010). Aerial application by UAS may provide additional benefit by expanding the range of application conditions (e.g., weather conditions), affording more efficient timing of treatment, and enabling operation in difficult terrain not accessible to conventional aerial applicators or ground equipment. The type of applicator used (e.g., tractor, aircraft), vehicle ownership model, (hired) labor expenses, fuel(s), and chemical inputs all factor into the cost of the operation. A cost-benefit assessment can determine whether the cost of using UAS for aerial application is worthwhile.

The 2015 NASA study presented here did not attempt to perform a quantitative cost-benefit analysis for precision aerial application using a midsize UAS. Instead, a positive outcome was assumed plausible, given the success of the RMAX in Japan and on-going academic research (Bonicelli et al., 2010; Batte and Ehsani, 2005). The study did, however, speculate on potential benefits of using a midsize UAS compared with current application means, such as conventional aerial applicators, smaller unmanned aerial applicators, and ground-based application equipment. The next three subsections discuss corresponding comparisons with each of these means.

Comparison with Conventional Rotary-Wing Applicators

Although conventional aerial applicators are often imagined as fixed-wing aircraft, conventional rotorcraft are also used and seem more appropriate for comparison with the unmanned rotorcraft used in the 2015 NASA study. According to a recent survey by the National Agricultural Aviation Association (NAAA), 87% of agricultural aircraft in use are fixed-wing aircraft; the remaining 13% are rotorcraft (NAAA, 2012). Rotorcraft are better suited for "small, congested areas that may be more challenging or simply too small a job" for a fixed-wing aircraft (Calleja, 2014). Compared with a conventional rotary-wing applicator, a midsize unmanned rotary-wing applicator might offer the following benefits:

- Increased operational availability. A UAS might be able to operate in environmental conditions that may not be suitable for conventional rotorcraft. Unmanned operations might be more resilient to weather issues and might not be impacted by visibility conditions or restricted to daylight operations, unless relying on visual observers.
- More timely application. It might be faster to deploy a UAS depending on ownership models, service provider schedules, and availability of conventional rotorcraft pilots, especially during peak seasons when conventional pilots and support personnel (e.g., mechanics, inspectors) are in high demand.
- Increased precision in application. A UAS may be capable of more precise delivery, closer to the crop canopy, than a conventional rotorcraft, over a wider range of conditions, due to size, human performance limitations, workload, and exposure considerations. Payload fraction would typically be higher for the UAS in comparison with a conventional rotorcraft, assuming all other things being equal.
- Increased safety. Agricultural aviation is known to be dangerous work. Aerial operations are conducted at very low altitude over terrain (as low as 4 to 6 ft above a field), with elevated risk of collision with ground-based obstacles (e.g., power lines, towers) or the terrain itself. Agricultural pilots must also manage the dispensing equipment and coverage of the fields, in addition to flying the aircraft (Suarez, 2000; Chamberlain, 2016). Unmanned aircraft eliminate the safety hazards associated with onboard personnel.
- Potential cost savings. Using a UAS might reduce operational expense over conventional rotorcraft, as fees for conventional aerial services can be significant. Cost savings might be realized in smaller, simpler vehicles (lower initial cost, storage costs, and continuing maintenance cost), the use of less fuel, and reduced certification costs. Costs associated with all of these aspects are currently unknown.

Comparison with Smaller UAS Applicators

The differences between a smaller unmanned applicator, such as the RMAX (approximately 207-lb maximum takeoff weight), and a larger one, such as the one in the 2015 NASA study (approximately 1000-lb maximum takeoff weight), are mostly related to size, weight, and power considerations (SWAP). SWAP affects range, endurance, equipage, and payload capacity, among other things. Compared with a smaller unmanned aerial applicator, a midsize unmanned aerial applicator might offer the following benefits:

- Increased payload. Larger payload capacity would enable sustained application operations over large fields, whereas the limited payload capacity of smaller vehicles would require repeated refueling or replenishing of the chemical tanks.
- Easier integration into farm management information systems (FMIS) (Carli and Canavari, 2013; Sørensen et al., 2010). Higher SWAP limits provide more power for onboard processing and communication, thereby providing an easier interface with data management and geographic information systems (GIS) than would be possible with a smaller UAS. This integration could enable UAS to operate in cooperation with (remote) tractors, supply chain vehicles (e.g., harvesters, transports), and other currently deployed fixed infrastructure systems.
- Increased efficiency and effectiveness. Larger UAS might have the potential to support real-time, sensor-based precision application (to augment map-based application) due to increased payload and processing power. This would increase responsiveness even further, thereby

aiding in application based on current soil or crop conditions, and allow for onboard processing of sampling data to increase application accuracy.

- Extended range. Larger UAS might have the SWAP available to carry heavier sensors and additional equipment (not suitable for smaller UAS) allowing a wider operational range such as BVLOS. Enhanced equipage, however, would likely incur additional certification costs, compared with a smaller UAS without BVLOS capability. That is, midsize UAS will not have the advantage of using the forthcoming sUAS rule or Section 333 exemption process.

Comparison with advanced ground equipment/tractors

Substantial progress has been made in the precision application of agricultural chemicals using ground equipment (Batte and Ehsani, 2005). Today, ground-based equipment (e.g., tractors) can map fields, drive themselves, and precisely calibrate their movements within inches to minimize waste in fuel and dispersed products. Advances in data analytics, global positioning systems (GPS), GIS, and remote sensing technologies have all contributed to making farming more precise (Munshi, 2013). Compared with a precision ground applicator, a midsize unmanned rotary-wing applicator might offer the following benefits:

- Reduced soil damage. A UAS would not cause soil entrainment or impaction that would occur with a ground-based mechanism.
- Operation in wet conditions. UAS can operate in wet soil conditions (e.g., rice fields, cranberry bogs), whereas tractors typically cannot.
- Operation in difficult terrain. A UAS can operate in terrain that tractors cannot (e.g., terraced fields).
- Efficiency. A UAS may be able to access the point of application more quickly than a tractor, depending on field size, ownership, and service provider availability.
- Improved application to tall crops (e.g., fruit trees). A UAS would likely be more flexible in terms of application height than tractors or other ground-based distribution systems, especially for larger crops.
- Improved human safety. UAS operations would reduce the contact between humans and agricultural chemicals, in comparison with human-operated ground equipment.

While it seems plausible that unmanned aerial applicators could provide some benefits, there is considerable uncertainty in the extent of those benefits. Such uncertainty is to be expected in a nascent industry. Field testing, experimental use, and university research within the agriculture community are needed to provide data to support cost-benefit analysis. In the meantime, the aviation industry is making progress in enhancing the technical capabilities of unmanned platforms and in regulating them. The next section provides some background information on the current state of UAS certification.

Overview of Certification Considerations for UAS

The FAA considers UAS to be aircraft and, therefore, subject to certification by national civil aviation authorities and the International Civil Aviation Organization (FAA-RM, 2013). That view differs from how the RMAX and similar agricultural rotorcraft have been regulated in Japan, where agricultural rotorcraft have been regulated as farming equipment by the Ministry of Agriculture, Forestry and Fisheries (MAFF). In most countries, the national civil aviation authority is responsible for regulating UAS, and more recently, regulation of UAS in Japan has come under the purview of the Japan Civil Aviation Bureau.

In the US, the Federal Aviation Regulations (FARs) provide regulatory requirements specific to aircraft, to airspace and operations within different airspace classes, and to pilots and other personnel involved in operating or managing aircraft. In the NASA study, the primary focus was on certification aspects pertinent to airworthiness of aircraft systems and equipment. Airworthiness can be broadly defined as the suitability of an aircraft for flight. 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. Airworthiness requirements account for the safety of the participants in the airspace system (by providing a vehicle capable of safe flight), but also of third parties and property. Clothier classifies people and property as follows (Clothier, et al., 2013):

1. First parties - people and property directly associated with the operation of the UAS (e.g., the remote pilot, observers, ground control station);
2. Secondary parties - people and property not directly associated with the safe operation of the UAS, but who are associated with the end use or derive direct benefit from the operation (e.g., the farmer, associated crops and equipment, etc.);
3. Third parties - people and property not directly associated with the event and who typically do not derive direct benefit from the activity (e.g., a neighboring farm).

All aircraft (e.g., commercial, private, general aviation, experimental, military, etc.) that operate in the NAS are required to be airworthy (14CFR, 2016). The effort required to establish airworthiness in compliance with FAA regulations and standards increases commensurate with the impact on public safety. In particular, aircraft used for commerce or hire are legally required to have an airworthiness certificate[2], unless specifically exempted. Part 21 of the FARs specifies the basic procedures for civil certification of aircraft products and parts in the US, including those for airworthiness. Other FAR Parts (e.g., Parts 23, 25, 27, 29, 31, and 33) stipulate airworthiness standards for conventional airplanes, rotorcraft, manned free balloons, and aircraft engines. These standards specify design and performance criteria needed to establish that an aircraft is capable of safe flight and landing. Other certifications such as those for pilots, flight crew members, and mechanics are also needed for commercial operations, but are beyond the scope of the work reported here. Public aircraft, that is, those that are operated for governmental purposes such as military operations, border patrol, law enforcement, firefighting, or scientific research, must comply with the standards set by individual government agencies. In many cases, those standards are based on the civil standards, but they do not have to be.

Three different certificates are relevant to airworthiness: a type certificate, a production certificate, and an airworthiness certificate. A type certificate is issued for a particular type design of a civil aircraft, engine, or propeller insofar as it complies with applicable airworthiness requirements. The quality system used for manufacturing aircraft is addressed through production certification. A production certificate is issued to confirm that a manufacturer can produce duplicate products under an FAA-approved type design. For an aircraft with a type certification, information about production and maintenance must be provided to obtain an airworthiness certificate. An airworthiness certificate indicates approval that each aircraft, as built, complies with its type design and is in a condition for safe operation. As such, airworthiness certification is applied on an airframe-by-airframe basis, whereas the type design applies to all aircraft of that particular design.

According to the FAA, the general certification regulations and processes for conventional aircraft are applicable to UAS (FAA-RM, 2013). Airworthiness standards for specific UAS types, however, have yet to be developed. Explicit exemptions to the current aviation regulations are currently being used to allow limited commercial UAS operations. The Section 333 exemption process imposes operational limitations on UAS in lieu of compliance with airworthiness standards. UAS that can comply with the limitations can be exempted from the airworthiness requirements in the FARs. Consequently, UAS operating under a Section 333 exemption are not required to have a type, production, or airworthiness certification. Typical considerations and operational limitations under a Section 333 exemption authorization include:

[2] According to FAR Part 91.7 “No person may operate a civil aircraft unless it is in an airworthy condition”.

- UAS mass (including payload) must be less than 55 lb.
- Operation over third parties is prohibited.
- Speed cannot exceed 87 knots, or 100 miles per hour.
- Altitude cannot exceed 400 ft.
- Operations are in the daytime under Visual Flight Rules (VFR).
- Operations are restricted to visual line-of-sight of the remote pilot.
- Operations must use visual observers to maintain visual line-of-sight (no first person view extension permitted).

Section 333 exemptions are granted for a specific purpose. Use of the same UAS for a different purpose currently requires a new exemption, unless multiple uses are in the original exemption, which is uncommon.

Similar limitations are expected under the forthcoming sUAS rule, which is projected to become Part 107 of the FARs. The limitations enable low-risk use of new technology while ensuring public safety by mitigating the potential for harm to third parties. Operation under these limitations also enables the collection of valuable operational data in a relevant environment that is essential to understanding unexpected failure conditions and interactions that will support the eventual development of regulatory standards.

Despite the large number of Section 333 exemptions to date, there are limitations to using sUAS to support precision agriculture. For example, farmers wishing to survey or treat anything other than small fields must relocate the aviation operation multiple times to provide the required coverage, given the limited range of sUAS (including VLOS). Additionally, the payload, including sensing equipment or agricultural chemicals and their distribution system, must be included in the 55-lb weight limitation. There are also acknowledged limitations to sUAS technology; Zhang and Kovacs provide a good discussion of sUAS limitations, including issues with aircraft stability and maintainability (especially in winds and turbulence), engine reliability, and sensor and actuator resilience (Zhang and Kovacs, 2012). Larger, more capable UAS that can operate BVLOS and carry heavier payload could potentially provide additional benefit and reduce overall operational costs.

NASA Study of an Unmanned Aerial Applicator

Lack of clear, definitive regulations for unmanned systems is often cited as the biggest limitation to commercial use of UAS (Nonami, 2007; Turner et al., 2016; Zhang and Kovacs, 2012). While progress has been made for sUAS used for crop surveillance and mapping, UAS-specific regulations and standards are still needed to support operation of larger, more capable UAS. A primary goal of the NASA study was to help fill the void in airworthiness standards which are needed to certify UAS to operate routinely and safely in the NAS. The study investigated the extent to which a selection of existing aircraft certification processes and airworthiness standards are suitable for UAS, and how, if necessary, they could be amended to better accommodate UAS. This work directly supports the FAA's incremental approach to gaining airworthiness approvals by "developing design standards tailored to a specific UAS application and proposed operating environment" (FAA-RM, 2013) and the European Aviation Safety Agency's (EASA's) efforts to regulate UAS (EASA, 2015).

To provide a starting point for the study, an operational concept and a UAS platform were selected. Precision aerial application was selected for the operational concept because of the low-risk nature of the operation and a well-documented interest in using UAS for agriculture work (Jenkins and Vasigh, 2013). A midsize platform was selected because midsize UAS represent a technical aviation challenge; they fall in between sUAS that may not require airworthiness certification and large UAS in high-risk environments that will likely require compliance with existing requirements for conventional aircraft. Midsize UAS represent a class of UAS that aims to minimize system costs by relying on commercial-off-the-shelf components instead of costly aviation-grade components. The project used the Dragonfly Pictures, Inc. DP-14 as its representative platform (shown in Figure 1). The DP-14 weighs approximately 1000 lb, has a payload capacity of 430 lb, and has an endurance of 2.4 hours.

The study continued with the development of a detailed concept of operations (ConOps) for precision aerial application with a UAS having design characteristics resembling those of the DP-14.

Figure 1. Dragonfly Pictures' DP-14 model Configured for Precision Application

Concept of Operations for Precision Aerial Application

The ConOps for precision aerial application focuses on spot treatment of crops in fields up to 160 acres, in quarter sections, in rural, sparsely populated areas. The general concept is to have an unmanned rotorcraft apply direct agricultural inputs to relatively small areas in a field of crops that have been determined by some means to need treatment (see Figure 2). Such an operation might be undertaken to eradicate a fungal, weed, or pest infestation before it encompasses an entire field, or correct a nutrient imbalance before permanent damage occurs to the crop. This ConOps is intended to be compatible with established precision agriculture principles: applying the right chemical to the right place at the right time. *A priori* knowledge about crop health, captured in a prescription map, is used to identify areas needing treatment. Prescription maps can be based on Landsat (Short, 1982) or other imaging data, such as data from conventional or unmanned aircraft, or may be developed by traditional methods, such as direct inspection of fields. The existence of such a prescription map suitable for generating a flight plan for the UAS is assumed in the ConOps. Example treatment areas are noted in Figure 2, with dashed white lines.

Figure 2. Concept of Operations for Precision Aerial Application with an Unmanned Aircraft

The unmanned rotorcraft is expected to operate a few feet above the crop canopy, at a height determined optimal for the spray operations (to achieve the precision desired and minimize spray drift). In the study's concept, operations can be conducted under daytime, nighttime, and reduced visibility conditions (such as fog or low-lying clouds), but always within radio line of sight (RLOS) of the remote pilot. Including the reduced visibility conditions puts this ConOps beyond the reach of currently authorized sUAS operations. Operations are limited to a designated operational boundary around the field (Figure 2, yellow lines), and an absolute containment boundary just beyond the operational boundary (Figure 2, red lines). The absolute containment volume includes an altitude limit of 400 ft with the boundaries. The containment boundary was established to mitigate the risk of fly-away events that could result in the vehicle entering an area in which it is not permitted to operate, or behaving in a manner that is hazardous to other aircraft or persons on the ground. The operational volume is also limited to airspace where air traffic control instructions are not provided (i.e., Class G airspace). This airspace is always near the ground and away from airports. Since altitudes less than 500 ft above ground level are not generally considered safely navigable for conventional aircraft, the airspace and altitude limits reduce, but do not eliminate, the probability of intruding air traffic (Voss, 2013; Copley, 2014). For example, other aerial applicators, both conventional and unmanned, may be operating near the designated field.

Containing the operation to a well-defined volume, restricted in altitude and inhabitants, is key to limiting public safety risk, that is, risk to other aircraft and to people and property in proximity to the operation. In the precision application ConOps, crashing an unmanned aircraft within the containment boundary is generally an economic concern, instead of a safety concern. Sufficient systems, equipment, and procedures must be in place to keep people outside of the operational volume, keep the vehicle within the volume, and ensure ground impact hazards are mitigated (Hayhurst, et al., 2015). If that can be done, then many of the airworthiness regulations for conventional aircraft, necessary to protect the physical aircraft (in proxy of the people onboard), are not necessary for this UAS. Therein lies the potential for reducing the effort needed to certify UAS built for operations similar to the precision agriculture ConOps.

Results of the Research Study

The goal of the research study was to investigate the extent to which airworthiness requirements can be reduced for a midsize UAS if it operates only within a low-risk environment. That is, does a midsize UAS need to comply with all of the design criteria specified in the existing airworthiness standards for conventional rotorcraft if the safety risk associated with that operation is low? A reduction in airworthiness requirements could also result in a reduction in certification cost, which would lower the overall cost of the UAS.

After developing the ConOps, the major research task was to generate a suggested set of design requirements for the DP-14. The set of design requirements necessary to establish the airworthiness of a particular aircraft is commonly documented in a type certification basis (FAA-TC, 2005). For this research study, the suggested set of design requirements for the DP-14 was referred to as a mock type certification basis and was based on the safety-related hazards and associated risks that need to be managed for precision aerial application. System safety processes and tools from the civil aircraft domain were used to identify hazards for the unmanned aerial applicator (SAE, 1996; RTCA, 2000). These methods facilitate systematic examination of an aircraft's functions, classification of failure conditions according to their severity, and means to mitigate expected hazards. The primary hazards for precision aerial application by a midsize UAS are listed in Table 1.

The hazards presented in Table 1 represent those key failure conditions that may result in an undesirable situation (e.g., death, injury, etc.) to first, second, or third parties. These hazards drive the safety-oriented airworthiness requirements. For example, consider the "loss of pilot situational awareness" hazard listed in Table 1. The pilot in command of an aircraft is required to have knowledge, or situational awareness, of the state of the aircraft and of the airborne and ground environment in which the aircraft is operating. If the pilot loses this situational awareness, then the pilot cannot be expected to make reasonable decisions regarding safe flight or successful landing. Ensuring situational awareness can be challenging for a UAS since the pilot is not onboard the aircraft. Degradation of situational awareness does not, by itself, result in injury or death. Rather, the degradation constitutes a loss of a safety margin. These margins allow for the possibility of safe operation during emergency situations or unexpected conditions and help to avoid injury or death.

Table 1. Primary Hazards for an Unmanned Aerial Applicator

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 unmanned aircraft for contingency and emergency functions • Loss of or degraded 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 of, and avoid intruder aircraft • Failure to detect, alert or warn of, and avoid dynamic or other obstacles on the ground (including people) • Explosion in the powerplant or fuel system	• Failure to recognize and avoid adverse environmental conditions • Failure to stay within the 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 (i.e., loss of means to be seen by other aircraft and observers) • Interference of spray system with any required UAS function

Another example hazard listed in Table 1 is "loss of structural integrity, especially of the rotor system." This hazard captures situations where the aircraft sheds high energy parts in flight due to the aircraft fracturing or parts breaking off in flight, or where the vehicle crashes and releases high energy parts. These parts, when moving at high speed, can injure people in close physical proximity to the operation. For an agricultural operation in a rural, sparsely populated area, the pilot and any associated crew, workers on a neighboring farm, or vehicles traveling on nearby roads may be in sufficient proximity to sustain harm from high energy debris. The hazard can be mitigated operationally by having a large buffer between the operational boundary and the containment boundary (see Figure 2). However, this solution, is impractical in many agricultural environments. Instead, design requirements were specified for the unmanned rotorcraft to ensure sufficient structural integrity of the unmanned vehicle, especially for the rotor system.

Generating the set of design requirements to mitigate the hazards in Table 2 started with the requirements already established for conventional rotorcraft (i.e., the airworthiness standards in Part 27 of the FARs for normal rotorcraft). FAR Part 27 contains approximately 260 requirements covering topics including structural strength, design and construction, powerplants and supporting systems, avionics, and operating limitations. Each paragraph in Part 27 was evaluated for applicability to the hazards in Table 1. Then, one of the following actions was taken for each requirement: (1) the requirement was accepted "as is" for the DP-14, (2) a minor modification to the requirement was made to make it suitable for the DP-14, (3) the intent of the requirement, but not the text, was included in a new generalized requirement (Neogi, et al., 2016), or (4) the requirement was determined not to be applicable at all. Only 11 of the 260 regulations in Part 27 were included "as is" in the mock certification basis for the DP-14; 56 were included with slightly modified text; and 74 were abstracted by intent into three issue papers proposing risk-based requirements on controllability/stability/maneuverability, structural integrity, and powerplant and supporting systems. The mock certification basis also included four additional issue papers that propose requirements for hazards not covered in Part 27: (1) vehicle containment within authorized boundaries, (2) detection and avoidance of other aircraft, (3) detection and avoidance of ground-based obstacles, and (4) command and control links. Altogether the set of design requirements in the mock certification basis for the DP-14 was much smaller than the set typically required for conventional rotorcraft.

The findings indicate that the ConOps has a significant effect on the hazards that require mitigation through airworthiness standards. A ConOps that limits risk to public safety may allow for a significant reduction in the design requirements needed for airworthiness certification, and subsequently a reduction in the cost of airworthiness certification as compared with conventional aircraft. However, it is imperative to note that a low-risk environment does not eliminate all airworthiness requirements for a midsize UAS which is capable of posing harm to people and property. Thus, some effort will be needed to develop airworthiness standards appropriate for UAS, even those operating in low-risk environments.

Challenges for the Adoption of Unmanned Aerial Applicators

A key barrier to the adoption of unmanned aerial applicators for precision agriculture that was addressed in this work is the lack of adequate airworthiness regulations and standards, specifically for midsize UAS. Lack of UAS-specific regulation and standards is not the sole barrier to the adoption of unmanned aerial applicators. As with most new technological advances, there are challenges and limitations. For example, conventional aerial applicators have a number of recognized limitations, including overspray leading to environmental contamination, operation during inclement weather conditions (e.g., high wind speed and temperature inversion), operation in the presence of fixed obstacles (e.g., power lines), calibration requirements, and inaccurate distribution (NTSB, 2014). While aerial application using an unmanned aircraft may address some of those limitations, UAS also bring their own unique challenges. Herein is a sampling of challenges specific to the unmanned aspect of aerial applicators which require additional research and development.

1. Substantiating economic benefit. While conventional aerial applicators have demonstrated their value to the agriculture industry, many farmers are not certain of the economic benefits of using UAS for precision agriculture (Zhang and Kovacs, 2012). Substantial amounts of data must be collected regarding field variability, operational costs, application input savings, and increased yield or increased crop quality before the viability of UAS precision application can be assessed. Cost-benefit analyses are essential. Demonstrations of economic and environmental benefits, including field testing, are needed to provide data to support these analyses (Aderhold et al., 1976).

2. Education. Using UAS in commercial agriculture is a very new enterprise, requiring education and supporting resources to raise awareness of the technology, its benefits, and limitations (Turner et al., 2016). Furthermore, unmanned applicators are participants in the NAS, and thus safety concerns, as well as basic airspace knowledge, would enhance their proper use, as well as maintain the current safety of the airspace system.

3. Reliability. The reliability of UAS used for commercial purposes, including agriculture, is largely unknown (Turner et al., 2016; Zhang and Kovacs, 2012). However, reliability will be an important factor in warranty and insurance provisions and costs. Most UAS intended for agricultural work today are built using commercial-off-the-shelf components from the hobbyist world to keep costs low. The expected reliability of unmanned aerial applicators built using those components will likely be less than the reliability of conventional aerial applicators. Thus, establishing reliability standards and expected reliability of UAS components are important areas of research.

4. Pilot/crew qualification and training. Qualification or licensing requirements and training will be needed for the people involved in operation of the UAS, especially for the pilot and on-site crew. Airman standards, needed for pilots flying aircraft with an issued airworthiness certificate, have not been developed for UAS operation yet.

5. Liability and insurance data collection. Establishing liability concerns for unintended application events is essential in determining the cost effectiveness of the operation, especially in light of the reliability concerns regarding the UAS. Furthermore, the ability to collect accurate data regarding actual product application to a precise physical area, correlated with eventual yield, is vital to determining the viability of unmanned aerial application. This data could also play a part in quickly enabling insurance claims for crop damage or destruction.

Altogether, much work is needed in the agriculture, aviation, and insurance domains to resolve the challenges in adopting unmanned aerial applicators.

Conclusions and Further Work

As Aderhold observed 40 years ago, agriculture is among the most promising civil uses of UAS (Aderhold et al., 1976). The rapid adoption of sUAS for aerial surveillance, imaging and mapping of crops is a testament to that promise. Using UAS for aerial application is a next logical step—a step already taken in Japan and just starting on a small scale in the US. Continued uptake of UAS technology for agriculture depends heavily on establishing a regulatory framework that addresses the hazards in aerial application. However, the rapid rate of technological development in UAS has outpaced current regulatory processes. Although recent regulatory actions by the FAA have made commercial use of UAS a possibility, it is only on a limited basis. To allow routine operation of UAS in the agriculture industry, as well as others, the FAA will need to establish certification criteria, not only for the physical UAS and its associated systems, but also for the people associated with its operation. Furthermore, operational rules, procedures, and communication infrastructure are also needed to enable routine use of UAS by the agriculture industry.

The NASA study of airworthiness criteria for a midsize unmanned aerial applicator was one small step towards supporting the development of a regulatory framework for UAS. The study demonstrated that a ConOps that limits risk to public safety (e.g., agricultural operations) may enable a significant reduction in the design requirements needed for airworthiness certification, and subsequently a reduction in the cost and complexity of airworthiness certification as compared with conventional aircraft. If taken to a full implementation, the results of the present study could facilitate the fielding of a UAS that could supplement ground precision spraying systems and conventional aerial applicators. Incorporating UAS into the set of tools available for precision agriculture has the potential to achieve:

- Reduced latencies between the identification of crop needs and the application of appropriate treatment due to the reduction in deployment times. This deployment could include operations in weather conditions not suitable for conventional aerial applicators or ground conditions not suitable for precision ground equipment (e.g., soft soil and rugged terrain).
- Reduced environmental contamination from overspray and increased precision due to the ability to operate closer to the crop canopy.
- Reduced treatment cost due to reductions in waste of the agricultural inputs (e.g., fertilizers, pesticides).
- Reduced safety hazards to agricultural workers from exposure to chemicals and to conventional aerial applicators by subsuming operations over difficult terrain or ground obstacles.

Continued evolution of UAS technology is necessary before UAS can be easily adopted at the farm level (Ehmke, 2013). To realize the potential promise of UAS for precision agriculture and other domains, further work is needed to address uncertainties in regulatory requirements, warranty and insurance provisions, and in overall cost and performance benefits.

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Nomenclature

BVLOS	Beyond Visual Line-of-Sight
C2	Command and Control
ConOps	Concept of Operations
EASA	European Aviation Safety Agency
FAA	Federal Aviation Administration
FAR	Federal Aviation Regulations
GIS	Geographic Information System
GPS	Global Positioning System
MAFF	Ministry of Agriculture, Forestry and Fisheries
NAAA	National Agricultural Aviation Association
NAS	National Airspace System
NASA	National Aeronautics and Space Administration
RLOS	Radio Line of Sight
RPAS	Remotely Piloted Aircraft System
sUAS	Small Unmanned Aircraft System
SWAP	Size, Weight, and Power
UAS	Unmanned Aircraft System
US	United States
VFR	Visual Flight Rules
VLOS	Visual Line-of-Sight