

Unmanned Aircraft System Handbook and Accident/ Incident Investigation Guidelines



ISASI



“Air Safety through Investigation”

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This Unmanned Aircraft System (UAS) Handbook and Accident/Incident Investigation Guidelines is published by the International Society of Air Safety Investigators and is adapted from the UAS Working Group report *UAS Investigation Guidelines* as submitted to and approved by the ISASI International Council on October 12, 2014. Its use is intended for professional air safety investigators and accident prevention specialists. Copyright © 2015—International Society of Air Safety Investigators, all rights reserved. Publication in any form is prohibited without permission.

EXECUTIVE SUMMARY

The *Unmanned Aircraft System (UAS) Handbook and Accident/Incident Investigation Guidelines* were developed by the ISASI UAS Working Group (WG). The ISASI UAS WG Terms of Reference directed participants to seek to accomplish the following tasks:

1. Determine properties of unmanned aircraft systems and their operations that differ from existing aircraft.
2. Identify additional investigative capabilities that may need to be developed or made more robust to support the investigation of UAS-involved accidents.
3. For Annex 13 to the Convention on International Civil Aviation, Aircraft Accident and Incident Investigation:
 - a. Determine the extent to which Annex 13 definitions for the States of Design, Manufacture, Occurrence, Registry and the Operator can be applied to unmanned aircraft systems, including their ground- and satellite-based components.
 - b. Assess the adequacy of current guidance regarding determination of the State responsible for conducting the investigation of a UAS accident.
 - c. Document any need to recommend changes to Annex 13 related to the above.
4. Identify a standard dataset that should be captured for each UAS-involved accident.
5. Identify additional UAS-specific training requirements for air safety investigators based on the above.
6. Identify additional regulations that may be needed to create or preserve evidence relevant to UAS accidents.
7. Make recommendations to the ISASI Council regarding the best means of addressing the above to other ISASI Committees and Working Groups for appropriate action.

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Key operational and physical differences between manned and unmanned aircraft that may drive ad-

ditional investigative personnel, training or equipment requirements are:

- The lack of a pilot aboard the unmanned aircraft, meaning the aircraft's condition, trajectory and surrounding airspace cannot be directly perceived by its pilot in command (PIC).
- Reliance on radio-frequency (RF) spectrum and continuous connectivity between ground control station and aircraft for safe operation, meaning a UAS pilot's control over their aircraft is subject to disruption of a type not experienced in manned aircraft;
- The varying and sometimes extremely limited abilities different types of unmanned aircraft have to separate themselves from other aircraft (meaning operation under "visual flight rules" as currently constituted is not always possible where alternate means of compliance with "see-and-avoid" rules are employed); and
- Occasional use of novel and exotic materials for propulsion or aircraft recovery, meaning accident sites involving systems where such materials are present may be unexpectedly hazardous to both first responders and air safety investigators alike.

The types of accidents and incidents most likely to result from these differences are:

- Midair collisions (unmanned/manned or unmanned/unmanned);
- Loss of aircraft control in flight;
- Fatalities/injuries on the ground upon ground impact (inability to select point of impact);
- Property damage on the ground upon ground impact or collision with obstruction (inability to avoid surface-based feature or to select point of impact);
- Loss of safe separation between an unmanned aircraft and another aircraft;
- Loss of aircraft control during ground movement; and
- Post-crash injury or illness at the accident scene.

FOREWARD

The *Unmanned Aircraft System (UAS) Handbook and Accident/Incident Investigation Guidelines* have been in development for six years. They started with the formation of the ISASI Unmanned Aircraft Systems (UAS) Working Group (WG) at the 2008 Annual Seminar in Halifax, Nova Scotia. Although initial interest was strong, the slow, drawn-out progress of regulatory activity on UAS operations seemed to have a somewhat chilling effect on participation and collaboration under the UAS WG banner.

The effort was re-booted at the 2011 Annual Seminar in Salt Lake City, Utah, and was built upon the following year at the 2012 Annual Seminar in Baltimore, Maryland. A core group of reliable, engaged participants emerged. However, although the assembly of reference materials moved steadily forward, getting pen to paper for the *UAS Handbook and Accident/Incident Investigation Guidelines* themselves remained a challenge.

Ultimately, this first edition of the *ISASI Unmanned Aircraft System Handbook and Accident/Incident Investigation Guidelines*, hereafter called *UAS Investigation Guidelines*, was primarily the product of a single author, supported by comments and edits from core WG members and a few non-ISASI advisors. As such, it may suffer from the limitations of a single author's perspective, although significant efforts were made to avoid a too-narrow view of the world of unmanned aviation. To that end, it retains some content which was suggested for removal by various individual reviewers. Although at one point the philosophy "when in doubt, take it out" was advanced in support of the pared-down perspective, the reason for deciding otherwise was simple.

Many aspects of unmanned aviation policy-making, including basic questions regarding pilot and system certification, continue to evolve. Some issues remain controversial. As such, both apparent positives and potential negatives associated with properties of, or operations associated with unmanned aviation require as broad and public a conversation as possible. At the same time the tougher challenge – to overcome personal biases and remain as objective as possible, regardless of the aspect of unmanned aviation being discussed – was taken seriously. Hopefully, this first effort has emerged as judgment-free as possible.

It also should be noted that some content was

included simply as an introduction to the nature of unmanned aircraft systems as a whole. Many participants in the WG process had limited or no experience in investigating UAS accidents, or even with UAS operations as they are currently conducted. This is to be expected given the newness of the field. However, it also showed that the *UAS Investigation Guidelines* themselves needed to provide a general starting point for those new to the subject, rather than strictly adhering to a step-by-step prescriptive approach to UAS investigations.

In the years ahead, significant changes in thinking about how and where to fly UAS are likely to occur, and some such changes are likely to be driven by UAS-involved accidents. For now, however, there is a great deal of improvisation, as well as no small amount of political involvement in the development of rules regarding UAS operations from one State to the next. These *UAS Investigation Guidelines* are intended to highlight where risk exists, as well as how and why that risk has been accepted as the unmanned aviation sector evolves into a stable element of the overall aviation system.

The *UAS Investigation Guidelines* also had to be sweeping enough to explain why all unmanned aircraft systems are not created equal. Apart from (1) not being capable of conforming to the "see-and-avoid" concept as it presently is applied, and (2) relying upon a continuous electronic connection between an unmanned aircraft and its pilot in command, unmanned aircraft may bear as little resemblance to each other as an Airbus A380 does to an ultralight. The tendency is to treat them as a unity for regulatory purposes, or to simplify their classification by reference to their physical properties and dimensions. This can result in either too much or too little safety-related rulemaking, as well as losing important distinctions between the capabilities of different types of UAS.

Supporters of efforts to enable "integrated" UAS operations side by side with those of manned aircraft need to understand the extent to which the former can conform to existing requirements governing the latter. For example, there is a growing possibility that the "instrument flight rules/visual flight rules" paradigm will be challenged by the need to accommodate certain limitations of, or desired applications for, unmanned aircraft systems. Similarly, the current system of separate classes of controlled and uncontrolled airspace is increasingly

likely to be influenced by commercial pressure to enable access to virtually all of them by unmanned aircraft not equipped for flight in complex airspace.

The growing practice of granting exceptions to current regulatory requirements simply because a given type of unmanned aircraft is larger, smaller, or intended to be flown well clear of manned aircraft is likely to be confronted at some point by unintended and unexpected interactions. The evidence already exists to show that such interactions can and do occur; air safety investigations may wind up providing the necessary impetus to respond to them.

Finally, some States are being challenged regarding the extent to which they should be regulating unmanned aviation at all. When a “small unmanned aircraft” is indistinguishable from a “model aircraft” but for the intent of the pilot flying it, the difficulty in crafting equitable and effective rules for the safety of all affected by such operations becomes obvious. However, a variety of residual issues still have yet to be resolved.

For example:

- Where and how are lines to be drawn – by altitude segregation, by aircraft size or speed, or by other means?
- Is something flown at an altitude below that used by most other aircraft being operated “safely?” If not, whose responsibility is it to take action against the operator – national civil aviation authorities or local governments?

Air safety investigators must understand these debates as they expand and mature. We must be prepared to document the extent to which their resolution succeeds – and fails – in the course of future investigations if we as a community are to prevent the recurrence of future unmanned aircraft accidents as we have for past and present accidents involving manned aviation.

In closing, some editorial notes seem in order to put the shape and content of this product in context. As noted above, during early reviews there were disagreements among WG participants regarding what it should include and what should be omitted. Some participants felt there was too much; some held that there wasn’t enough. Some felt it wasn’t prescriptive enough, while others held it was too prescriptive and tried to “set investigative priorities.” For a document with no regulatory identity or authority of any type, neither argument seemed particularly persuasive. This product is informational only.

There are a host of matters that have yet to be dealt with adequately in the context of UAS opera-

tions themselves, such as the determination of in-flight conditions, maintaining clearance from clouds, weather avoidance, and the potential hazards of GPS-derived versus barometric altimetry. The *UAS Investigation Guidelines* were created to serve as an atlas to the many subjects touched upon by unmanned aviation, but they are not the proper place for exploring as yet uncharted terrain.

There was a sense on the part of some that every reference to “accidents” should be amended to embrace “accidents and incidents” (without reference to “unusual occurrences” or other lesser-consequence events), or that the U.S. military distinction between “accident” and “safety” investigations should be reflected in the civil-oriented *UAS Investigation Guidelines*. There also were comments to the effect that more detailed training material or examples of previous UAS-involved accidents and recommendations should be provided, while others felt the *UAS Investigation Guidelines* as a whole already might be straying into a regime more properly addressed by the ISASI groups dedicated to training development or government ASI activities.

These debates were difficult to adjudicate, in part because fully addressing all of them likely would have further delayed the release of this document by a year or more. Ultimately, the philosophy that “perfect is the enemy of ‘good enough’” held sway. With the delivery of this first effort, the UAS Working Group is ready to step aside to let other ISASI member-run groups take the raw material provided and mold it into tools specifically geared to the needs of their respective constituencies.

Readers are urged to use the list of references in Appendix 3 as a starting point for independent research, and to realize that there never will be a “last word” on the safety of unmanned aircraft systems... just as there never will be in the broader arena of aviation itself.

Thanks to all members of the ISASI UAS Working Group who unselfishly gave of their time and who with great deliberation produced the essence of this *Unmanned Aircraft System Handbook and Accident/Incident Investigation Guidelines*. Members of the Working Group and others who provided technical guidance are: Thomas A. Farrier, WG Chairman; Mike Cumbie, MO5142; John Darbo, MO4218; Darren Gaines, MO3918; Doug Hughes, MO4415; Justin Jaussi, MO6105; Roy Liggett, MO5452; John Stoop, FO4873; and Al Weaver, MO4465. Technical Advisors: Adam Cybanski, Canadian Forces; and Beverley Harvey, TSB Canada.

PREFACE

There is growing awareness in the air safety investigator (ASI) community that there are fundamental differences between manned and unmanned aircraft, and that those differences need to be fully understood when planning for and carrying out accident investigations involving the latter. The urgency with which the differences need to be addressed will vary widely from one State to the next. However, controlling many of the risks associated with unmanned aircraft system (UAS)¹ operations is best accomplished as part of the regulatory process that allows them in the first place.

Since the primary reason air safety investigations are conducted is to prevent future accidents, civil aviation regulators and national aviation investigative authorities need to begin dialogue on unmanned aviation issues sooner rather than later. To be proactive in preventing UAS-related accidents, ASIs need to help regulators apply lessons learned from manned aircraft accidents to the emerging issues associated with unmanned aircraft operations. There is no point to repeating the safety evolution of the present-day aviation environment with a new generation of foreseeable UAS

-related accidents.

Based on the above, it appears there are two key challenges facing the ASI community with respect to unmanned aviation:

- Being ready to conduct future accident investigations involving unmanned aircraft systems with procedures and capabilities that take into account the differences they bring to the aviation environment; and
- Making sure safety lessons written in blood from previous accident investigations stay learned.

These *UAS Investigation Guidelines* are intended for use by a wide range of ASI audiences. The publication's purpose is solely to introduce readers to major issues associated with the emergence of the UAS sector in the context of air safety investigation requirements and challenges. Any specific capabilities or limitations of UAS described throughout the *UAS Investigation Guidelines* are for illustrative purposes only. In particular, it is understood that the rapid development of UAS technology may overtake some of the *UAS Investigation Guidelines'* content.



CHAPTER 1

Purpose and Structure of the UAS Investigation Guidelines

The *Unmanned Aircraft System (UAS) Investigation Guidelines* were developed by the International Society of Air Safety Investigators (ISASI) Unmanned Aircraft Systems (UAS) Working Group (WG). The ISASI UAS WG Terms of Reference directed participants to seek to accomplish the following tasks:

1. Determine properties of unmanned aircraft systems and their operations that differ from existing aircraft.
2. Identify additional investigative capabilities that may need to be developed or made more robust to support the investigation of UAS-involved accidents.
3. For *Annex 13 to the Convention on International Civil Aviation, Aircraft Accident and Incident Investigation*:
 - a. Determine the extent to which Annex 13 definitions for the States of Design, Manufacture, Occurrence, Registry and the Operator can be applied to unmanned aircraft systems, including their ground- and satellite-based components.
 - b. Assess the adequacy of current guidance

regarding determination of the State responsible for conducting the investigation of a UAS accident.

- c. Document any need to recommend changes to Annex 13 related to the above.
4. Identify a standard dataset that should be captured for each UAS-involved accident.
5. Identify additional UAS-specific training requirements for air safety investigators based on the above.²
6. Identify additional regulations that may be needed to create or preserve evidence relevant to UAS accidents.
7. Make recommendations to the ISASI Council regarding the best means of addressing the above to other ISASI Committees and Working Groups for appropriate action.

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The remaining chapters of this document individually address, as appropriate, each of the seven main tasks.



CHAPTER 2

Differences between Manned and Unmanned Aircraft

Introduction

The definition of what constitutes an “unmanned aircraft,” “unmanned aircraft system,” “remotely piloted aircraft,” “remotely piloted aircraft system,” and similar terms associated with unmanned aviation varies widely from State to State. Similarly, the circumstances under which any such aircraft or system is considered to have been involved in an investigation-worthy accident, incident or unusual occurrence must be individually established based on the associated regulatory structure and operational environment.

For example, in 2010 the U.S. National Transportation Safety Board modified its Title 49 rules to include the following:

Unmanned aircraft accident means an occurrence associated with the operation of any public or civil unmanned aircraft system that takes place between the time that the system is activated with the purpose of flight and the time that the system is deactivated at the conclusion of its mission, in which:

- (1) Any person suffers death or serious injury; or
- (2) The aircraft has a maximum gross takeoff weight of 300 pounds or greater and sustains substantial damage.

In 2012, the Congress of the United States enacted Public Law 112-95, the *FAA Modernization and Reform Act of 2012*, which contained the following definitions:

Section 331:

The term “unmanned aircraft” means an aircraft that is operated without the possibility of direct human intervention from within or on the aircraft.

The term “unmanned aircraft system” means an unmanned aircraft and associated elements (including communication links and the components that control the unmanned aircraft) that are required for the pilot in command to operate safely and efficiently in the national airspace system.

The term “small unmanned aircraft” means an unmanned aircraft weighing less than 55 pounds.

Section 336:

“Model aircraft means an unmanned aircraft that is—

- (1) capable of sustained flight in the atmosphere;

- (2) flown within visual line of sight of the person operating the aircraft; and

- (3) flown for hobby or recreational purposes.

Based on the above, it is clear that the first priority of any air safety investigator faced with the prospect of inquiring into any occurrence involving an unmanned aircraft of any size or type is to understand the regulatory structure governing UAS operations. Once their authority and obligation to investigate are clearly established, air safety investigators need to recognize that the similarities between manned and unmanned aircraft far outnumber their differences.

At the same time, the similarities relied upon to assert the rights of unmanned aircraft to fly side by side with manned aircraft in shared airspace may not outweigh their *differences* with respect to their readiness to operate under the same set of rules as other aircraft. History has proven that placing aircraft operating under different rules in shared airspace will result in accidents.

While the path taken from one State to the next may vary, concerns for the safety of the general public typically arise whenever aircraft of unknown or unproven reliability are operated overhead. For UAS at the smaller end of the size spectrum, there are some indications that civil aviation authorities may be willing to accept a certain amount of risk on behalf of the public in exchange for sustaining the growth of the sector as a whole. However, from a narrower perspective, the principal safety issue that always must be considered is the ability of aircraft operators to interact safely with other operators within the existing aviation system, regardless of how their aircraft are designed, operated, or certified.

In exploring these matters further, civil aviation authorities and national investigative entities will find it useful to develop a working understanding of the nature of the differences *among* unmanned aircraft systems, as well as those between manned and unmanned aircraft in general, and how those differences affect the regulation, operation and risks associated with specific unmanned aircraft flown in specific environments. At the same time, all parties should be clear that the mere fact that an aircraft involved in an accident is unmanned is not evidence that all such aircraft are unsafe. Likewise, the fact that an unmanned aircraft is involved in an accident should not automatically be-

come the central feature of the ensuing accident investigation unless and until its differences are proven relevant to the inquiry.

With the above caveats firmly in mind, it is equally important to acknowledge that while the *types* and *consequences* of accidents involving unmanned aircraft systems may be indistinguishable from those involving manned aircraft, the underlying *cause* or *causes* of such accidents may be quite different. As such, unmanned aircraft accidents may lead investigators to make very different recommendations for future prevention than would be the case for manned aircraft accidents occurring under similar circumstances.

Also, the possibility always is present that some types of accidents largely controlled by previous preventive actions could reassert themselves in the unmanned sector. The nature of unmanned air-

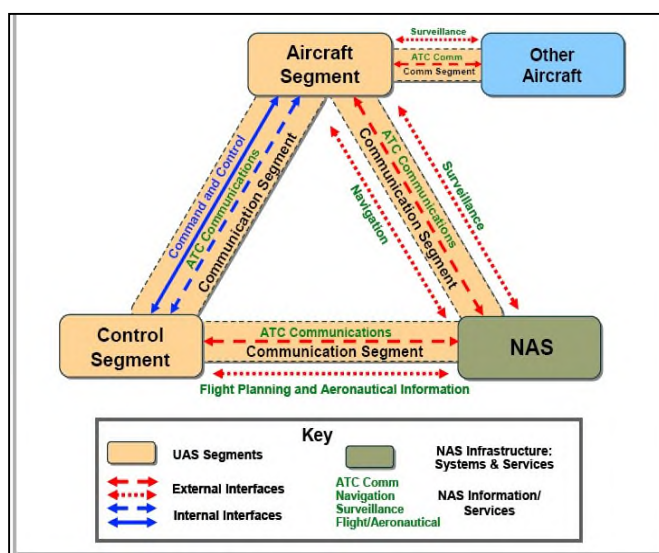


Figure 1. Common Components of an Unmanned Aircraft System (from DO-304, Guidance Material and Considerations for Unmanned Aircraft Systems (March 22, 2007))

craft systems and the limitations they impose upon their pilots – such as the inability to assess flight conditions beyond whatever data on them has been provided for in the system’s design – may prevent previously developed preventive strategies or systems from operating as effectively as they normally do for manned aircraft. Such effects may not be observed for some time, especially if unmanned aircraft operations are relatively infrequent and typically receive special handling.

Key Concepts Underlying Unmanned Aircraft Systems

In 2007, RTCA Special Committee 203 first offered an information architecture diagram (Figure 1) that shows the requirements for an unmanned aircraft system at a glance:

Note that the three principal nodes depicted above – the unmanned aircraft, the ground control station (GCS), and the airspace within which they operate – always are present, no matter if one is referring to a hand-launched aircraft of thirty minutes’ endurance or a jet-powered, intercontinental-capable high altitude aircraft. This is one of the main reasons why this diagram is so powerful when used to examine both the conceptual basis *and* the implications of unmanned aviation.

Most UAS operators assert a desire to move toward a system state where unmanned aircraft are allowed access to non-segregated airspace on a “file and fly” basis and are handled the same as manned aircraft. This notional end state should be considered a point of departure for exploring the extent to which unmanned aircraft systems – either in general or where individual systems lack certain capabilities required of manned aircraft – are capable of achieving side-by-side participation in shared airspace, and which should be a topic of discussion in any accident sequence where both manned and unmanned aircraft are involved.

For the foreseeable future, unmanned aviation is best conceptualized as “unoccupied aircraft piloted from physically separate ground control stations.” Active piloting, where a single responsible pilot in command is required to exercise one-to-one supervision over the operation of a single unmanned aircraft as a “human in the loop” (HITL) or a “human on the loop” (HOTL), is crucial to an unmanned aircraft’s safe participation in the existing aviation system.

Finally, it is important to acknowledge that there is no regulatory structure within which autonomous flight can be carried out safely, at least in the United States, because manned aircraft are at liberty to fly anywhere that unmanned aircraft can outside special use airspace. This has increased interest in some circles for establishing segregated airspace for the exclusive use of unmanned aircraft, even as other members of the unmanned sector continue to insist on unfettered access to the system as a whole.

Key Differences between Manned and Unmanned Aircraft

For the purpose of these UAS Investigation Guidelines, the following should be considered the key

operational and physical differences between manned and unmanned aircraft:

- The lack of a pilot aboard the unmanned aircraft, meaning the aircraft's condition, position, trajectory, and surrounding airspace cannot be directly perceived by its pilot in command (PIC).
- Reliance on radio-frequency (RF) spectrum and continuous connectivity between ground control station(s) and aircraft for safe operation, including as a substitute for the PIC's limitations described above; this has two potential consequences:
 - ◊ A UAS pilot's control over their aircraft is subject to disruptions not experienced in manned aircraft; and
 - ◊ There can be delays in both communications between the pilot and air traffic control and in the pilot's control inputs being received and executed by the aircraft;
- The varying and sometimes extremely limited abilities different types of unmanned aircraft have to separate themselves from other aircraft (meaning operation under "visual flight rules" as currently constituted is not always possible where alternate means of compliance with "see-and-avoid" rules are employed); and
- Occasional use of novel and exotic materials for propulsion or aircraft recovery, meaning accident sites involving systems where such materials are present may be unexpectedly hazardous to both first responders and air safety investigators alike.

The types of accidents and incidents most likely to result from these differences are:

- Midair collisions (unmanned/manned or unmanned/unmanned);
- Loss of aircraft control in flight;
- Fatalities/injuries on the ground upon ground impact (inability to select point of impact);
- Property damage on the ground upon ground impact or collision with obstruction (inability to avoid surface-based feature or to select point of impact);
- Loss of safe separation between an unmanned aircraft and another aircraft;
- Loss of aircraft control during ground movement; and
- Post-crash injury/illness at an accident scene.

In addition, the reliance of UAS on electronic connectivity between aircraft and pilot means the failure of the command and control link can have a variety of outcomes depending on:

- The type of UAS involved (and thus the amount

of system degradation to be expected following such a failure);

- The sophistication of on-board systems associated with both post-loss behavior and the ability of sensors aboard the aircraft to enable detection and avoidance of conflicting traffic;
- The familiarity of the responsible air traffic controller with the management of UAS-related emergencies; and
- The volume of airspace within which unexpected maneuvers can be accommodated safely.

Finally, one of the immediately obvious differences between manned and unmanned aircraft – and among different types of unmanned aircraft – is the enormous range of sizes to which unmanned aircraft are being built. Estimates vary widely as to the proportion of large versus small unmanned aircraft that eventually will constitute the global market. However, it is safe to say that the economic advantages of those at the smaller end of the size spectrum are likely to make them far more popular, and in far wider use, than their larger brethren.

The mass and performance of any aircraft has obvious implications regarding the amount of risk a given system or operation might entail. However, for the purposes of air safety investigations, these attributes are most worthy of consideration in the context of the amount of damage a given unmanned aircraft might be expected to inflict on another aircraft or on people or property it collides with on the ground.

At the same time, it is important to remember that some equipment and/or capabilities normally expected of aircraft in a given class of airspace may be impractical to install in smaller unmanned aircraft with limited range, payload or on-board electrical power. This possibility should be explored any time a small-size UA is part of any accident sequence in complex or congested airspace.

The above should be taken into consideration in determining the scope and level of effort that may be required for any investigation involving an unmanned aircraft system. While none may prove to be relevant to a given accident sequence or aftermath, all represent potential complications that must be understood fully in order to include or exclude them from detailed consideration, and that may drive the need for additional investigative resources – at least on a temporary basis – beyond those normally required for manned aircraft accidents and incidents.

Special Aspects of Unmanned Aircraft System Differences

“Detect and Avoid” Systems—Detect and avoid (DAA) systems, sometimes referred to as “sense and avoid” or “detect, sense and avoid” systems, are still largely in their infancy. Although some commentators try to equate DAA with existing flight path surveillance and warning capabilities like traffic alert and warning systems (TAWS), DAA represents a significantly more complex set of cooperative and interrelated technologies.

The simplest way to think of a high-functioning DAA system is to understand that it must in very rapid and continuous succession:

- Detect electronic signals from aircraft equipped with transponders, Mode S “squitters” or Automatic Dependent Surveillance – Broadcast (ADS-B);
- Detect non-emitting aircraft or surface-based obstacles that would be visible to the naked eye (e.g., gliders, vintage aircraft, balloons, buildings, antennas);
- Process all such targets through an algorithm that allows for performance differences among the various types of aircraft that could be encountered or the maneuvering required to avoid a fixed obstruction;
- Command the unmanned aircraft or its pilot to maneuver in such a way as to remain well clear of the conflict; and
- Annunciate any course, airspeed or altitude change to the pilot or directly advise the appropriate controlling agency that it has executed an autonomous avoidance maneuver that has it off its assigned heading or altitude

An additional property of DAA systems as currently envisioned is that they most likely will incorporate two distinct sets of behaviors. The first response to encounter detection will be for the system to maneuver the aircraft – or to provide guidance to the pilot supporting such maneuvering – so as to remain “well clear” of conflicting traffic or obstacles (a subjective term requiring an as-yet undetermined objective threshold). Such autonomous or directed maneuvering ideally will be carried out without violating an air traffic control clearance or other regulatory requirements such as altitude, proximity to congested areas, etc.

The second response will become controlling should a conflict progress to the point where more “TCAS-like” response is needed, and would be in-

tended to prevent an imminent collision. This functionality is more likely to be automated, both to avoid latency issues (see Chapter 3) and because a UAS pilot would have no way of gauging the actual proximity of the other aircraft or the precise avoidance maneuver needed that would ensure safe separation while not exceeding the unmanned aircraft’s flight envelope.

Various technical solutions for DAA challenges are being explored, including sensor combinations that fuse visible or infrared imagery with electronic detection equipment. It is unlikely that an industry-level standard, incorporating all of the capabilities described above while imparting an acceptable weight and electrical power penalty, will be in place for the foreseeable future. However, work is proceeding to this end, with RTCA Special Committee 228 having established a working group specifically directed toward this effort.

The complexity of DAA architecture and system logic alone is not the only reason why specialist knowledge most likely will be required to explore a given collision scenario. For the near term, the larger problem is that government-approved performance standards and specifications for DAA systems themselves do not yet exist. At the same time, pressure to move forward with efforts to integrate manned and unmanned aircraft operations in shared airspace is likely to drive regulators’ acceptance of DAA systems that are deemed capable of reducing the risk to other aircraft and to the public, but which are based on proprietary or otherwise non-certified criteria.

Finally, it is worth noting that many observers consider DAA systems to have the potential to be inherently superior to human vision in the “see-and-avoid” role. Human perception is limited or adversely affected by any number of conditions, both from an anatomical and an “attention” perspective.* A continuously scanning DAA system never would be looking the wrong way, distracted or otherwise taken away from its designed purpose. When any conflict enters the detection threshold, such a system will warn of or react to it as appropriate.

By the same token, the likely pace of DAA evolution versus demand for expanded UAS operations most likely will result in tremendous variability among DAA installations. This in turn will mean investigative authorities will need to have access to subject matter experts who can evaluate the effectiveness of individual DAA solutions that

may come into question as a result of an aviation accident or incident.

Cockpit Design-While the subject of cockpit design may be considered largely in the domain of a human factors investigation (see Chapter 3), the context of an aircraft accident investigation puts a somewhat different perspective on the issues that may arise where unmanned aircraft systems are involved.

The “cockpit” of an unmanned aircraft is a ground control station not physically attached to the aircraft in any way. Its complexity and sophistication may be indistinguishable from that of an airliner’s flight deck, or it could be as simple as a hand-held control box identical to one used to control model aircraft. In any event, except for a few instances where military operators are attempting to move toward some type of “common cockpit” capable of being configured to fly a variety of different UAS, it is highly unlikely that the human-machine interface (HMI) in use has been developed with much attention to existing cockpit/flight deck design requirements or the requirements of flight in the existing aviation system.

While this may seem counterintuitive, many UAS designs were brought into service through accelerated procurement processes (e.g., the “Advanced Technology Concept Development” (ACTD) initiatives) on an urgent basis. Because they were intended for use during armed conflict but would be incapable of defending themselves from aerial engagement, their development was conditioned by an implied assumption that there would be little or no competing use of the airspace within which the unmanned aircraft were intended to operate.

The procurement strategy for some early medium and high altitude long endurance UAS also placed an emphasis on maximizing the likelihood of efficient, successful mission accomplishment. While the solutions to certain challenges (e.g., control redundancy, payload operations, etc.) were novel and elegant from an engineering perspective, they did not always take into consideration pilot workload, usage and task prioritization issues routinely accounted for in the design of certificated manned aircraft and addressed through formal system safety programs.

A well-documented example of the kinds of problems resulting from these trade-offs is that of a U.S. Customs and Border Protection *Predator B* that crashed in Arizona in 2006. The aircraft was on patrol along the southern U.S. border when it experienced a “rack lock-up” that disabled the

pilot’s controls. He switched over to the sensor operator’s position – which was equipped with identical controls – only to see the aircraft immediately begin to lose altitude. He was unable to regain control, and the aircraft crashed.

Among the multiple issues uncovered in the course of the investigation was the discovery that proper use of the appropriate checklist would have prevented the loss; the sensor operator’s console was not properly set up to assume control of the aircraft when the switchover was made. However, the HMI aspect of this is that controls normally used by the pilot have a separate, alternate use when running the payload sensors, virtually guaranteeing that a breakdown in checklist discipline would have a catastrophic outcome at some point during the system’s life cycle. Fortunately, in this case the hidden trap was discovered without loss of life and has been addressed to some extent by subsequent design and training fixes.

The point of this discussion is that the potential involvement of cockpit layout and “switchology” issues involvement in an unmanned aircraft accident investigation is not necessarily a matter for human factors specialists alone. Rather, investigators will need to be trained to explore *how* the system as a whole is routinely operated, any previously encountered design issues reported by its users, and how misleading, incomplete or inappropriate design features or informational cues can have unexpected or confusing outcomes. Exploring these matters is not a human factors engineering or human performance line of inquiry so much as an *operations* line of inquiry that will require specialist knowledge to effectively pursue.

Accidents Where UAS Differences from Manned Aircraft May Be a Factor

Midair Collision-A midair collision involving an unmanned aircraft and a manned aircraft probably is the most likely type of event that typically comes to mind when considering worst-case scenarios involving UAS operations in shared airspace.*

Determining how the two aircraft came into conflict may require examining how their respective operations were being conducted and what they entailed; the presence and effectiveness of rules and procedures intended to separate manned and unmanned operations; the qualifications of the unmanned aircraft pilot (if different levels of certification are allowed by the State of Occurrence); and similar issues of airspace utilization and crew certification. At some point the question of whether one

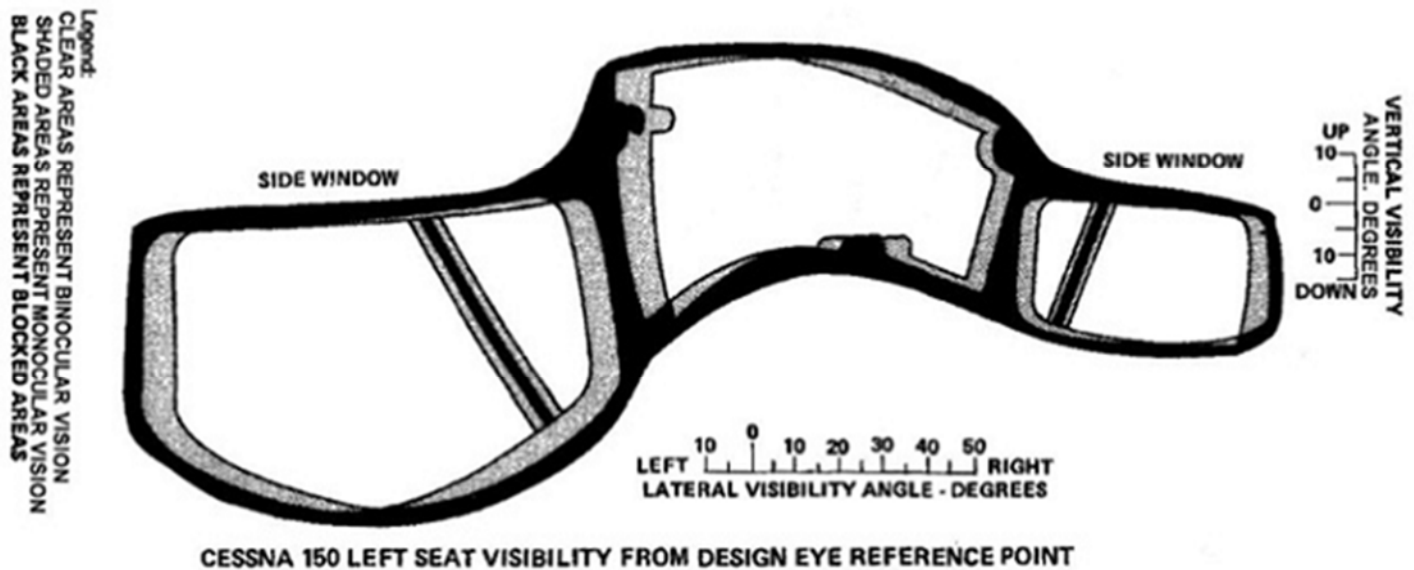


Figure 2. Example Design Eye Reference Point Diagram (*Transportation Safety Board of Canada*)

or both pilots had the ability to see and avoid (or detect and avoid, as appropriate) the other prior to impact is likely to arise. Once a given investigation turns to this issue, it is likely to become far more complex, and developing recommendations intended to prevent the accident’s recurrence will become more challenging.

If a manned and unmanned aircraft are involved, traditional means of determining the manned aircraft pilot’s perspective first should be employed. Investigators may wish to determine if the manned aircraft’s pilot could have seen the unmanned aircraft by examining the collision geometry against possible impediments to cockpit visibility, such as through use of a design eye reference point diagram like that shown in Figure 2.

Once the unmanned aircraft has been located on this type of diagram (i.e., from the manned aircraft pilot’s point of view), investigators will need to take into consideration how the unmanned aircraft would have appeared. Unmanned aircraft come in all shapes, sizes and colors, in some cases meaning a much smaller than usual target, perhaps with little contrast against the prevailing background, may have been presented to the manned pilot. Also, unmanned aircraft operate at a variety of airspeeds depending on their type, meaning a conflict could have developed much more quickly than usual or, conversely, with so little relative movement as to make it virtually imperceptible. This part of the analysis should allow a determination to be made as to whether the manned pilot reasonably could have had the ability to see and avoid the

unmanned aircraft prior to impact.

When the question turns to the unmanned aircraft pilot’s ability to avoid the collision, it will be necessary to determine how (or if) the involved system compensates for the pilot’s inability to directly see and avoid other aircraft. In some cases, civil aviation authorities may have made a deliberate risk decision to accept such a limitation without further mitigation, or by relying purely on the UAS pilot having direct visual contact with his/her aircraft at all times based on how and/or where the unmanned aircraft is intended to operate. However, it is also possible that active and/or passive “detect and avoid” systems may be in use as well.

In exploring a midair collision from an unmanned aircraft system perspective, it is important to bear in mind that so-called “airborne sense and avoid” (ABSAA) systems that perform DAA functions are *aircraft-based*. While some concepts are similar to traffic alert and collision avoidance systems (TCAS), detecting other aircraft and providing direction to the pilot regarding the best avoidance maneuver, most involve a fusion of active and passive sensors supported by on-board logic that identifies conflicts and automatically takes or directs action to separate the unmanned aircraft from them.

If an unmanned aircraft that should have been capable of avoiding a collision by virtue of ABSAA nevertheless is involved in a collision, investigators will be faced with a highly complex technical problem. They will have to determine how the encounter unfolded, including if:

- The conflicting traffic was capable of being detected by the available sensor suite;
- The detection value was sufficient to trigger the appropriate warning and/or autonomous response (if autonomous maneuvering is enabled in the installed DAA system); and
- Whether the amount of time between detection and avoidance maneuver (if any) was within design parameters, as well as whether those parameters were appropriate to the geometry of the encounter.

These questions normally will require significant engineering and modeling and simulation expertise to address, most of which is not within a typical ASI's knowledge base.

In contrast to the above, "ground-based sense and avoid" (GBSAA) systems typically support separation between manned and unmanned aircraft by maintaining surveillance over a defined portion of the sky using surface-based sensors, most commonly using radar capable of seeing both transponder-equipped and non-squawking aircraft. Three key issues most likely will need careful scrutiny wherever a collision or loss of separation takes place in a GBSAA-protected volume of airspace:

- Whether the system successfully detected the conflict in a timely manner;
- Who and how the system warned of the conflict; and
- Whether the UAS pilot's response was appropriate to the warning.

As with many aspects of UAS operations, there are no settled specifications or performance standards for GBSAA systems. Similarly, while there are a number of innovative approaches to providing GBSAA services at various locations, there is no consensus regarding the system architecture used to enable them. Some concepts involve dedicated radar systems, while others use existing air traffic control radar where those systems have been evaluated and deemed suitable based on their altitude coverage, ability to effectively track non-cooperative targets, etc.

At the same time that investigation into the point-of-view and surveillance dimensions of the accident sequence is undertaken, all recorded data captured by the involved UAS – including the "take" from any sensors oriented in the direction of the axis along which the collision took place – should be obtained for examination as well. This will allow investigators to assess the extent to which unmanned aircraft system crews typically rely on normal spectrum, low-light or infrared cameras to scan for conflicting traffic, as well as the

field of view offered by each such system.

It may be procedurally acceptable or legally conformant to use on-board sensors to support collision avoidance, or even as an alternate means of compliance with a State's implementation of the "see and avoid" principle. However, it may be difficult for investigators to determine the *reasonableness* of using such systems for clearing an unmanned aircraft's flight path if doing so is considered an approved technique. As such, close consultation with regulatory and certification authorities may become necessary on that point.

Loss of Control Accidents (Airborne)-

Unmanned aircraft, like their manned counterparts, sometimes are involved in accidents where the pilot in command loses control of the aircraft. However, with unmanned aircraft, investigating such accidents and incidents can be a more complex process simply because there are many more ways such a failure might occur. One's traditional mental image of an "out of control" aircraft must be supplemented to include another scenario altogether, where an unmanned aircraft autonomously flies itself to a final destination that may or may not be known.

For investigations conducted under existing models and taxonomies, it is useful to distinguish between events involving the failure of the control and non-payload communications (CNPC) link from those where the link is in operation but the aircraft becomes uncontrollable. In the former case, the pilot may no longer be in or on the control loop, but a reasonably sophisticated aircraft may remain stable and navigate itself to a pre-determined point (following a "lost link profile"). Alternately, it may fail to revert to the preprogrammed profile and instead take up an unknown trajectory ("flyaway").

In the latter case, for the purpose of this discussion, a UA loss of control takes place when the pilot is no longer able to change the aircraft's heading, airspeed or altitude through an otherwise functioning CNPC link. This type of malfunction typically is the result of a mechanical or structural failure affecting the movement or condition of a primary flight control or control surface, or due to a failure in the transmission of a control input or its translation into a control input aboard the aircraft. To date such failures have proven to be rare, but when they occur they are extremely difficult to diagnose remotely.

For UAS accident and incident investigators, the greatest virtues of just about every unmanned air-

craft occurrence – and particularly in cases of loss of control resulting in the loss of an aircraft – are (1) having a live pilot to talk to, and (2) having the possibility of obtaining significantly more performance data than is usually captured by a flight data recorder readily available in the ground control station, at least where more complex UAS are involved.⁵ The pilot’s testimony can provide significant clues regarding the cause of virtually any kind of accident; rich recorded data can augment the pilot’s recall and understanding of the sequence of events and possibly provide clues as to any disconnects between perception and reality where such might exist.

At the same time, as is the case with all UAS accidents – and especially those involving loss of control – it is vital to remember that a pilot’s ability to provide information about the sequence of events is almost totally dependent on the extent to which the system itself provided that pilot with information, and that data provided to the ground control station is totally dependent on a functioning downlink throughout the period of interest.

Loss of Control Accidents (Ground) and Ground Collisions—The possibility of a runaway unmanned aircraft on the ground is hardly without precedent in manned aviation. Brake failures, aircraft getting away from their pilots after being “prop-started” and a host of other scenarios have played out over time. Similarly, collisions with fixed obstacles or other aircraft regularly take place in manned aircraft operations and should be expected in unmanned operations as well. In general, unmanned aircraft should be assumed to have the same potential vulnerability to such mishaps as their manned counterparts, and many such events are likely to be traceable to the same or similar causes and precursors.

At the same time, differences between manned and unmanned aircraft can have a bearing on the nature and outcomes of ground accidents involving the latter. For example, the failure of a CNPC link during ground operations can have unexpected or difficult-to-avoid consequences, particularly if one takes place in close proximity to other aircraft or surface obstacles. Most unmanned aircraft incorporate on-board logic that will immediately apply the aircraft’s brakes and/or shut down its engine immediately upon detecting a lost link.

Unmanned aircraft systems intended to be taxied to or from a takeoff or landing surface typically provide their pilots with the means and a process for doing so safely. UAS pilots may watch

marshallers with forward-looking optics, follow taxi lines, and stop at hold-short lines, just as they would from the cockpit of a manned aircraft. However, investigators must bear in mind that, while such operations may appear to be conducted in an identical manner to those performed by manned aircraft, UAS pilots operate under significant limitations with respect to their field of view.

System/Component Failure or Malfunction—Accident sequences that begin with component failures or malfunctions can be particularly insidious in unmanned aircraft simply because of the potential delay in the pilot’s becoming aware of a developing situation. Unlike manned aircraft, UAS pilots cannot directly perceive anything that might cue them to a mechanical problem: no sounds, no smells, no vibrations, no “control feel.” Virtually everything they know about the condition of their aircraft must be transmitted down through the same limited amount of bandwidth that must be shared with critical flight performance and navigation data.

As they gain experience with how operational or performance issues show up in regular service, UAS manufacturers have become adept at identifying the relative criticality of different component failures or flight conditions. Since there are no standards regarding what needs to be provided to a UAS pilot for situational awareness, each manufacturer determines data requirements based on history, known system limitations and vulnerabilities, and available transmission and reception resources.

Investigators considering the possible role of a system or component failure in an observed accident sequence will need to familiarize themselves with the specifics of the downlinked data provided to the UAS pilot. If it is concluded that the aircraft’s condition deteriorated in such a way that warning should have been provided prior to failure, the feasibility of implementing recommendations regarding future instrumentation will be highly dependent on the demand such instrumentation will add to the system in terms of weight, electrical power or downlink requirements... not just the unit cost as might be the case with manned aircraft recommended to receive a component repair or upgrade.

For unmanned aircraft, investigators also must bear in mind that system or component failures could entail malfunctions of the ground control station, not just the unmanned aircraft. A completely airworthy, properly operating unmanned aircraft can be lost if the ground control station supporting

its operation becomes unusable or unreliable. In some cases, GCS-related problems may appear to be aircraft problems; if a second GCS or control position is not available to take over the operation in a timely manner, an otherwise preventable accident may occur. Once that has happened, it may be difficult to diagnose the exact nature of the GCS problem because uncertainty may remain regarding link stability, local interference, or other potentially distracting and irrelevant lines of inquiry.

Beyond the fundamental differences between manned and unmanned aircraft cited to this point, other differences may present themselves in the course of a UAS systems investigation. In particular, investigators may not assume that flight-critical components necessarily conform to standards established for comparable components in manned aircraft. Similarly, equipment subject to technical standard orders or other means of guaranteeing a specific level of performance or reliability aboard manned aircraft may be substituted for with less stringently manufacturer or certified avionics aboard unmanned aircraft.

Until contentious issues of cost, airworthiness certification authority and other “comparability” issues associated with integrating unmanned aircraft into shared airspace are resolved, investigators must be prepared to encounter, document and analyze the performance of on-board systems that would not be acceptable in manned aircraft in the course of accident and incident investigations.

CHAPTER 3

Augmentation and Supplementation of Existing Investigative Capabilities for UAS Investigations

Investigative Skills and Knowledge Associated with UAS Attributes

It is likely that specialized investigative skills will be required to explore the involvement of one or more of the above differences in a given accident sequence or its aftermath. As may be expected, such skills will be needed to support analysis of the unique attributes listed above.

Human Factors—The human factors domain as it relates to unmanned aviation must be considered from two distinct perspectives:

- The extent to which an unmanned aircraft system pilot in command is expected to be a “pilot,” with the body of knowledge and physical attributes expected of those flying manned aircraft;

and

- The extent to which an unmanned aircraft’s pilot can be reasonably expected to accurately perceive the flight environment and the immediate surroundings of his/her aircraft – in other words, to have appropriate situational awareness – when physically separate from that aircraft.

To the first point, at this writing there is insufficient objective research available to allow air safety investigators to make any independent judgments regarding how an unmanned aircraft system pilot should be trained or certified. Such decisions are properly the domain of the national aviation authorities who regulate unmanned aircraft system operations. If the circumstances surrounding a given accident under investigation suggest deficiencies in these areas, appropriate findings and recommendations should be made.

On the other hand, there is a large body of compelling historical information that points to how the safe operation of aircraft is highly dependent on the pilot’s physical condition and fitness to fly. Again, each State that allows unmanned aircraft operations has to make determinations regarding the specific standards to which each pilot should be held. The distinctive nature of UAS operations includes not subjecting the pilot to some of the more physically challenging aspects of flight, such as high physiological altitude or exposure to high Gs. In the same way, some accommodations may be possible for certain typical requirements, like normal color vision or some physical impairments, simply based on how unmanned aircraft are flown.

This is not to say that some aspects of unmanned aircraft system operation do not place demands on the physical or mental faculties of UAS pilots. For example, visual acuity is critically important for any UAS operation where the pilot or a visual observer must keep the aircraft in sight to keep it clear of other aircraft and obstacles. Similarly, being properly rested is a necessary adjunct to any complex mental activity, as is good general health. Where a pilot’s fitness to fly or to carry out the responsibilities associated with flying might come into question in the course of an accident investigation, such issues certainly will be worth exploring in the context of the existing body of regulations applicable to the operation.

The second perspective on human factors – how UAS pilots obtain and maintain situational awareness regarding the conduct of their operations – is much less clearly understood. One of the principal limitations under which such pilots must work is in

having the vast majority of their situation(al) awareness regarding their aircraft's operation, as well as the condition of both the aircraft and the environmental conditions surrounding it, confined to the visual sense. Further, the manner in which much of the available data regarding these parameters is presented often requires interpretation; for example, in some systems accumulating ice must be deduced by noting decreased performance, altitude loss and similar symptoms rather than simply looking out a window and seeing ice.⁶

Throughout the first century of flight, aviation human factors experts made great progress in determining the best means of presenting information to pilots, distinguishing between the different types and criticality of flight-related information as well as developing context-based rules for prioritizing it. Various types of displays have been developed to simplify the identification of anomalous conditions, performance trends indicative of developing system problems, and differing severity of malfunctions. At the same time, there always has been at least an implicit understanding that direct perception of the symptoms of some problems, such as unexplained sounds, vibrations or smells, often supports their diagnosis or correction.

None of these cues are available to an unmanned aircraft pilot directly. A conscious decision must be made by each UAS designer as to which information is important enough to warrant being added to the limited data stream from aircraft to pilot. Even if it is deemed desirable to devote a certain amount of bandwidth to purely aircraft state data, developing digital surrogates for sensory-type information is relatively easily for some conditions (e.g., identifying a rough ride through rapid excursions in G-forces), but quite difficult for others (e.g., the smell of an overheating electrical component, the accumulation of smoke, etc.).

Another consideration is that the criticality of some flight conditions – such as turbulence or icing – varies widely from system to system. So, it is not a simple matter to standardize downlinked data across the entire constellation of unmanned aircraft systems. This is especially the case where requiring unnecessary data to be transmitted and displayed could result in pilot interpretation problems, information overload, a failure to provide data that might be more useful, or additional potential sources of on-board malfunctions associated with the information collection and transmission itself.

Following the above line of reasoning, it is not unreasonable to assume that at least some future accidents with UAS involvement may require the

commissioning of specific human factors studies to explore investigators' theories of potential accident scenarios. This could include determining what a pilot could have reasonably concluded about an emerging aircraft problem based on the information available, what more could have been done to support their situation awareness under given operational conditions, or similar issues. Human factors expertise also may need to be applied to developing recommendations to prevent future accidents as well. This might entail addressing such issues as the kinds of automation needed to support certain types of flight activity, automated functions might need to be made more visible to pilots to support situation or mode awareness, etc.

Finally, simply describing the constellation of possible human factors issues arising from unmanned aviation does little to ensure that the needed expertise will be available to explore them. Governments must take conscious steps as soon as possible to support the growth of a qualified talent pool and an unmanned aviation-focused academic establishment to deal with such challenges as they arise. While it might be ideal to have unmanned aviation human factors specialists embedded in each national aviation authority, as a practical matter it would seem more useful to ensure that funding for the academic community is made available to develop experts who could support both public and private needs for such skills.

Telecommunications—While telecommunications and frequency management expertise periodically is called upon in present-day aviation accident investigations involving manned aircraft, it is likely to become far more prominent once unmanned aircraft become regular participants in the overall aviation system. One of the cornerstones of unmanned aircraft systems operation is the remote location of the pilot/operator. At a fundamental level, this means that the entire concept of unmanned aviation (other than where the aircraft are completely autonomous) is dependent upon uninterrupted RF-based connectivity with adequate capacity for all needed data to be exchanged without loss or distortion.

Prior to the advent of widespread unmanned aircraft operations, the regulatory relationship between aviation and telecommunications largely was settled. Portions of the RF spectrum have long been reserved for aircraft voice communications and navigation equipment; whenever new requirements for additional capabilities have emerged (e.g., Airphones, onboard WiFi, satellite communications, controller-pilot data link communications),

they have been aligned with the appropriate parts of existing allocations on the basis of how they operate, and accommodated at a regional or global level as needed.

However, it is important to note that in recent years it has been rare for such new requirements to be related to the *safety* of flight. Rather, they have been driven by the emergence of new technologies intended to increase the efficiency of tasks already conducted in aviation operations, or they have been created for the convenience of aircraft operators or passengers. Unmanned aviation has raised the stakes in the relationship between those who regulate flight and those who regulate resources *supporting* flight, since access to spectrum – and lots of it – is a prerequisite to making use of unmanned aircraft safely and effectively. At the same time, unmanned aircraft move, meaning the frequencies used to control cannot be allocated using the location-based model applied to air traffic control or navigational aid frequencies.

There are two distinct aspects of how the finite resource of spectrum must be managed in order for unmanned aircraft to be operated safely, both of which will require expert knowledge to interpret in the event of an aviation accident in which the reliability, stability or adequacy of control-related links may be in question: the *frequencies* used, and the *bandwidth* required on each of those frequencies. To understand the distinction between the two, a brief explanation is in order.

In the earliest days of radio, it was easiest to generate and broadcast signals of comparatively long wavelengths (in the “low frequency” and “high frequency” bands). These signals also had the side benefit of covering very long distances by virtue of their property of being reflected by the ionosphere, “skipping” over the horizon. As people learned the relative advantages and disadvantages of different types of transmissions at different frequencies, it became obvious that some organizational scheme would need to be imposed on all of the prospective users of the airwaves to prevent their mutual interference. To some extent, the physics of electronic communications argued in favor of assigning certain uses to specific frequencies. For the rest, however, competing applications vying for exclusive use of part of the spectrum often had to be individually licensed on the basis of availability.

The responsibility for such assignments was first worked out at the international level through an existing communications-oriented body – the

“International Telegraph Union,” now the International Telecommunications Union (ITU) – with individual nations granted portions of the spectrum for their respective exclusive use, and other portions protected to enable commonality for worldwide systems to operate, such as those dedicated to aeronautical activity. However, many current UAS activities share portions of the spectrum with other operations. Military UAS often operate on military-reserved frequencies. There also is a small portion of the spectrum set aside exclusively for short-range hobbyist/model aircraft use, which at least in the U.S. is required to be entirely noncommercial.⁷

The vast majority of UAS command, control and communications most commonly are carried out in the range of frequencies between 900 megahertz (MHz) and 30 gigahertz (GHz). There are three “services” under which aviation-specific spectrum is allocated by the ITU:

- Aeronautical mobile (route) service (AM(R)S);
- Aeronautical mobile satellite (route) service (AMS(R)S); and
- Aeronautical navigation radio service (ARNS).

Allocations for UAS uses are complicated by needing to be made from the first two of these, each of which is separately administered. The reason why different domains are involved becomes clearer by looking at Figure 3.

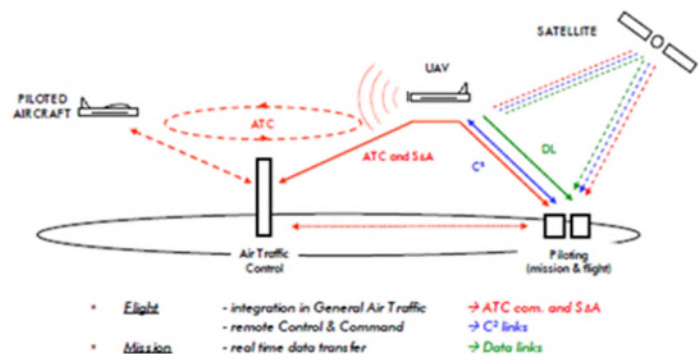


Figure 3. UAS communications segment spectrum/bandwidth requirements by communications node (from an issue paper prepared for the World Radiocommunication Conference 2007, Spectrum for UAS (Unmanned Aircraft Systems): Status of WRC-2007 preparation and proposal for a new agenda item for WRC- 2011, Didier Petit and Alain Delrieu)

The ITU has identified three distinct types of “radiocommunications” required to operate an unmanned aircraft in controlled airspace:

- Radiocommunications in conjunction with air traffic control relay;

- Radiocommunications for UA command and control;
- Radiocommunications in support of the sense and avoid function.⁸

In addition to the above, many UAS incorporate data downlinked from a payload such as an on-board camera or other sensor, which may use an entirely different part of the RF spectrum but which, by the nature of how its “take” is used, may also be flight-critical. To provide for all of these requirements, unmanned aircraft systems require significant amounts of bandwidth to support both uplinked and downlinked data. Most unmanned aircraft have separate downlinked data streams – one for control, the other with the payload “take.”

Figure 3 shows that the remote location of the pilot and the need to downlink both control and payload data from the aircraft drive requirements for different frequencies. The amount of data that each frequency hosts requires significant space from competing or potentially interfering signals, and, for security may utilize several separate frequencies among which the transmission can “hop.” Further, the vast majority of beyond line of sight (BLOS) UAS operations require satellite service (although some terrestrial methods are being explored) for both data and voice support.

Previously, the UAS community has acknowledged the complexity of unmanned aviation and the relationship among its various components, but has tended to downplay the criticality of *how* those components must interact to assure their safe operation. In response to the need to re-imagine the functional relationships between pilot and aircraft – and to graphically illustrate the different types of data exchanges that need to take place through the various links – RTCA Special Committee 228’s Working Group 2 (WG2) reconsidered the original architectural diagram shown in Figure 1.

The new “control chain” conceptual model now in use by WG2 (Figure 4) differs from the original RTCA DO-304 notion of “segments.” The ground control station now is envisioned as the place where human-machine interface takes place, and a new

hardware/software node is referred to as the “communication infrastructure.” This change appears to have been made to enable the revised model to accommodate varying levels of connection complexity, from radios to a ground-based data distri-

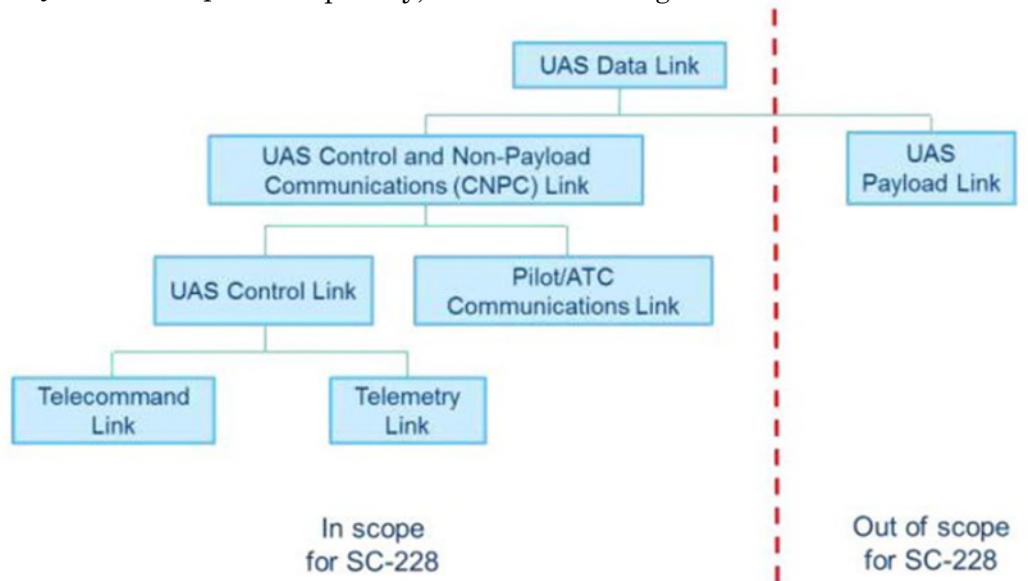


Figure 4. RTCA SC-228 WG2 “Taxonomy of UAS Data Links”

bution system that is envisioned to provide a “signal in space” from terrestrial stations to airborne aircraft.

While the updated vision of UAS system logic doubtless is helpful for engineers, it is somewhat daunting for those new to unmanned aviation. However, WG2 also re-imagined how to portray the different types of flight-required datalinks, which is helpful in understand both the complexity of links and how they are used. These demands drive separate but equally pressing bandwidth requirements.

What Figure 4 is intended to show is that there are a number of data exchanges constantly occurring between a GCS and a UA, especially where a BLOS operation is in progress. SC-228 is not concerning itself with any requirements for spectrum that may be needed to support payload data (although some types of UAS see payloads as providing possible alternate means of compliance with see-and-avoid requirements – a flight-critical function).

Also, SC-228 appears to be confining its attention to the far left side of the diagram, where only the telecommand (uplink) and telemetry (downlink) data supporting BLOS operations would be accorded “protected” bandwidth. Requirements for air traffic control (ATC) communications presumably are to be met through existing spectra, although how this is to be assured has yet to be determined.

Beyond the *system* complexity arising from the multiple parts of the RF spectrum needed for UAS operations, the *bureaucratic* complexity described above suggests there could be a purely “management” aspect to UAS-related telecommunications issues that may arise in the course of an accident investigation.

Consider a scenario where a link became unusable at a shorter range than should have been the case, or was disrupted by interference due to an inappropriate or inadequate allocation of spectrum for unmanned aviation operations. Delving into a possible accident sequence of that type, and then developing meaningful recommendations to prevent its recurrence, requires specialist understanding of the properties of radio waves at different frequencies, the administration of available spectrum, the degrading effects of intentional or unintentional interference, and the matching of available spectrum with intended use as a function of suitability rather than its just being “open.”

Different governments (i.e., ICAO member States) are organized quite differently for regulatory purposes. ASIs need look no further than their own domain to realize that the relationship between their country and others in the aviation environment is to some extent conditioned by their State’s participation in ICAO. A similar relationship typically exists between individual nations and the ITU, which governs the allocation of spectrum, maximum output power of transmitters, and a whole array of similarly vital aspects of RF applications. Therefore, investigators need to act as soon as possible to identify points of contact in the appropriate agencies within their respective governments to be ready to address issues of the type described in advance of an accident requiring their mobilization.

Based on the foregoing discussion, the reasons why telecommunications expertise will be essential to UAS-related air safety investigations should be apparent. However, as mentioned earlier in this section, the reliance of UAS on their “communications segment” also brings with it two specific concerns: the potential for its disruption (control link failure), and the practical implications of having a built-in lag in the communications between pilot and controller *and* pilot and aircraft (latency).

1. *Control Link Failure Impacts*

From a purely operational perspective, a frequently made analogy is that UAS control link

failure (i.e., a “lost link” occurrence) is pretty much the same as a failure of two-way radio communications, even when it occurs in controlled airspace. Proponents of this line of reasoning rarely step through the actual consequences; they simply assert that the two events’ impact on surrounding aircraft and the ATC system is equivalent, as is the controller’s response to them.

Unfortunately, such is not the case, at least for the foreseeable future. A manned aircraft’s crew flying on an instrument flight plan follows the clearance issued to them, even if communications fail. From the clearance limit onward, there are well-defined procedures regarding what the pilot is to do based on what he or she was told to expect, and nothing normally will prevent them from following those procedures. They also can communicate their situation via transponder in most situations, either by squawking 7600 or 7700 as appropriate to their circumstances.^{9*}

An unmanned aircraft system control link failure cannot be described in terms of “standard procedures” because each such failure may have a completely unpredictable outcome, a highly specific, well-defined outcome, or something in between. Such variability begins at the moment of link failure:

- Was only the pilot’s ability to control the aircraft affected, or were voice communications with ATC disrupted as well?
- If the latter, how does air traffic control become aware of the aircraft’s degraded operational state? Is it programmed to change its transponder squawk, will it do so immediately or is there a built-in delay between the failure and the initiation of any on-board programmed behavior?
- Was the unmanned aircraft programmed to proceed to orbit at a known point (sometimes referred to as a “flight termination point”) or return to its point of origin in the event of control link failure? Was the flight termination point changing throughout the flight? If so, where will the aircraft turn toward, and how long might it be before it takes up a new heading, airspeed or altitude?

Assume that an unmanned aircraft is in BLOS operation and any programmed delay between link failure and initiation of a “lost link profile” has elapsed. What will the aircraft do next? There is no way to answer this question without knowing the specifics of the aircraft’s designed capabilities *and* the specifics of its pre-programming.

Even if you know that it has been programmed

Schematic of the Information Flow

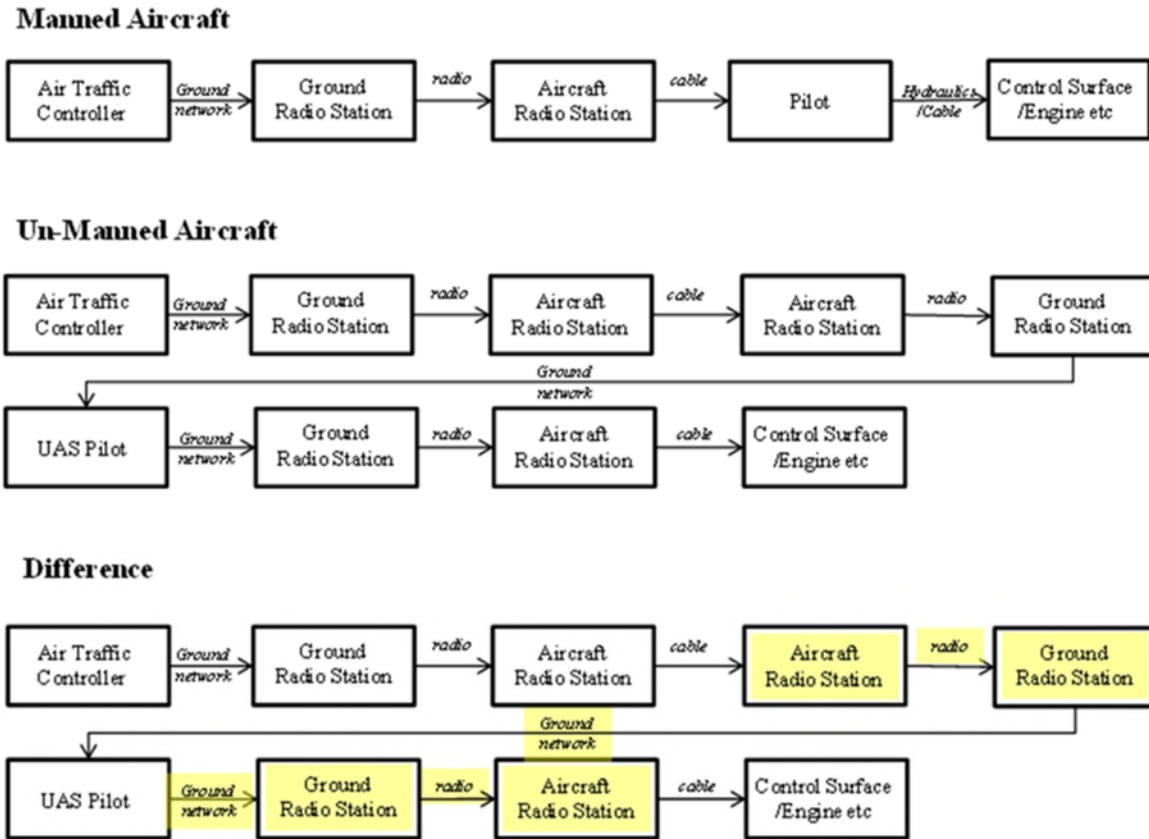


Figure 5. Differences between Manned and Unmanned Aircraft Transactions (ICAO Aeronautical Communications Panel Working Paper, ACP-WGF24/WP15, 21-25 March 2011)

to proceed to a particular point in space – say, in military reserved airspace – and ATC is in contact with the pilot, there is no way to determine precisely how the aircraft will navigate itself to that point in space. This situation can be compounded in complexity by taking place outside radar surveillance; control link failures frequently are accompanied by downlink failures, meaning the pilot in command may no longer be receiving positional or performance information from the aircraft and thus cannot advise air traffic controllers of its position.

The kinds of imponderables cited in this example are likely to persist for some time. The contents of UAS flight plans and ATC progress strips will have to evolve significantly to include critical information that allows controllers to anticipate the next moves of an unmanned aircraft that unexpectedly reverts to what is for all practical purposes an autonomous mode of operation.

In the interim, any investigation resulting from a control link failure will need to be augmented by personnel with an intimate understanding of the involved system’s architecture and post-failure

decision logic, and who do not have an institutional stake in the investigation’s outcome. The potential for control link disruption is perhaps the single greatest common vulnerability across the entire spectrum of unmanned aviation, and the tolerability of this vulnerability has a direct bearing on the acceptability of the concept of unmanned aircraft systems themselves.

2. Latency Impacts-When air traffic control communications first began being supported by satellites, questions arose regarding the potential effects of delays in control instructions being received and executed. The term “latency” came into use to describe the lag time required for a given transmission to be transmitted to a satellite in low Earth or geosynchronous orbit and then re-transmitted to its intended recipient.

The advent of unmanned aircraft systems brought a new dimension to the latency issue in the context of flight operations. A great deal of useful research was conducted on the effects of communications latency when it first was introduced, and

much of it was captured for consideration by the now-disbanded “Access 5” UAS study group.¹⁰ However, referring back to Figures 1 and 3 earlier in these *UAS Investigation Guidelines*, it is clear that long-distance telecommunications are needed to support unmanned aircraft systems operations both for communications and for aircraft control. Thus, “latency” for unmanned aircraft has implications both for the timely *reception* of control instructions and for the subsequent *execution* of those instructions.

This issue has been considered at some length in the ICAO environment. For example, at a March 2011 meeting of the Aeronautical Communications Panel (ACP), a presentation on UAS “availability, continuity and latency” suggested that the addition of the need for “non-payload” communications could drive the total time between when an instruction is issued and carried out (“transaction time”) to exceed standards established by ICAO Document 9869, *Manual on Required Communications Performance (RCP)*.

The paper’s author concluded, “The UAS transaction time to meet the overall RCP10 requirements probably is insufficient to be met by a satellite system.” This is an extremely strong statement, but is based purely on engineering analysis. Nevertheless, it has yet to make any meaningful impact on the evolution of beyond line of sight unmanned aircraft systems, certification requirements, or policies to date.

Figure 5 illustrates the problem graphically. Each step of the transaction for an unmanned aircraft responding to a control instruction takes measurable time due to latency, which must be added to the total time necessary for the controller to issue the instruction and the pilot to respond to it. The time involved is extremely small, but the speed with which aircraft operate and conflicts develop makes any delays a matter of some concern.

Despite the relatively small amounts of time lag involved, latency has been observed to have one concrete effect on beyond line of sight UAS operations: unmanned aircraft landing attempts made via satellite-based control links rarely succeed. The disconnect between instrument readings, visual information relied upon for pilot orientation and control inputs almost invariably result in the pilot being well behind the aircraft, reacting to flight conditions that already have affected the aircraft in pitch or roll. This is one of the principal reasons behind ongoing efforts to develop reliable autoland systems for high-value BLOS unmanned aircraft.

It has been suggested that latency challenges should form the basis of new approaches to UAS development, including possibly placing more decision-making and control capability directly aboard unmanned aircraft themselves. The safety record of unmanned aircraft, including those involved in accidents where their control links have been compromised, will provide support for or direction to such efforts, as will the outcomes of UAS-involved accidents. However, until unmanned aircraft are capable of independent two-way communications via natural language or datalink messages to controlling agencies, latency is likely to be a normal and unchanging aspect of BLOS UAS operations.

Security Impacts—One final telecommunications issue that may need to be explored in the context of an unmanned aircraft-involved accident is the possibility that a failure observed in the sequence of events was deliberately induced instead of accidentally encountered. In the past, where bombings, hijackings or intentional crewmember actions have been the cause of aircraft losses, evidence of criminal acts usually has been identified fairly quickly, and the investigative responsibility and process has migrated from safety to law enforcement authorities.

In unmanned aviation, actions intended to disrupt the conduct or control of a flight may be much harder to trace or prove. The control link itself could be attacked; alternately, Global Positioning Satellite (GPS) signals could be jammed or meaconed (overridden by a stronger, apparently valid but incorrect signal). Individual investigative and civil aviation authorities will need to consider developing their own criteria for exploring the possibility of criminal activity in the course of an unmanned aircraft system-related aircraft accident based on their individual threat assessments and the specific circumstances surrounding a given event.

To sum up, the telecommunications expertise necessary, civil aviation and national investigative authorities need to be prepared to either develop their own resources or identify sources of support with working knowledge of the following subject areas:

- Availability/suitability of supporting ground-based telecommunications architecture.
- Availability/degradation of satellite-based over-the-horizon telecommunications.
- Availability/adequacy of allocated RF spectrum in the vicinity of an unmanned aircraft accident.

Aircraft Structures—Investigators specializing in structures-related factors are likely to have a lively set of challenges before them in any major accident investigation involving an unmanned aircraft. The fundamental issues likely to be on the table are:

- For any accident involving in-flight structural failure of an unmanned aircraft:
 - ◊ How was the aircraft constructed?
 - ◊ To what standards was the airframe built?
- For any accident involving a midair collision between a manned and unmanned aircraft resulting in the loss of the manned aircraft:
 - ◊ What parts of the manned aircraft were affected by the initial impact?
 - ◊ With what force did the impact take place?
 - ◊ What unmanned aircraft components imparted the greatest part of that force?
 - ◊ What role, if any, did the size, mass, velocity, airframe pliability or general construction of the unmanned aircraft play in how impact forces were applied and distributed?
 - ◊ How much force was the manned aircraft designed to tolerate at the point of impact?
 - ◊ Are current manned aircraft design standards adequate to withstand the type of collision observed in the accident sequence?
 - ◊ Are current unmanned aircraft design standards adequate to ensure the frangibility of the airframe (where appropriate) in the event of an impact with a manned aircraft or inhabited structure? ¹¹

Most structures investigators and aeronautical engineers have the necessary expertise to carry out a UAS-involved investigation. However, such investigations may entail understanding how unmanned aircraft designers elected to solve certain challenges absent both formal certification standards and the need to protect human occupants.

Unmanned aircraft often incorporate design features that add robustness to certain components and forego it in others. As such, qualified investigators would be well served by having the opportunity to visit and consult with unmanned aircraft manufacturers in advance of an investigation, simply as a way of calibrating themselves to recognize the tradeoffs and weight-saving compromises made in the end items.

Electrical Propulsion Systems—Investigators specializing in powerplant-related inquiries are likely to need some grounding in the emerging types of propulsion systems used by many cutting-edge unmanned aircraft. It is common knowledge that many unmanned aircraft make use of non-aviation

certified conventional powerplants (e.g. snowmobile engines and other high-torque, lightweight designs). It is less well known that the emphasis in many unmanned aircraft designs is on extreme endurance, which has led to a host of innovative approaches to generating and delivering electrical power to propellers that are totally unfamiliar to most of the aviation community.

Three basic approaches to electric drive technology and ancillary system support currently are being used or tested on unmanned aircraft:

1. Battery power. This is by far the most common in small UAS applications. Significant research is being conducted in an effort to increase their power (to support the powering of on-board systems other than the motor) and capacity (to enhance their range or loiter capability).

2. Solar power. Solar-powered unmanned aircraft, intended for long-duration operations at high altitude, are being explored in increasing numbers. Their large wingspans are well suited to the installation of significant solar cell arrays on their upper surfaces.

3. Fuel cells. Fuel cell technology has grown steadily in recent years, and the unmanned aircraft community is exploring ways of leveraging its efficiency and relatively light weight against a whole range of on-board electrical requirements.

Pre-Accident Hazard Assessments

Investigative authorities may wish to make a study of the specific unmanned aircraft systems certified for operation within their State or area of responsibility in advance of any accidents, simply to apply some of the thinking suggested above to the specific scenarios most likely to be encountered based on the certificated systems in use and to anticipate the types of expertise that may be required under certain scenarios.

- Line-of-sight signal propagation and transmitter range limitations.
- Availability/usage of RF spectrum and sufficient bandwidth in a location where control loss or degradation was observed.
- Individual unmanned aircraft system reliance on uplinked and downlinked data for control, situation awareness and two-way communications.

To avoid unnecessary and time-consuming development of comprehensive hazard assessments and similar tools for identifying and quantifying risk, investigators should start by asking themselves a simple question: “Would the worst credible

outcome of encountering this hazard with an unmanned aircraft be any different than it would if the involved aircraft was manned?" If not, investigators need not expend energy on an unmanned aircraft-specific investigation, and may instead proceed with a regular investigation.

On the other hand, if one of the unique aspects of unmanned aviation appears to have played some part in the accident sequence, the responsible authorities would be well advised to fully commit to an in-depth investigation capable of quantifying their exact involvement – as well as any means of preventing their recurrence – in detail.

Beyond the top-level, first-order differences listed above, there are many possible differences in a number of areas where the scope and level of effort that may be required for an investigation involving an unmanned aircraft system, or specialized investigative skills that may be required, could vary widely from State to State and accident to accident. Areas where the possibility of variability or special provisions may come into play include:

- Regulations –
 - ◊ Unmanned aircraft system certification standards
 - ◊ UAS pilot (operator) certification standards
 - ◊ UAS operating rules, including specific limitations for certain classes of airspace
 - ◊ Aircraft categorization, especially where a given unmanned aircraft may be operated remotely or in a manned (optionally piloted) configuration
- Propulsion system –
 - ◊ Reciprocating engine (aviation versus non-aviation-certified)
 - ◊ Turboprop engine (aviation versus non-aviation-certified)
 - ◊ Turbojet/turbofan engine (aviation versus non-aviation-certified)
 - ◊ Electrical (battery, fuel cell, solar, hybrid)
- Communications system –
 - ◊ Pilot-in-command (PIC) to air traffic control (ATC) line-of-sight communications
 - ◊ PIC to ATC passing through aircraft
 - ◊ PIC to ATC enabled by satellite
- Control link –
 - ◊ Line-of-sight (LOS) only
 - ◊ Beyond PIC's visual range (non-satellite)
 - ◊ Beyond line of sight (BLOS)¹²
- Special features –
 - ◊ Flight termination/ballistic recovery systems
 - ◊ Payloads capable of interfering with other on-board systems
 - ◊ Payloads used to fulfill flight-critical functions

(e.g., navigation, see-and-avoid, etc.)

Considerations for Investigations Involving Beyond Line of Sight UAS Operations

When faced with the need to initiate an investigation involving BLOS UAS operations, investigative authorities will need to make early decisions regarding how their resources should be deployed. The on-scene investigation will remain a necessary component of the overall inquiry. However, the condition and proper operation of the ground control station or stations in use at the time of the accident, as well as the status of the satellite or network in use at the time of the occurrence, are equally important elements that must be established as quickly as possible.

A possible worst-case scenario might involve two separate ground control stations in different parts of the world attempting a transfer of operational control at the time of the occurrence. This would mean securing evidence and gathering testimony at as many as four different locations:

- The crash site;
- The two GCS sites; and
- A satellite or network operations center.

To date, satellite operators have had relatively little direct involvement in accident investigations, generally serving to provide information supporting such inquiries rather than being the focus of some aspect of the accident sequence itself. Air safety investigators and regulators may wish to reach out to such service providers in advance of an accident or incident investigation to ensure the appropriate operational, legal and personal relationships are in place in advance of need.

Investigation of Accidents Involving Model Aircraft

Formal air safety investigations are not constituted to investigate model aircraft accidents, and Annex 13 is not applicable to them. However, at some point air safety investigators and investigative authorities may be confronted by a situation where a "model" aircraft – one identified by rule, manufacture or common practice as being intended for hobby or recreational use only – is determined to have been involved in an aviation accident sequence of events.

The extent to which the involvement of a model aircraft's involvement could be a complication will vary greatly based on the specific legal and regulatory distinctions made from one State to the next. This in turn means legal expertise, hobbyist

knowledge of model aircraft construction and operations, and familiarity with spectrum regulation differences between recreational and “licensed” radio-controlled operations all could come into play.

The narrow perspective of conducting an accident investigation – especially one solely devoted to looking for ways to prevent the next accident and chartered as such by national laws – may help investigators avoid having to address the separate and distinct issues of liability, conformity to existing rules as opposed to their adequacy, and so forth. Still, even identifying the operator of such an aircraft could be challenging under some circumstances. This issue will be explored in more detail below.

A few States have taken the first steps toward establishing rules for UAS at the smaller end of the size spectrum and distinguishing between recreational and civilly regulated remotely piloted aircraft (the preferred term of art in some circles). This has been a matter of some urgency in Europe, where movement toward establishing a regulatory framework for aircraft with takeoff weights in excess of 150 kilograms (330 pounds) has created a concomitant need for individual States to establish rules for the operation of UAS below that threshold.¹³

In the United States, Public Law 112-95 (the *FAA Modernization and Reform Act of 2012*) makes it clear that model aircraft are a subset of the larger family of unmanned aircraft, while at the same time prohibiting the Federal Aviation Administration from making any rules governing their operation. However, it also limits model aircraft operations to the following conditions (Section 336):

(1) The aircraft is flown strictly for hobby or recreational use;

(2) The aircraft is operated in accordance with a community-based set of safety guidelines and within the programming of a nationwide community-based organization;

(3) The aircraft is limited to not more than 55 pounds unless otherwise certified through a design, construction, inspection, flight test, and operational safety program administered by a community-based organization;

(4) The aircraft is operated in a manner that does not interfere with and gives way to any manned aircraft; and

(5) When flown within 5 miles of an airport, the operator of the aircraft provides the airport operator and the airport air traffic control tower (when an air traffic facility is located at the airport) with

prior notice of the operation (model aircraft operators flying from a permanent location within five miles of an airport should establish a mutually-agreed upon operating procedure with the airport operator and the airport air traffic control tower (when an air traffic facility is located at the airport)).

A model aircraft not meeting all of these criteria could be construed as a *de facto* small UAS, for which the United States and most other States have yet to issue formal operating rules. Regardless, if a model aircraft is involved in any sequence of events requiring investigation, its legal status (use, location, etc.) will need to be documented and evaluated in terms of how any of those factors may have contributed to the observed outcome.

On the other hand, if it can be demonstrated that the outcome would have been no different had a formally certificated UAS instead of a model aircraft been involved (as where no difference may exist between a manned or an unmanned aircraft’s involvement, as suggested above), investigators should document that fact as well to ensure hobbyist activities are not unreasonably brought into question or unfairly constrained.

Separate from a model aircraft’s legal operating status, investigators may face a number of purely investigative challenges similar to those associated with small UAS accidents, including:

- Identifying and locating the operator of the model aircraft;
- Confirming the exact type of model aircraft in use;
- For midair collisions, determining the exact trajectories of both aircraft relative to each other at the time of impact; and
- Reconciling the observed impact damage with the physical properties of the model aircraft.

The last could be important because, unlike small UAS manufactured in accordance with ASTM F2910, *Standard Specification for Design and Construction of a Small Unmanned Aircraft System (sUAS)*, model aircraft are not customarily designed in consideration of:

- Maximum speed;
- Maximum weight;
- Minimization of the likelihood of fire, explosion, or the release of hazardous chemicals, materials, and flammable liquids or gasses, or a combination thereof, in flight or in the event of a crash, hard landing, or ground handling mishap;
- Containment of post-crash fire;

- Protecting first responders from hazards at the crash site;
- Use of flame-resistant materials;
- Use of energy-absorbing structures; or
- Protection against battery-induced fires.¹⁴

The criticality of a model aircraft’s physical properties as observed following its impact with another aircraft, a person, or an object on the ground all will need to be evaluated against the ASTM criteria to determine if they are relevant to the observed outcome.

CHAPTER 4

Annex 13 to the *Convention on International Civil Aviation*: Recommendations Relative to UAS Investigations

Recommendation Regarding Determining the State of Occurrence

The State of Occurrence for an unmanned aircraft accident should be determined in the same manner as is currently used to make such determinations for manned aircraft accidents.

Special Circumstances Where Additional Accredited Representatives May Be Warranted

Provisions should be made allowing for additional accredited representatives to investigations involving unmanned aircraft systems as follows:

State of Design—If the State of Design for the aircraft differs from the State of Design for the ground control station in use at the time of an accident, both States should be invited to provide accredited representatives.

State of Manufacture—If the State of Manufacture for the aircraft differs from the State of Manufacture for the ground control station in use at the time of an accident, both States should be invited to provide accredited representatives.

Aircraft and Ground Control Station Registered in Different States—If an unmanned aircraft system involved in an accident has its aircraft registered in one State and its ground control station registered in another State, both States should be invited to provide an accredited representative to the investigation; however, the investigating State should specifically determine if certification compatibility issues played any part in the accident sequence.

Location of Pilot/Operator Different from State of Occurrence

The location of the ground control station – and thus, the pilot in command – of an unmanned aircraft system may be different from both the State of the Operator and the State of Occurrence.

- Consequently if a pilot in command is operating an unmanned aircraft under the rules of the State of the Operator at the time of an accident, the location of the ground control station should not result in an automatic invitation to the hosting State to provide an accredited representative unless an infrastructure issue under the control of that State (e.g., electrical power, telecommunications availability) may have played a role in the accident sequence.
- If a pilot in command is operating an unmanned aircraft under the rules of a State hosting the system’s ground control station – other than the State of the Operator or the State of Occurrence – at the time of an accident, the hosting State should be invited to provide an accredited representative.

CHAPTER 5

Data Fields Associated with UAS Operations Requiring Capture

Overview

The Commercial Aviation Safety Team (CAST) and the International Civil Aviation Organization (ICAO) have a standing Common Taxonomy Team, known as CICTT. According to its Web site (www.intlaviationstandards.org), the purpose of this group is “to remove constraints on aviation safety analysis and sharing. These constraints are created by the lack of common global descriptors of aviation safety events and standards for aviation safety data and information.”

CICTT’s work is aimed at developing standards for safety data collection that would harmonize existing systems with common definitions and terminology, working from the ICAO accident reporting system (ADREP) as a baseline. The CICTT effort revolves around developing standard descriptions for the following:

- Aircraft Make/Model/Series
- Aircraft Engine Make/Model/Submodel
- Aviation Occurrence Categories – Per the ADREP system, there are fifteen primary occurrence categories, all of which are accounted for

under the CICTT taxonomy:

- ◇ Abnormal runway contact (ARC)
- ◇ Birdstrike (BIRD)
- ◇ Controlled flight into or toward terrain (CFIT)
- ◇ Collision with obstacle(s) during take-off and landing (CTOL)
- ◇ Fire/smoke (non-impact) (F-NI)
- ◇ Ground Collision (GCOL)
- ◇ Loss of control - inflight (LOC-I)
- ◇ Airprox/ ACAS alert/ loss of separation/ (near) midair collisions (MAC)
- ◇ Ground Handling (RAMP)
- ◇ Runway excursion (RE)
- ◇ Runway - wildlife presence (RI-A)
- ◇ Runway incursion - vehicle, aircraft or person (RI-VAP)
- ◇ Powerplant failure or malfunction (SCF-PP)
- ◇ System/component failure or malfunction [non-powerplant] (SCF-NP)
- ◇ Undershoot/overshoot (USOS)
- Phases of Flight
- Human Factors Taxonomy (performance in relation to environment)
- Aerodrome Taxonomy
- Positive Taxonomy (i.e., “What went right to prevent an accident?”)

CICTT and UAS

A working group has been established under CICTT, chaired by a representative of the National Transportation Safety Board, to modify all of the common taxonomies – including “ATA Codes” as needed – to incorporate UAS-specific data fields and descriptors. This is being accomplished in part through reference to a working safety database maintained by the U.S. Federal Aviation Administration’s Unmanned Aircraft Systems Integration Office.

ISASI UAS Working Group Position and Recommendations

The position of the ISASI UAS Working Group with respect to data collection is that unmanned aircraft-involved events should be recorded and mapped the same as manned aircraft events to the maximum extent possible. The entry of standard powerplant identifiers may be complicated by the not-infrequent use of non-aviation-certified engines in unmanned aircraft; however, phases of flight should remain identical to those already in use. The only additions to the Aerodrome standard that possibly could be needed might be references to

specialized launch-and-recovery equipment permanently or semi-permanently installed on airport runways or taxiways to facilitate UAS operations.

Accordingly, the three principal thrusts of the CICTT effort with respect to unmanned aircraft systems should be:

(1) Ensuring that existing occurrence categories are sufficiently broad enough to allow the inclusion of UAS-involved events with the same or equivalent outcomes;

(2) Adding primary and secondary occurrence types to accommodate UAS-related events sufficiently different from manned events that they require separate categorization; and

(3) Expanding the human factors taxonomy as needed to ensure pilot-to-aircraft interface, perception and awareness issues are adequately captured for analysis and corrective action.

The CICTT standard *Aviation Occurrence Categories: Definitions and Usage Notes*, version 4.6 (October 2013) discusses some UAS-related issues, but does not do so in a manner that fully distinguishes the unique failure modes to which unmanned aircraft are susceptible. It also explicitly limits inclusion of unmanned aircraft to those that have “a design and/or operational approval,” which may exclude future unmanned aircraft systems built to conform to consensus standards instead of receiving formal certification. (This conforms to Annex 13 criteria for investigations as well.)

In particular, the current CICTT approach to addressing UAS control link failures is over-broad and conflates unmanned aircraft flight control failures associated with the airframe alone with those affecting the unique electronic link between pilot and aircraft. Under “Loss of Control – Inflight,” the following explanatory note is provided:

For unmanned aircraft events, includes hazardous outcomes involving deviation from intended flightpath associated with anticipated or unanticipated loss of datalink. However, if loss of datalink is the direct result of a system/component failure or malfunction, code the occurrence as System/Component Failure or Malfunction (Non-Powerplant) (SCF-NP) only.¹⁵

From the standpoint of being able to identify causes and make relevant recommendations, is important to distinguish between mechanical/aircraft-based malfunctions resulting in an uncontrollable aircraft from those specifically attributable to the so-called “communications segment” between pilot and aircraft. The intent of designers and regulators alike is to have the latter condition result in predictable behavior that ideally would conclude

CHAPTER 6

UAS-Specific Air Safety Investigator Skills

with the safe recovery of the aircraft.

It is equally important to capture events where the pilot in command has deliberately (or negligently) severed the control link. Such may be the case where the flight manual prescribes such action as necessary to restore control or place the aircraft in a known mode of operation or, alternately, where the aircraft is flown into an area where satellite coverage is not available and/or line-of-sight range of the link is exceeded.

The CAST/ICAO Common Taxonomy is intended to promote and support preventive actions as well as simply recording events once they have taken place. Therefore, the ISASI UAS Working Group recommends adding three primary occurrences for unmanned aircraft:

- Loss of Control Link (Two-Way) (LOCL-T): Failure of the complete control and non-payload communications (CNPC) link between an unmanned aircraft and its associated remote pilot station.¹⁶
 - ◊ *Usage note: Use this coding when control commands are not received by the aircraft and the datastream from the aircraft to the remote pilot station ceases.*
- Loss of Control Link (Uplink) (LOCL-U): Failure of datalink transmission from a remote pilot station to its associated unmanned aircraft.
 - ◊ *Usage note: Use this coding when the pilot in command (PIC) has no ability to affect the trajectory of the unmanned aircraft and the aircraft reverts to a pre-programmed self-guiding mode but continues to provide performance and positional data to the PIC.*
- Loss of Control Link (Downlink) (LOCL-D): Failure of datalink transmissions from an unmanned aircraft to its remote pilot station
 - ◊ *Usage note: Use this coding when the pilot in command still can direct the trajectory of the aircraft but cannot receive datalinked confirmation that control commands have been received and/or properly executed.*

The ISASI UAS Working Group also recommends adding one secondary occurrence for unmanned aircraft:

- Flyaway (FLYA): Failure of a UAS to conform to pre-programmed behavior following Loss of Control Link (Two-Way or Uplink).

The four principal areas in which unmanned aircraft systems physically differ from manned aircraft – as noted above – are the lack of an on-board pilot, their reliance on RF spectrum for safe operation, their limited and varying abilities to separate themselves from other aircraft, and their occasional use of novel and exotic materials for construction and propulsion. As discussed throughout this monograph, these differences may manifest themselves in how an accident sequence plays out, as well as in the types of recommendations air safety investigators may need to make to prevent the recurrence of similar accidents in the future.

To be prepared to deal with both of these possibilities, anyone currently designated by a State to serve as investigator-in-charge of an accident investigation should be provided familiarization training regarding unmanned aircraft system characteristics and operations as conducted within their area of responsibility.¹⁷ As a minimum, specific topics should include:

- Nationally employed definitions of “unmanned aircraft” and “unmanned aircraft system” or equivalent terminology (e.g., “remotely piloted aircraft”)
- Classification methodology (e.g., size, weight, speed) used to differentiate among unmanned aircraft
- How differences among UAs influence their interactions with manned aircraft (e.g., infrastructure requirements for takeoff and landing, authorized types of operations, etc.)
- Applicability of national rules to UAS operations with respect to airspace, altitude, etc.
- UAS certification procedures.
- Authorized spectra for the control of unmanned aircraft.

The syllabi of training courses used to certify future investigators in charge should incorporate similar material as well.

Beyond ensuring that generalist investigators have at least a basic understanding of the above, investigative authorities need to ensure that designated ASIs have access to specialists possessing the expert knowledge needed for detailed exploration of the issues described in Chapter 3. In particular, ASIs must be prepared to delve into in-depth investigations of the vulnerabilities and dependencies among the different components linking the pilot in

command with the unmanned aircraft, as well as the unmanned aircraft's behavior in the event of a failure of any part of the "communications segment." Effectively conducting an investigation where such issues arise will be extremely challenging, and advance identification of resources to support it will be the key to the ASI's ultimate success.

CHAPTER 7

Evidence Preservation Following Unmanned Aircraft System Accidents

On-Scene and Ground Control Station Investigations

The on-scene investigation of an accident involving an unmanned aircraft may be complicated by a number of factors, most notably:

- Determining that an unmanned aircraft actually was involved due to limited residual physical evidence; and
 - Limited numbers of identifiable or identifying components (e.g., parts with serial numbers).
- Similarly, investigators faced with an accident with unmanned aircraft involvement must remember that it is possible that much of the most critical evidence related to the unmanned aircraft's operation leading up to the occurrence may not necessarily be found at the scene (although some autopilot-related avionics may yield useful data in some cases). They will need to locate and secure the "cockpit" – the ground control station – and apply expert knowledge to the technical problem of retrieving from it everything relevant to the unmanned aircraft's operation leading up to the occurrence itself.

Testimony from the Pilot-in-Command and Other Crew Members

Locating the pilot in command and tracing the ownership of unmanned aircraft involved in accidents conceivably could be the single most difficult task facing air safety investigators looking into events involving UAS. Therefore, investigating authorities should consider establishing rules – or requesting the passage of laws – addressing:

- The pilot in command's duty to self-identify when their aircraft is involved in an accident, incident or unusual occurrence, or fails to return from a flight.
- The obligation of operators to incorporate a means of identifying the aircraft (registration,

serial number, etc.) that will survive impact forces and post-crash fire.

- The preservation of ground control station-based data relevant to the accident flight, including both aircraft performance and payload-provided data available based on the configuration of the system at the time of the occurrence.

CHAPTER 8

UAS Investigation Procedural and Functional Considerations

There are two basic considerations regarding the incorporation of specialized or novel elements that may be part of unmanned aircraft system accident sequences into existing investigative guidance:

1. Adapting current procedural checklists to cue users to inquire into UAS-specific issues in conjunction with existing steps/processes in each investigation.
2. Ensuring current criteria for the development of accident final reports incorporate relevant UAS-unique content into both the factual and analytical portions of such reports.

The rapid growth of the unmanned aviation sector means there is significant interest across the air safety investigator community in developing a common, end-to-end investigation checklist specific to unmanned aircraft systems. However, such an effort will be extremely work-intensive. The decision was made not to further delay the release of the first ISASI *UAS Investigation Guidelines* to incorporate such a checklist into this document.

By the same token, a number of organizations around the world – most notably the Canadian Forces – have expended significant efforts toward developing guidance of this type, aligned with current and emerging ICAO publications. The United States Army has created a UAS-specific reporting and investigation form (DA Form 2397-U, *UAS Accident Report*, available at http://armypubs.army.mil/eforms/pdf/a2397_u.pdf) well suited to the gathering of operational, environmental, personnel and equipment-related data associated with a given event.

Users of this document are encouraged to contact their counterparts in States currently supporting UAS operations if they need to quickly obtain working examples or advanced prototypes that can be used in response to an urgent need. However, priority should be given to examining existing guid-

ance on an individual basis and modifying it as discussed below.

Near-Term Investigation of UAS Accidents and Incidents

For the foreseeable future, every unmanned aircraft system accident and incident investigation has the potential to be groundbreaking in some respect. There are many unknowns regarding the extent to which unmanned aircraft can safely perform operations currently carried out by manned aircraft. There are similar unknowns regarding the safety or practicality of applying unmanned aircraft technology to activities previously considered unsafe for manned aircraft to conduct.

The only way these issues can be explored objectively is through informed consideration of how the tradeoffs, accommodations and legacy rules applied to unmanned aviation are playing out in real-world operations. In a larger sense, each UAS accident or incident represents an opportunity to assess the extent to which the body of rules governing both manned *and* unmanned aviation has adequately provided for the latter. At the same time, investigators can provide essential feedback to policymakers regarding the effectiveness of the regulatory approach in use, the extent to which manned and unmanned operations may be conducted on a cooperative and/or a segregated basis in shared airspace, and the validity of both use and risk assumptions that have been applied to their respective rulemaking challenges.

In the near term, however, air safety investigators must recognize that there are significantly different and even competing philosophies regarding the desirability of regulating unmanned aircraft the same as manned aircraft, somewhat less stringently, or with a minimal level of authority over them. Perspectives vary from State to State, from region to region, and even among different governmental, quasigovernmental and standards development entities chartered to normalize UAS-related activities. Investigators need to understand the current landscape within which UAS occurrences are taking place to make useful recommendations aimed at preventing their recurrence. This will not be an easy task.

Different States are making different decisions regarding how UAS pilots should be licensed; the amount of training they should receive; and, the extent to which they should cooperate with or avoid surrounding aviation operations. They are debating airworthiness, certification and registration re-

quirements; equipment minima; and, operating criteria. These considerations are being shaped by market forces such as the emergence of a UAS manufacturing sector and entrepreneurial applications of unmanned aviation technology, existing airspace structure and usage, and a host of other variables. The only truly common goals are to continue to provide a safe flying environment for all stakeholders, and to foster opportunities to take advantage of emerging UAS capabilities consistent with the need for safety.

Preliminary Considerations

Air safety investigators faced with the possible need to investigate an occurrence involving an unmanned aircraft or unmanned aircraft system need to consider several issues.

First and foremost is the question of jurisdiction and investigative authority. If a manned aircraft is involved in an accident or incident that meets State reporting and investigative criteria, the complicating factor of an unmanned aircraft system in the sequence of events in no way prevents the occurrence from being investigated as usual. However, an accident or incident involving only an unmanned aircraft system must be examined for some possible complicating elements:

- Do the State's rules distinguish between unmanned aircraft systems used for hobby or recreational purposes and those used for other purposes, e.g., commercial or business-related activities? In the U.S., radio-controlled model aircraft flown purely for pleasure are not subject to either Federal Aviation Administration or National Transportation Safety Board scrutiny.
- Do the State's rules establish a size threshold below which regulatory oversight is minimized or not exercised? In some European Union countries, UAs below a certain weight (such as 25 kg) are not subject to regulation; in others, no rules exist for anything less than 150 kg.
- Did the occurrence take place in special use or restricted airspace not subject to civil aviation authority? If so, responsible military or law enforcement entities may be willing to allow civil air safety investigators to participate in their internal inquiries, but the terms of such cooperation are best negotiated in advance of need.
- Was an "optionally piloted vehicle" (OPV) involved? An OPV is one certificated to be flown by either an on-board pilot or via CNPC link. A case may be made that an accident or incident involving an OPV almost always is subject to

investigation if the civil aviation authority's determination of its airworthiness might be called into question.

Once the question as to the investigative authority's right and obligation to conduct an investigation is resolved, the investigation should be treated as any other. However, a suggested practice that may aid the development of recommendations is for the investigator to note each instance where:

- Regulatory guidance for unmanned aircraft differs from manned aircraft; *and*
- That difference had a clear effect on either the sequence of events or the observed outcome.

The latter may illuminate challenges associated with how manned and unmanned aviation operations are being integrated. However, it also provides an opportunity to document cases where the regulatory approach to unmanned aircraft systems can be shown to have been better suited to their activities than manned aircraft requirements would have been, as seen in a less severe outcome than otherwise might have been expected.¹⁸

Tailoring Local Guidance to Incorporate UAS-Related Considerations

To meet the needs described above, the following two sections contain suggested areas for fact-gathering and/or exploration specifically in the course of a UAS investigation. They are organized following the general outlines for investigations and final reports set forth in ICAO Document 9756, *Manual for Aircraft Accident and Incident Investigation*, Part III (Investigation) and Part IV (Reporting), respectively.

Areas of Investigation-

1. Wreckage (on-scene) investigation

The on-scene investigation of a crashed unmanned aircraft of any size or type should be conducted the same as that of any manned aircraft. The most notable differences that might be encountered would involve the possible presence of unusual or potentially hazardous materials (HAZMAT) in either aircraft structures or the propulsion system; the operator and first responders should be contacted to evaluate the risk of these threats prior to arriving at the scene.

In the case of an accident or incident involving a line-of-sight system investigators need to carefully document the pilot in command's location relative to the aircraft, as well of that of any visual observer(s). Ensure surrounding terrain, structures, time of day, ambient light and sun angle are captured as well.

2. Organizational investigation

There is significant potential for the organizational investigation to be an important part of any inquiry involving unmanned aviation. As a starting point, investigators will need to assess the operator of the UAS in terms of the following:

- Is it an enterprise dedicated to providing manned and unmanned aviation-based services?
- Are its services limited to unmanned aviation only? If so, how long has it been in operation and to what extent is its management structure aligned with the requirements of safely supporting an aviation enterprise?
- Does it use unmanned aviation simply as a means of furthering other business interests, with its primary activities being unrelated to aviation?

Once these basic determinations have been made, the relationship between the operator and the person or entity that exerted operational control over the UAS' flight activity must be established:

- How was the mission scheduled and conducted?
- Who did the pilot in command work for?

Given that UAS have many useful applications in the realm of law enforcement and public safety, investigators also must take into consideration the operator's risk tolerance and sense of urgency in the course of carrying out flight operations. The requirement for risk mitigation plans supporting individual UAS operations or activities is not universal, but such plans should be sought and reviewed where available.

3. Operations investigation

The operations investigation of a UAS-related occurrence should be approached the same as that of any other accident or incident. However, it is important to examine each UAS operation in the context of:

- The activity in progress;
- Any regulatory structure in place supporting (or alternately, not anticipating) such activity;
- The adequacy of flight and operations guidance (manuals, etc.) supporting the activity in progress;
- Expected and unexpected interactions between unmanned and manned aircraft;
- The number of unmanned aircraft involved in the specific flight activity of interest at the time of the occurrence, and how many of those aircraft were operating autonomously or under the control of a single ground control station;

- Any control handoffs that might have been in progress or incompletely carried out between separate ground control stations at the time of the occurrence, the method of control being exercised (e.g., line-of-sight to line-of-sight, line-of-sight to beyond line-of-sight, etc.), and the means by which one PIC coordinated transfer of control to the next;

The status of the global navigation satellite system (GNSS) in use at the time of the occurrence;

- Expected and unexpected effects of the unmanned aircraft system on nonparticipants and the general public;
- Means used to advise the public of the presence of unmanned aircraft operations in a given location (if required); and
- The extent to which the UAS operation itself was compatible with the airspace and geographical location where it was carried out.

Attention also should be given to the extent to which the pilot in command's attention may be divided between the aviation environment and a location of interest on the surface, i.e., conflicting "mission" priorities. (See "Investigating human factors" below.)

4. Aircraft operational environment

Particular concerns related to UAS operations and capabilities that should be taken into consideration in evaluating the aircraft operational environment may include:

- Terrain
- Weather (VMC versus IMC, rapidly changing, unforecast winds, etc.) and how the PIC is able to monitor it
- Illumination (daylight, artificial light, etc.)
- The nature and quality of on-board sensors
- Pilot workload required to carry out the desired flight activity
- Interactions between the pilot in command and responsible air traffic control facilities
- The proximity of obstructions to the unmanned aircraft
- The proximity of the unmanned aircraft to congested, heavily populated or heavily trafficked areas or open-air assemblies of people (e.g., sporting events)

5. Aircraft performance investigation

The definition of "aircraft performance" in applying existing investigative processes to unmanned aircraft systems needs to take into consideration the entire system, including the performance of the control and non-payload communica-

tions (CNPC) link as it might be influenced by terrain, structures, precipitation, or the surrounding radiofrequency environment. In this context, the ground control station must be understood to be part of the "aircraft" as well.

Conventional "performance" charts showing power available/required in various flight regimes may not be available to investigators, necessitating experimentation (and the possibility of incurring a second accident) to properly document the aircraft's operating envelope.

6. Flight recorders

There are several sources of recorded data that may be available to support a UAS-related investigation, many of which go well beyond the conventional meaning of "flight recorders." Non-volatile memory cards located in the wreckage – both those associated with on-board control operations and those integral to the payload – may contain useful data. On-scene investigators should be provided as much information as possible regarding the types of avionics that may be useful in this role and provided photographs or undamaged examples to guide their efforts.

In addition, the entire ground control station should be evaluated with an eye for what might be designed specifically with recording in mind versus what might contain potentially useful data as a by-product of its performing a normal control or payload-related activity. The term "digital source collector" is used by some manufacturers and operators to refer to capture systems of this type.

Finally, if the CNPC link was maintained through a ground or satellite-based network, the provider of network services may possess useful and relevant data regarding the integrity of the link itself.

7. Reconstruction of wreckage¹⁹

As with manned aircraft, the reconstruction of wreckage only should be considered for unmanned aircraft if essential to identifying a particular point of origin for fire or on-board explosion or the site of an external impact suffered in flight.

For any accidents or incidents involving unmanned aircraft, investigators may find hands-on access to a similarly equipped and painted UA of identical configuration useful for evaluating:

- Field of regard (field of vision) of on-board sensors.
- Antenna locations, especially relative to the direction from which the control signal was emanating.

- The visibility of the UA as it would have presented itself to ground-based observers and the pilots of other aircraft.

8. Structures investigation

For the most part unmanned aircraft are not designed to manned aircraft standards, and their airworthiness may not be predicated on existing criteria for manned aircraft. Further, many unmanned aircraft manufacturers have no experience with designing or producing full-scale aircraft, meaning both the methodologies and their solutions to specific design issues (especially those related to weight and endurance) may be unorthodox. Still, for the most part some documented process should have been applied to the design and construction of any unmanned aircraft operated in non-reserved airspace. That process should be used by investigators as a starting point for detailed inquiry.

With the above considerations firmly in mind, investigators will need to proceed objectively in each case where a structures investigation is essential to establishing the cause of a given accident or incident. Straightforward (and possibly time-consuming) engineering analysis may be required to assess the failure mode, the adequacy of the basic design and the validity of the airworthiness certification itself.

Investigators also should bear in mind that the lessons of aviation history in some cases are being re-learned by a new cohort of airframe manufacturers. It is possible that the specific failure suspected or observed may never have played a part in either a manned or unmanned aircraft accident investigation before. However, it is just as possible that such failures might have been common in previous generations of manned aircraft, and that designs or manufacturing processes abandoned in current aircraft manufacture might have been employed in the unmanned aircraft under scrutiny for reasons of simplicity, cost-effectiveness, or ease of construction.

9. Mid-air collision investigation

The possibility of mid-air collisions between manned and an unmanned aircraft is one of the catastrophic scenarios forecast by those attempting to chart a path for the safe integration of unmanned aircraft systems into the existing aviation system. To date, however, there have been a bare handful of such incidents recorded in civil aviation operations.

The investigation of an unmanned aircraft-involved midair collision should proceed as any other such investigation. However, the alternate

means of compliance being used to compensate for the UA's lack of onboard see-and-avoid capability must be thoroughly scrutinized and its effectiveness fully established. The three most common means of clearing an unmanned aircraft's flight path are:

- a. Ground-based visual observer (either the pilot in command or a person fulfilling a purely observer role).
- b. Airborne visual observer (from a chase plane, either the pilot or a separate crewmember).
- c. Electronic "sense and avoid" systems; these are subdivided further into –
 - Ground-based sense and avoid (GBSAA) systems using dedicated radar systems or a functionality reliant on existing air traffic control radar coverage; or
 - Airborne sense and avoid (ABSAA) systems consisting of either:
 - ◊ A purely aircraft-based system that can detect non-emitting and/or emitting aircraft and autonomously execute an avoidance maneuver; or
 - ◊ An aircraft-based surveillance system that provides situational awareness data via a downlink to the pilot in command for appropriate action.

Investigators need to understand all of the aviation system components available for keeping aircraft separated as they operated during the accident or incident sequence, including any system logic that may have been used by a UAS DAA system in trying to keep a VFR operation "well clear" of other aircraft.

10. Fire pattern investigation

The need for any fire pattern evaluation will be dictated by the circumstances surrounding the loss of a given unmanned aircraft. Since occupants are not at risk, any such investigation reasonably may be confined to the propagation of an on-board fire from its point of origin to where it could have had an effect on flight-critical components.

11. Powerplant Investigation

A powerplant investigation – if deemed necessary in the course of the inquiry based on the presumed sequence of events – is likely to be somewhat less straightforward than that of other investigative activities for the foreseeable future. The aviation expertise of airframe and powerplant experts may not be applicable to the propulsion system used by an unmanned aircraft involved in an accident.

Unmanned aircraft may be powered by normally aspirated or supercharged piston engines. They

may be equipped with turboshaft or turbojet engines. They may run on electric motors, powered by batteries, solar power, or even fuel cells. They may use separate on-board power supplies for propulsion and payload, or meet all on-board power requirements with engine-driven generators or alternators.

In particular, the relationship between the unmanned aircraft's powerplant and its other systems – especially its CNPC-related avionics – may be critical to understanding an observed failure or series of failures. It could be that an engine shut down because it was designed to do so as a safety feature following a separate failure. It also could be that an engine shutdown was an unexpected consequence of a previously unsuspected sneak circuit or similar unanticipated system-level failure. Regardless, given the innovation applied to solving a variety of operational problems and limitations that arise in unmanned aircraft design, investigators must be prepared to enter uncharted territory as they enter into each new powerplant investigation.

Investigators also must be alert to the possibility that an unmanned aircraft's engine might be in use in manned aircraft as well, although perhaps as an aviation-certified variant of a non-aviation design. For example, some light sport aircraft engines are adapted from motorcycles, snowmobiles and similar efficient, high-torque uses. However, many of these engines conform to aviation-specific technical standard orders. Without knowing the differences between the certified and non-certified versions of such engines, investigators cannot know if a failed engine component observed in a UA accident is shared by its manned counterpart.

12. Systems investigation

For the most part, UAS "systems" investigations will be similar to and in some cases less complex than those supporting manned aircraft. The most notable exceptions to this general rule are:

- Evaluating and verifying the integrity of the entire CNPC link, from the pilot's hands to the control surfaces or actuators. (The NTSB and other entities consider a CNPC failure a flight control malfunction.)
- Ensuring the proper function of avionics and other systems not unique to unmanned aviation, but whose design does not conform to established standards or technical standard orders required of manned aircraft.
- Assessing the accuracy and adequacy of the information downlinked to the pilot with respect

to the aircraft's performance, trajectory, position and condition.

The last of these three could be particularly challenging, and might require out-of-the-box thinking and interactions between systems engineers and human factors experts in the course of the investigation itself. (See "Investigating human factors" below.)

Most air safety investigators will find it familiar and convenient to focus on known or suspected CNPC failures as part of broader "systems" investigations. In such cases, several key pieces of factual information need to be established early in the investigation, particularly with respect to the "lost link" program the unmanned aircraft was programmed to follow:

- How long was the aircraft supposed to wait to re-establish contact with its GCS before initiating its lost link behavior?
- Did the aircraft follow its pre-programming in carrying out its flight to its rally/home/ flight termination point?
- Was the location to which the unmanned aircraft was required to autonomously navigate following a CNPC failure appropriate to the operation? To the airspace? To the surrounding terrain?
- Was the CNPC failure accompanied by complete loss of the pilot's awareness of the aircraft's location?
- Was the CNPC failure accompanied by other failures resulting in air traffic control's inability to monitor its route of flight from the point of failure to its designated rally/home/ flight termination point?

Associated with this issue is the extent to which the system under investigation requires some form of interaction between CNPC link data (which may be conveyed within a reserved or protected part of the electromagnetic spectrum) and payload data such as cameras and other sensors not operating within UAS-specific frequencies.

Finally, investigators confronted with evidence of a CNPC malfunction of some type must resist the temptation to automatically treat such anomalies as the *cause* of the occurrence under investigation. A control link can be compromised by a number of conditions, either internal or external to the aircraft or the larger unmanned aircraft system.

13. Maintenance Investigation

Maintenance investigators may find themselves confronted by a variety of challenges, including:

- Lack of technical data
- Lack of standard aircraft record-keeping
- Lack of clearly defined flight-critical systems
- Lack of established maintenance intervals for systems or structures

Although some work is underway to establish ATA codes for failed components specific to UAS, no broad scheme for doing so has been generally accepted to date. The CAST/ICAO Common Taxonomy Team (CICCTT) is addressing this issue.

However, it is likely to be several years before any resulting standardized reporting and tracking framework is mandated for UAS manufacturers and operators, meaning the extent and quality of record-keeping may vary widely from one user or system to the next.

Based on the above, it is recommended that maintenance investigators work to assemble evidence and records in a manner as similar to a regular aircraft investigation as possible. Such efforts should include all components of the unmanned aircraft system, from the ground control station through the communications segment to the unmanned aircraft itself. Any cases where existing laws or rules inhibit the collection of such materials (such as that owned or maintained by telecommunications providers) should be flagged for separate action following the completion of the investigation, when its absence can best be assessed.

14. Helicopter Investigation

For the most part, unmanned aircraft systems have yet to be formally categorized in a manner that aligns with their manned equivalents. Just as lighter-than-air unmanned aircraft are not necessarily treated as blimps, airships, dirigibles or balloons, rotary-wing unmanned aircraft tend not to be explicitly identified as “helicopters.”

Nevertheless, except where the UAS incorporates a novel combination of technologies to achieve specialized performance or endurance capabilities, it typically will be appropriate to conduct investigations involving their loss or malfunction as if they were the manned system they most resemble. This allows them to be examined in terms of generally understood expectations regarding their design and performance.

For rotary-wing UAS, the basic questions to be asked are:

- How many rotors and how many powerplants does the aircraft incorporate?
- What is the effect of the failure of one or more of the powerplants?

- For an electrically powered rotary-wing UA, what is the effect of gradual depletion of the power supply? Will the aircraft compensate for a dying battery automatically, or must the pilot take action to recover it safely?
- What is the effect of the failure of one or more rotor system?
- Is the aircraft self-stabilizing in one or more axes, or must the PIC continuously monitor the UA’s operation to ensure its stability?
- Was the aircraft operated in an environment where its CNPC link was likely to be compromised? If so, what is the expected aircraft behavior upon link failure?
- If there were other rotary-wing aircraft in the vicinity of the accident/incident UA, how were their operations de-conflicted before and during the operation leading up to the occurrence under investigation?

15. Investigating Human Factors

There have been a number of research projects and academic studies carried out to date regarding human factors considerations associated with unmanned aviation (*see Appendix 2, System Safety and Human Factors Studies*). However, for the most part these draw upon specific experimental designs or inferences regarding how unmanned aircraft can and should be flown. Air safety investigators will greatly increase the understanding of the relative importance of different aspects of the unmanned aviation experience by documenting when-
ever and wherever its unique attributes contribute, lead to or directly result in an accident or incident.

Given the newness of the sector and the limited amount of data available regarding the involvement of both traditional and UAS-unique human factors, there is no clearly defined set of occurrences deserving special attention from investigators. However, the following should be documented for follow-on study even if they do not appear to be directly related to the accident or incident sequence at hand:

- The level of pilot training and expertise required by the activity versus the specific conditions encountered in the course of the activity under investigation.
- The pilot’s means of exercising control over the aircraft (e.g., handheld controller, keyboard and mouse, “cockpit” emulation, etc.).
- Differences between manned and unmanned aircraft pilot tasks required to carry out a specific type of operation or flying activity.

- Instances where habit transference from manned aviation resulted in the inappropriate or incorrect operation of an unmanned aircraft.
- The amount and type of feedback provided to the PIC regarding the performance and condition of the unmanned aircraft (including the availability and use of “first person view” technology, tactile feedback provisions, etc.).
- Displays and warning systems alerting the pilot to impending or actual hazards (in place and functioning during the event or needed, as appropriate).

In addition to the classic “human/machine interface” issues suggested by the above, human factors investigations also need to consider the *suitability* of UAS technology or platforms being applied to the specific task in progress at the time of the occurrence. This is a somewhat different take on how decision-making issues usually are explored in the course of an investigation.

Investigators historically tend to focus on whether a given accident sequence was started or sustained by improper decisions based on incomplete information or improper risk assessment. While there are many advantages to unmanned aviation, there are purely operations-based disadvantages as well, although many are not necessarily taken into consideration at the time the decision is made to carry out a given operation.

As observed earlier in these *UAS Investigation Guidelines*, unmanned aircraft systems are highly prized for conducting “dull, dirty and dangerous” activities. This perspective is based on the removal of a human from exposure to a hazardous environment, or one where inattention is likely to interfere with his or her proper performance of the aviation task. However, there are aviation-based tasks where the physical separation of the pilot from the aircraft tends to reduce the margin of safety of the overall operation by virtue of their inability to instantly perceive and respond to an abrupt or unexpected change in the flying environment.

Investigators should be alert to the tendency for humans to “perceive everything as a nail when they have a hammer” and make an independent judgment as to the suitability of the use of an unmanned aircraft system in any operation during which an accident or incident occur.

16. Survival, evacuation, search, rescue and fire-fighting

The biggest challenge associated with any UA-related search and recovery activity typically will be in locating the wreckage itself, particularly for

smaller unmanned aircraft. However, when approaching the scene of an unmanned aircraft accident – especially one involving a system with which the investigators are not personally familiar – on-scene personnel should be alert to the possible presence of latent hazards associated with the unmanned aircraft itself, such as specialized fuels, high-capacity electronic components, high voltage batteries, or materials emitting toxic by-products of combustion.

Post-crash fires associated with and confined to unmanned aircraft crashes may be of significantly shorter duration than those involving manned aircraft simply because of the lack of interior furnishings, primary or supplemental oxygen systems and other components that tend to prolong manned aircraft fires. However, high altitude long endurance (HALE) UAS may contain a surprising amount of fuel supporting their long-range performance. So, both firefighters and investigators need to apply the same standards of crash site safety to a UAS accident scene they encounter as they would any other aircraft accident scene.

Injuries or subsequent occupational illnesses experienced by first responders should be tracked by investigators wherever novel materials or fuels are known or later identified as having been present at a crash scene. If necessary, a system for reporting such illnesses should be created where none currently exists.

17. Pathology Investigation

The only time in-depth investigations into this subject area should be required are in cases where either (a) a UAS crewmember died or was incapacitated, or (b) where UAS involvement in an accident directly resulted in a fatality or injury. Otherwise, routine toxicological testing of participants should be conducted as would be the case for any comparable event involving a manned aircraft.

18. Investigation of [explosives] sabotage

While this portion of Doc 9756 is narrowly concerned with criminal attacks against manned aircraft, UAS investigators should ensure that the possibility of *any* form of intentional interference with an unmanned aircraft’s operation is a part of a UAS accident investigation resulting in fatalities, injuries or significant property damage until it can be definitively ruled out.

Purely electronic attacks – which may be difficult to prove through physical evidence alone – may come in the form of:

- Meaconing (deliberate misdirection of the aircraft through interference with its navigational inputs).
- Intrusion (deliberate misdirection of the aircraft through the transmission of misleading air traffic control directions to the pilot by any means; alternately, external takeover of an unmanned aircraft by an unauthorized operator).
- Jamming (targeted disruption of CNPC links).
- Interference (broad-spectrum disruption of an entire channel or frequency).

19. Investigating system design issues

Unmanned aircraft systems tend to be designed with specific applications and functionality in mind. The priorities in the design of the airframe itself tend to relate to measures that will increase payload, range/endurance, or both. The lack of certification standards to date has resulted in significant technological innovation, but also a tendency to steer away from redundancy in critical systems due to their associated weight and/or electrical power penalties.

Where single-point failures initiated, contributed to or sustained an accident sequence, they should be fully documented. Other design considerations have been addressed in appropriate sections above.

20. Other unmanned aircraft system-related issues

The one truly unique aspect of unmanned aircraft operations (apart from the systems' reliance on CNPC links) is the need for alternate means of compliance with the near-universal requirement for pilots to see and avoid conflicting traffic, obstacles and terrain. Some of these requirements may be met by use of detect and avoid systems of various types (see "Mid-air collision investigation" above). However, many DAA systems are intended solely to keep a UA clear of other aircraft, and do not incorporate any kind of terrain awareness and warning system (TAWS) logic or functionality.

Investigators considering the possibility of a controlled flight into terrain (CFIT) scenario involving an unmanned aircraft need to understand the information available to the PIC as well as the system design; in some cases, GNSS-generated altitudes may be used where the reference datum significantly differs from where "sea level" or "ground level" might actually exist.

Another novel aspect of unmanned aviation which may come to light, particularly in the course of the systems investigation, is the means by which the pilot's inputs are translated into control surface

movements. There are several means by which UAS designers have solved this technical problem, many of which adapt off-the-shelf autopilots, flight management systems or even hobbyist radio-control systems to UAS use.

As a rule of thumb, the more complex the series of transactions necessary to translate a pilot input into an aircraft maneuver, the greater the opportunity for software error, hardware malfunction, or single-point failures to occur. There have been UAS accidents resulting from obscure failures in the conversion of commands from one language to another, as well as in the fidelity of signals transmitted by systems less (and occasionally more) complex than required by the scope of control they exercise over the aircraft as a whole. While these points were mentioned in the "Systems investigation" section above, they bear repeating here: the radiofrequency limitations of CNPC add complexity and vulnerability to the system, but an intact link is capable of transmitting faulty commands as well as correct commands executed incorrectly upon receipt.

Finally, it is important to note the possible involvement of traffic alert and collision avoidance systems (TCAS) in unmanned aircraft-related accidents or incidents where a collision, near mid-air collision or loss of safe separation takes place. TCAS algorithms were not created with unmanned aircraft in mind; their performance is substantially different in some cases, they may climb or descend at different rates than comparable aircraft, and some have limitations on the extent of bank they can handle based on their aerodynamic properties. Moreover, most transponders used to emit signals recognizable by ATC radar beacon systems have not been built to existing TSOs, meaning the response of TAWS systems detecting them cannot be considered predictable or reliable.

Any sequence of events involving the loss of safe separation between a manned and an unmanned aircraft should consider the possibility that TCAS might have played a part in misleading one or both pilots if (1) the manned aircraft involved was TCAS-equipped, or (2) the unmanned aircraft was designed with a "TCAS" function that could have been in use at the time of the occurrence.

Final Report Content

1. Factual information

History of the flight: Ensure the purpose of the unmanned aircraft system's operation and the operator's level of aviation expertise are addressed.

Injuries to persons: Specifically identify injuries directly caused by an unmanned aircraft itself; injuries caused by damage to a manned aircraft leading to a subsequent accident should be treated as incidental to the fact that the accident sequence was started or sustained by an unmanned aircraft's involvement.

Damage to aircraft: Document as for manned aircraft accidents. If the ground control station suffered damage resulting in its abandonment or the loss of control over the unmanned aircraft, ensure that the sequence of events accurately describes the chronology of the entire failure scenario, starting with the ground-based initiating event(s) as appropriate.

Other damage: Document as for manned aircraft accidents.

Personnel information: Document as for manned aircraft accidents. Specifically examine pilot/observer/other participant qualifications against minimum requirements established by the State of Occurrence. Be prepared to address any disparity between the level of training or proficiency required by rules and the demands of the activity in progress at the time of the occurrence.

Aircraft information: Document as for manned aircraft accidents. Ensure that full particulars are gathered with respect to the unmanned aircraft, the ground control station, and the network/satellite system (if any) in use at the time of the occurrence.

Meteorological information: Document as for manned aircraft accidents. Ensure that ambient lighting and the presence of ceilings or obscurations to vision from a ground-based perspective are noted where appropriate.

Aids to navigation: Document as for manned aircraft accidents. If equipped with navigation-specific equipment, the unmanned aircraft should have a means of transmitting its location and trajectory to the pilot in command; document if that downlink is part of the primary control system or is provided

via a separate channel. If the system makes use of global navigation satellite system (GNSS) information, ensure that the status of the supporting constellation at the time of occurrence is documented. Note if the UAS is equipped with receiver autonomous integrity monitoring (RAIM) equipment. Note if the navigation system represents a single-point failure opportunity or if back-ups (e.g., inertial navigation system) are provided.

Communications: Document as for manned aircraft accidents. Include all information relevant to the status and specific CNPC link architecture in use, including band (e.g., L-band, C-band, Ku-band, non-protected spectrum), data rate, etc. Also describe any hand-off of control from one GCS to the next in progress at the time of the occurrence in this section if relevant.

Aerodrome information: Document as for manned aircraft accidents. If UAS-unique ground support equipment (e.g., catapults, rail launching systems, arresting gear) was required and in use at the time of the accident, include such information in this section.

Flight recorders: List all devices from which recorded data was obtained from the unmanned aircraft and the ground station, as well as that captured by any third-party providers of networked CNPC services.

Wreckage and impact information: Document as for manned aircraft accidents. Ensure specific locations of ground-based participants relative to the aircraft and surrounding obstacles to visual or electronic line of sight are depicted where appropriate.

Medical and pathological information: Document as for manned aircraft accidents.

Fire: Document as for manned aircraft accidents.

Survival aspects: Document as for manned aircraft accidents if relevant.

Tests and research: Document as for manned aircraft accidents. Distinguish among outside analyses previously completed and applied to the investigation, projects specifically conducted to support the investigations, and follow-on projects needed to support or affirm the validity of specific recommendations.

Organization and management information: Characterize the involved UAS operator as –

- ◊ A public use operator performing governmental or public safety functions
- ◊ A provider of manned and unmanned aviation services
- ◊ A provider of exclusively unmanned aviation services
- ◊ A user of unmanned aircraft systems whose primary business employs manned aircraft as part of its overall enterprise (e.g., aerial photography, utility patrol, cartography)
- ◊ A user of unmanned aircraft systems whose primary business is enhanced by but not reliant upon aviation as part of its overall enterprise (e.g., real estate, livestock management, agriculture)

Additional information: Document as for manned aircraft accidents.

2. Analysis

Flight operations: Specifically address any of the following as appropriate –

- Crew qualification: document if crewmembers –
 - ◊ Conformed to State rules for manned aircraft pilots
 - ◊ Conformed to State rules for unmanned aircraft pilots/other crewmembers
 - ◊ Had no rules in place applicable to the operation in progress at the time of occurrence
- Operational procedures
- Weather
- Air traffic control
- Communications
- Aids to navigation: note if GNSS was required/available and if any other aids to navigation were available to the PIC.
- Aerodrome

Aircraft: Specifically address any of the following as appropriate –

- Maintenance
- Performance
- Weight and balance
- Instrumentation
- Systems

Human factors: Specifically address any of the following as appropriate –

- Physiological. Factors which incapacitate, confuse, disorient, distract or dull perceptions, including:
 - ◊ Disease or illness
 - ◊ Pharmacological effects
- Psychological:
 - ◊ Task-Saturation
 - ◊ Awareness
 - ◊ Decision-making
 - ◊ Insight
 - ◊ Affective Behavior
 - ◊ Psychomotor Complement
 - ◊ Perceptual issues
 - ◊ Habit Interference
 - ◊ Knowledge
 - ◊ Judgment
 - ◊ Personality
 - ◊ Fatigue
 - ◊ Learning
 - ◊ Background
 - ◊ Motivation
 - ◊ Personal Discipline
- Psychosocial. Factors with indirect influences on performance, generally involving how the individual relates to others or groups:
 - ◊ Stress
 - ◊ Supervision
 - ◊ Communication
- Ergonomic. Ground control station/handheld controller visibility, fit and reach issues relative to the physical dimensions of the human.

Survivability: Document as for manned aircraft if appropriate.



APPENDIX 1

Significant Aspects Of The Draft Italian Unmanned Aviation Regulations

Mezzi Aerei a Pilotaggio Remoto (or “Remote Control Small Unmanned Aircraft”), the initial draft of a proposed new Italian regulation for unmanned aircraft systems (UAS), is not available in English at this writing. (Only one page on the *Ente Nazionale Per L’Aviazione Civile* (ENAC) official site, plus selected links from it, is in English – see http://www.enac.gov.it/servizio/info_in_english/index.html.) The draft regulation contains a number of points of interest on issues related to both civil aviation authorities and investigators who may need a frame of reference as to how some of the issues discussed in these *UAS Investigation Guidelines* have been addressed in an operational context.

ENAC draws a clear distinction between UAS (*sistemi aeromobili a pilotaggio remoto/ SAPR*) and model aircraft (*aeromodelli*): “Neither the activities carried out by unmanned aircraft systems nor model aircraft are currently governed by ENAC, so it is therefore necessary to define a regulatory framework enabling their safe operation.” In addition to addressing model aircraft, the draft regulation is aimed at two distinct UAS sectors: those using unmanned aircraft weighing less than 20 kg (44 lbs.) (which will not be issued airworthiness certificates), and those weighing between 20 and 150 kg (330 lbs.).

The upper 150 kg limit is based on European Parliament and European Council Regulation (EC) 216/2008 “on common rules in the field of civil aviation;” Annex II of that regulation exempts unmanned aircraft below that threshold from European-level regulation, so the Italian regulation is in part intended to ensure there is no regulatory gap involving UAS in their national airspace.

The draft regulation provides a European Aviation Safety Agency-compliant definition and framework for “special operations” authorizations that resembles a combination of the U.S. Certificate of Waiver or Authorization (COA) and Special Airworthiness Certificate processes, as well as several useful definitions:

- Visual Line of Sight (VLOS) – “Operations are carried out under conditions and at such dis-

tances that the remote pilot stays in visual contact with the aircraft, without the help of optical and/or electronic [aids], and in accordance with the rules applicable to the affected airspace.”

- Beyond Line of Sight (BLOS) – “Unlike VLOS, operations are conducted at a distance so as not to allow the remote pilot to remain in direct and constant visual contact with the aircraft, or to abide by the rules applicable to the affected airspace.”
- Congested Area – “Areas used as commercial, industrial, residential or sports areas where you may have permanent, or even temporary, gatherings of people.”
- Sense and Avoid – “Any features *on board* that allow the separation of aircraft, equivalent to see and avoid, in accordance with the rules of the air for aircraft with a pilot on board.” [*emphasis added; a ground based sense and avoid system is not acceptable under Italian regulations*]
- UAS [Visual] Observer – “A person specifically designated by the operator who, through the visual observation of the unmanned aircraft, shall assist the remote pilot’s safe conduct of flying by assisting him in maintaining compliance with rules of the air, and by providing directions to the pilot to prevent potential collision conditions with other traffic and prevent emergency situations.”

Two interesting provisions in the Italian regulation are:

- (1) Unmanned aircraft must give way to all other aircraft; in return, an explicit assumption is made that other pilots most likely will not be able to see the unmanned aircraft in order to avoid it; and
- (2) Direct overflight of virtually all types of infrastructure (power plants and transmission lines, railroad stations and tracks, dams, military facilities, ports, hospitals and prisons), including highways, is prohibited except where specifically approved.

The Italian draft regulation sidesteps their current problem of lacking certification standards by requiring all of their small UAS certifications to be

issued as “restricted” type certificates (for the heavier aircraft) or “permits to fly” for the smaller ones. It states that optionally piloted aircraft currently possessing their own type certificates may be certified as unmanned aircraft based on those certificates plus a separate certification of compatibility with the other components in the total unmanned aircraft system of which it is a part.

Also, the Italian draft regulation offers a useful take on qualifying for certification or “special operations” by providing for such authorizations to be granted once initial test flights have been successfully and safely accomplished, a formal risk assessment performed, and operators certify:

- Operations can be conducted safely and securely in proposed locations and airspace, under limits prescribed by ENAC.
- The pilot is licensed and has been trained in type.
- The operator has adequate liability insurance.
- An operations manual has been developed that describes procedures for safe operation of the UAS, including the maximum distance at which the system may be operated and the unmanned aircraft seen by its pilot or observer.

The UAS hazards of the greatest concern to the Italians appear to be:

- “Loss of control of the unmanned aircraft” (*perdita del controllo del mezzo*);
- Loss of containment within assigned airspace (*[perdita] fuoriuscita dal volume assegnato*);
- Inability to land safely or terminate the flight in case of emergency; and
- Collision threat to persons and other aircraft in the air.

Italian small UAS pilots will be required to have one of the three certificates (civil, sport or commercial) prescribed by European regulations as well as a Class II medical, and requires them to maintain currency by performing and logging at least three takeoffs and landings every 90 days. Small UAS operations will require conformity to all rules of the air, including equipment requirements as applicable based on the class of airspace to be used; interim relief is granted from see-and-avoid requirements under VLOS as noted above, but BLOS operations are limited to day VMC in segregated airspace until certified systems enabling “sense and avoid” of conflicting traffic, as well as capabilities for remaining clear of clouds and surface obstructions, are available.

Some of the equipment requirements levied by the Italian regulation are noteworthy. In particular, flight termination must be possible either manually or automatically, where “termination” means the execution of an emergency landing. This capability must be available even when the control link has failed. The purpose of this capability is to ensure the unmanned aircraft remains within its authorized operating airspace at all times. The regulation also makes it clear that link stability is an issue of both safety and security, and that the type of link selected for a given operation takes into consideration where that operation is to be conducted.

One brief portion of the draft regulation is, in effect, 14 CFR Part 119 stripped down to a few sentences, requiring commercial and non-commercial operators intending to fly unmanned aircraft weighing 20 kg/44 lbs. or more (and some smaller UAS based on the type of operations and number of aircraft involved) to have:

- A technical (maintenance) and operations organization appropriate to the intended activity;
- Qualified pilots;
- An Operations Manager;
- A continuing airworthiness program;
- An operating manual with content as described above; and
- A certificate of airworthiness/permit to fly based on the intended operating configuration.

In addressing model aircraft, the draft regulation defines them in terms of both their weight (less or greater than 20 kg/44 lbs. maximum takeoff weight) and, for the small systems, their propulsion systems. Model aircraft operations are limited to daylight operations only; must be conducted in continuous visual contact of the “builder” without optical or electronic system assistance; pose no risk to people or property; and be limited to altitudes of 50 meters AGL or below.²⁰ Model aircraft operations must be covered by liability insurance and must be conducted using only those portions of the electromagnetic spectrum authorized for hobbyist operations.

Finally, one passage (Article 21) briefly, simply and directly addresses a key issue of concern in the United States and elsewhere: “Privacy issues are not within the institutional competence of ENAC. The operator must observe any such regulations in force.”

Appendix 2

Proposed Addition to U.S. Title 14, Code of Federal Regulations

Part 107 – Small Unmanned Aircraft Systems

There are two basic approaches to bringing unmanned aircraft into a currently operating aviation system:

1. The unmanned aircraft may be required to conform to rules governing existing flight operations; or
2. The system itself may be required to adjust to the limitations of its unmanned participants.

These two philosophies tend to lead regulators in one of two “integration” directions: allow those unmanned aircraft that are most capable of operating in the same manner as manned aircraft greater access to airspace, or give unmanned aircraft the opportunity for the maximum access to airspace possible, regardless of their ability to conform to existing rules governing manned aircraft operations.

However, in some cases regulatory agencies are attempting to chart a middle path. For example, in the winter of 2015, the U.S. Federal Aviation Administration (FAA) announced it “has decided to proceed incrementally and issue a rule governing small UAS operations that pose the least amount of risk.” To that end, on February 15, 2015, the FAA issued for public review and comment a “notice of proposed rulemaking” (NPRM) addressing the certification and operation of small (less than 55 pound) unmanned aircraft in U.S. domestic airspace. (Readers interested in review the entire document – which runs to nearly 200 pages – should search on-line for it; a link may be available at www.faa.gov/uas, but this may be taken down at some point.) The NPRM:

- Formally establishes a series of UAS-related definitions.
- Requires “operator” certificates for sUAS pilots as opposed to manned aircraft pilot licenses/certificates.
- Requires registration of all small unmanned aircraft.
- Requires sUAS to be “airworthy,” i.e., in a safe condition for flight, but excuses them from formal certification processes.

The reasoning behind these broad permissions incurring “the least amount of risk” is not clearly explained in the NPRM’s preamble. However, to a

certain extent a claim of this type can be made based on the provisions of the proposed rule that tend to keep manned and unmanned operations clear of each other. For example, the operating altitude of a small unmanned aircraft is limited to no higher than 500 feet (150 meters) above ground level (§107.51(b)). Section 107.41 imposes limitations on sUAS access to certain classes of airspace; a small unmanned aircraft may not operate in Class A airspace, and may not operate in Class B, Class C, or Class D airspace or within the lateral boundaries of the surface area of Class E airspace designated for an airport, unless the operator has prior authorization from the ATC facility having jurisdiction over that airspace.

Other controls that tend to keep manned and aircraft apart, or to increase the likelihood of manned aircraft being able to see small unmanned aircraft in time to avoid them, are provided as well. Right-of-way is addressed by the simple expedient of requiring sUAS to give way to all other aircraft (§107.37); this provision also has the virtue of avoiding the need to deal with the question of unmanned aircraft designs in different categories (e.g., single-engine, rotorcraft, etc.). Counter-detection concerns are to some extent reduced by limiting sUAS operations to daytime only (§107.29), under visual meteorological conditions only, and §107.51 specifies that sUAS may not exceed 87 knots (100 miles per hour) calibrated airspeed at full power in level flight.

Finally, sUAS weather minima are somewhat more stringent than those required by 14 CFR §91.155 (“Basic VFR weather minimums”) in some classes of airspace. The minimum flight visibility as observed from the location of the ground control station must be no less than 3 statute miles (5 kilometers); and, the minimum distance of the small unmanned aircraft from clouds must be no less than 500 feet (150 meters) below the cloud and 2,000 feet (600 meters) horizontally away from the cloud. (§ 107.51(c) and (d))

By the same token, the proposed rule contains some provisions that are less restrictive than those applicable to manned operations. The safety impact of these more relaxed requirements cannot be determined due to a lack of relevant safety data or research. For example:

- §107.9 requires unmanned aircraft opera-

tors to report (within ten days of occurrence) accidents involving any injury to any person or damage to any property other than the small unmanned aircraft. This is both more and less restrictive than the corresponding NTSB rule. (49 U.S.C. 830.2)

- §107.13(d) requires sUAS owners or operators to comply with “all applicable airworthiness directives.” However, it is not clear under what authority – or by whom – airworthiness directives could be issued on aircraft lacking production, type or airworthiness certificates.
- §107.31 requires “the operator or visual observer” [emphasis added] to be able to see the unmanned aircraft throughout the entire flight in order to know its location, attitude, altitude, and direction; to observe the airspace for other air traffic or hazards; and to ensure that the unmanned aircraft does not endanger life or property. However, §107.33 makes the use of a visual observer optional: “If a visual observer is used during the aircraft operation...” [emphasis added]. Section 107.31 also relieves pilots in command from the requirement to see their aircraft at all times where an observer is used.

Finally, there are some provisions in the proposed rule that address unique aspects of sUAS operations. For example, §107.25 prohibits their operation from a moving vehicle or aircraft. In acknowledgment of the differences between the purpose of sUAS operations and those of manned aircraft, §107.49 establishes preflight familiarization, inspection, and other requirements to be accomplished prior to flight, including:

- Assessing the operating environment, considering risks to persons and property in

the immediate vicinity both on the surface and in the air. This assessment must include local weather conditions, local airspace and any flight restrictions, the location of persons and property on the surface, and other ground hazards as appropriate.

- Ensuring that all persons involved in the small unmanned aircraft operation are pre-briefed on their roles and responsibilities and potential hazards;
- Verifying that all links between ground station and the small unmanned aircraft are working properly; and
- Ensuring that there is enough available power for the small unmanned aircraft system to operate for the intended operational time and to operate after that for at least five minutes.

All users of the UAS Guidelines should take from this example both the challenges associated with writing a separate set of rules specific to unmanned aviation and the difficulty of reconciling such rules with those governing existing (i.e., manned) aircraft operations. This case study also shows that enabling UAS access to airspace on an “integrated” basis is easy to set as a goal, but extremely difficult to implement.

Air safety investigators are invited to take note of potential sources of risk that may result from the compromises that needed to be made in the various provisions of this proposed rule. If manned and unmanned aircraft are intended to be kept separate as much as possible, but a midair collision occurs, two key issues will need to be considered: how the various “segregation” provisions failed, and whether the resulting adverse interaction between manned and unmanned operations were preventable with all parties following the respective sets of rules established for them.

APPENDIX 3

Recommendations For Further Reading

The body of literature associated with unmanned aircraft systems (also referred to as “remotely piloted aircraft systems” in some arenas) is large and growing on an almost daily basis. A significant amount of popular writing on the subject tends to be somewhat advocacy-oriented, either pro or con. Air safety investigators looking to expand their understanding of UAS and their issues should not avoid accessible writing of this type, but should treat it with caution.

Similarly, some technical writing on UAS topics contains an element of advocacy as well. This is understandable, since the sector is trying to grow and many collective efforts are being exerted to that end. In the aggregate, government-industry publications may be considered the most reliable sources of current information, simply because they are expending the greatest energy in studying many of the issues addressed in this document. Again, such sources should not be discounted simply because of their authorship – they just need to be read with a critical eye and due consideration given to what they might leave unsaid on the more controversial or difficult-to-manage issues.

The following list is by no means exhaustive. It was assembled from suggestions made by ISASI UAS Working Group members from the body of reference materials with which they were familiar. Where on-line versions are available, the URL is provided; the Microsoft Word version of the *UAS Investigation Guidelines* provides links to them that may be clicked for direct access.

* * * * *

Concepts of Operations and Roadmaps

Federal Aviation Administration, *Integration of Unmanned Aircraft Systems into the National Airspace System: Concept of Operations, version 2.0* (September 2012) (<http://www.suasnews.com/wp-content/uploads/2012/10/FAA-UAS-Conops-Version-2-0-1.pdf>)

Federal Aviation Administration, *Integration of Civil Unmanned Aircraft Systems (UAS) in the National Airspace System (NAS) Roadmap*, First Edition – 2013 (http://www.faa.gov/about/initiatives/uas/media/uas_roadmap_2013.pdf)

Joint Planning and Development Office, *Unmanned Aircraft Systems (UAS) Compre*

hensive Plan: A Report on the Nation’s UAS Path Forward, September 2013 ([http://www.faa.gov/about/office_org/](http://www.faa.gov/about/office_org/headquarters_offices/agi/reports/media/UAS_Comprehensive_Plan.pdf)

[headquarters_offices/agi/reports/media/UAS_Comprehensive_Plan.pdf](http://www.faa.gov/about/office_org/headquarters_offices/agi/reports/media/UAS_Comprehensive_Plan.pdf))

National Defense Research Institute, *The RAND Corporation, Applications for Navy Unmanned Aircraft Systems* (2010) (<http://www.rand.org/pubs/monographs/MG957.html>)

U.S. Department of Defense, *Unmanned Systems Integrated Roadmap: FY2013-2038* (Reference Number: 14-S-0553) (<http://www.defense.gov/pubs/DOD-USRM-2013.pdf>)

U.S. Air Force, *United States Air Force RPA Vector: Vision and Enabling Concepts 2013-2038* (February 2014) (http://www.defenseinnovationmarketplace.mil/resources/USAF-RPA_VectorVisionEnablingConcepts2013-2038_ForPublicRelease.pdf)

System Safety and Human Factors Studies

Chris W. Johnson, DPhil, Department of Computing Science, University of Glasgow, Scotland, UK and **Christine Shea, PhD**; ESR Technology Ltd, Birchwood Park, Warrington, Cheshire, UK, *“The Hidden Human Factors in Unmanned Aerial Vehicles”* (http://www.dcs.gla.ac.uk/~johnson/papers/UAV/Johnson_Shea_UAS.pdf)

Jason S. McCarley and Christopher D. Wickens, University of Illinois at Champaign-Urbana, *“Human Factors Concerns in UAV Flight”* (2004) (<https://www.hf.faa.gov/docs/508/docs/uavFY04Planrpt.pdf>)

Federal Aviation Administration, Office of Aerospace Medicine, *Human Factors Implications of Unmanned Aircraft Accidents: Flight Control Problems*, April 2006 (http://www.faa.gov/data_research/research/med_humanfacs/oamtechreports/2000s/media/200608.pdf)

Federal Aviation Administration, Office of Aerospace Medicine, *An Assessment of Pilot Control Interfaces for Unmanned Aircraft*,

April 2007 (http://www.faa.gov/data_research/research/med_humanfacs/oamtechreports/2000s/media/200708.pdf)

Federal Aviation Administration, Office of Aerospace Medicine, *An Investigation of Sensory Information, Levels of Automation, and Piloting Experience on Unmanned Aircraft Pilot Performance*, March 2012 (<http://www.trb.org/Main/Blurbs/166911.aspx>)

Office of the Under Secretary of Defense for Acquisition, Technology and Logistics, *Unmanned Aircraft Systems (UAS) Ground Control Station Human-Machine Interface (HMI) Development and Standardization Guide*, version 1.0 (2012) (https://ucsarchitecture.org/system/files/5/original/UAS_GCS_HMI_Guide_19July2012.pdf) 1347481941)

Tobias Nisser and Carl Westin, Lund University School of Aviation, Human Factors *Challenges in Unmanned Aerial Vehicles (UAVs): A Literature Review* (2006) (<http://www.lusa.lu.se/upload/Trafikflyghogskolan/HumanFactorsChallengesUnmannedAerialVehicles.pdf>)

United States Air Force, 311th Human Systems Wing, *Human Factors Considerations in Migration of Unmanned Aircraft System (UAS) Operator Control* (HSW-PE-BR-TR-2006-0002) (<http://www.wpafb.af.mil/shared/media/document/afd-090121-046.pdf>)

U.S. Army Aeromedical Research Laboratory, *The Role of Human Causal Factors in U.S. Army Unmanned Aerial Vehicle Accidents*, USAARL Report No. 2004-11 (March 2004) (www.dtic.mil/cgi-bin/GetTRDoc?AD=ADA421592)

Rules and Recommended Practices

Australian Government, Civil Aviation Safety Authority, CASR Part 101 – *Unmanned aircraft and rocket operations* (<http://www.casa.gov.au/scripts/nc.dll?WCMS:PWA::pc=PARTS101>)

International Civil Aviation Organisation, **Circular 328** – *Unmanned Aircraft Systems (UAS)* (http://www.icao.int/Meetings/UAS/Documents/Circular%20328_en.pdf)

Joint Authorities for Rulemaking on Unmanned Systems (JARUS), JARUS-ORG, draft version 0.17 (27 April 2014) (<http://jarus-rpas.org/index.php/deliverable/category/11-external-consultation-on-jarus-org>)

UK Civil Aviation Authority, CAP 722: Unmanned Aircraft System Operations in UK Airspace – Guidance (<http://www.caa.co.uk/docs/33/CAP722.pdf>)

U.S. Army, Army Regulation 95-23, Aviation: Unmanned Aircraft System Flight Regulations (July 2010) (http://www.apd.army.mil/pdffiles/r95_23.pdf)

Accident and Incident Reports and Formats

National Transportation Safety Board, CHI06MA121, **General Atomics Predator -B, Brief of Accident**, 04/25/2006 (http://www.nts.gov/aviationquery/brief.aspx?ev_id=20060509X00531)

Scientific and Technical Information Program Office, National Aeronautics and Space Administration (NASA / TM-2007-214539), *Preliminary Considerations for Classifying Hazards of Unmanned Aircraft Systems*, February 2007 (<http://shemesh.larc.nasa.gov/people/jmm/NASA-2007-tm214539.pdf>)

U.S. Department of the Army, DA Form 2397 -U, *Unmanned Aircraft System Accident Report (UASAR)* (<https://safety.army.mil/accidentreporting/FORMS/AviationAccidentFormsInstructions/tabid/463/Default.aspx>)

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Access 5 Project Office, *Sense-and-Avoid Equivalent Level of Safety Definition for Unmanned Aircraft Systems* (January 2005) (<http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20080017109.pdf>)

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International Telecommunications Union – Radiocommunications Sector (ITU-R), Report ITU-R M.2171, *Characteristics of*

unmanned aircraft systems and spectrum requirements to support their safe operation in non-segregated airspace (December 2009) (http://www.itu.int/dms_pub/itu-r/opb/rep/R-REP-M.2171-2009-PDF-E.pdf)

Keven A. Gambold, MAS BSc, GAPAN North America, *Unmanned Aircraft System Access to National Airspace* (November 2011) (<http://www.gapan.org/file/917/uas-access-to-national-airspace-paper.pdf>)

END NOTES

1- The term “unmanned aircraft system” shows some signs of being gradually supplanted by the term “remotely piloted aircraft system” (RPAS). The International Civil Aviation Organization (ICAO) itself seems somewhat divided on the matter. It is true that the remote location of an unmanned aircraft’s pilot is a critical distinction between manned and unmanned operations. However, it is to some extent misleading to label the family of aircraft in such a way as to imply that a pilot always is part of their operation. In some modes of operation – those conducted autonomously by design, as well as those resulting from failures of the electronic link between pilot and aircraft – the nominal pilot in command has no ability to change the trajectory of the aircraft in any way. Therefore, this document uses the term “UAS,” although future revisions may change all such references to “RPAS” if generally accepted usage moves in that direction.

2- Chapter 6, related to UAS training for investigators, is a high-level discussion of basic knowledge needed. Follow-on work will be needed to translate its observations and recommendations into lesson plans.

3- For an excellent discussion of this issue, see the Australian Transport Safety Bureau, *Limitations of the See-and-Avoid Principle* (April 1991) - <http://www.skybrary.aero/bookshelf/books/259.pdf>.

4- It is only fair to point out that a collision between two unmanned aircraft may be just as possible, and perhaps more so, if the preferred means of trying to make UAS operations safe relies on airspace segregation that puts multiple unmanned aircraft in a narrowly constrained altitude band or geographical location. However, a UAS-on-UAS collision is likely to have far less

impact on the public or in the media than one involving loss of life. The latter also would be far more likely to drive immediate political responses that could have a detrimental effect on the scope, or even the viability, of the unmanned aviation sector.

5- To the latter point, it is important to bear in mind that datalink failures could result in the immediate cessation of performance data flow from the aircraft to the GCS. For this reason, some manufacturers incorporate separate on-board flight data recorders similar to those traditionally used aboard aircraft. ICAO is working toward a standard set of recommended provisions to this end.

6- This example in turn suggests issues regarding the extent to which necessary information can be provided efficiently and interpreted effectively, as well as the availability of RF spectrum, bandwidth, and on-board resources for transmitting it. These are non-trivial issues that barely have been addressed as efforts to expand the unmanned aviation sector have gained momentum, and which may not come to the fore until documented in conjunction with accidents and their ensuing investigations.

7- 47 CFR 2.106, Non-Governmental Footnote 46: “In the bands 72–73 and 75.4–76 MHz, the use of mobile radio remote control of models is on a secondary basis to all other fixed and mobile operations.” Fifty channels (72.0 –73.0 MHz) are available for model aircraft devices, which must limit their emissions to a bandwidth of 8 kilohertz(kHz). *See generally* 47 CFR Part 95.

8- Report ITU-R M.2171 (12/2009), *Characteristics of unmanned aircraft systems and spectrum requirements to support their safe operation in non-segregated airspace* (M Series: Mobile, radiodetermination, amateur and related satellites services).

9- Uniform use of the code “7400” to designate an unmanned aircraft operating autonomously as a result of control link failure is being studied by the FAA and ICAO at this writing.

10- Access 5 materials were preserved by NASA and provide valuable insight into a host of the issues referred to throughout these *Guidelines*; see http://web.archive.org/web/20060627203947/www.access5.aero/site_content/index.html.

11- Similar considerations will need to be addressed in the case of a damaging UA collision with a surface structure or feature.

12- Some systems are beginning to be provided with hybrid control systems that use a combination of terrestrial lines of communications and conventional (non-satellite) radio control of the aircraft. BLOS-equipped aircraft invariably have (usually separate and parallel) LOS capabilities, meaning that the latter can be employed to effect a safe recovery if the aircraft is programmed to come into the range of a suitably equipped GCS following satellite-supported link failure.

13- As an example, see Appendix 1 and 2 to see how Italy and the U.S. have addressed these issues.

14- See generally ASTM F2910-14, *Standard Specification for Design and Construction of a Small Unmanned Aircraft System (sUAS)*, Paragraph 5 (“Requirements”).

15- The SCF-NP definition includes the following: “For unmanned aircraft, includes failure or malfunction of ground-based, transmission, or aircraft-based communication systems or components or datalink systems or components.” The separate *Definitions and Usage Notes* document for SCF-NP expands upon this over-generalized perspective on control link failures; “unanticipated lost command and control link to a UAS” is prescribed for use as follows: “To be coded regardless of where the failure occurred, i.e., on the unmanned aircraft, in the remote pilot station (coded with a –RPS suffix), or in the communication infrastructure between them, whether the communication infrastructure is ground, air or space based, or a combination.” It also explicitly excludes “lost links that are anticipated.”

16- “Remote pilot station” appears to be becoming increasingly popular in ICAO usage vice the more common “ground control station.” Since it is the preferred term in the CICTT issuances, it is included to match other existing references. Per ICAO Circular 328, *Unmanned Aircraft Systems*, Remote Pilot Station (RPS) is defined as “the station at which the remote pilot manages the flight of an unmanned aircraft”.

17-Historically, most air safety investigators (or at least investigators-in-charge) have been drawn from the ranks of certificated pilots. An operational aviation background provides most of the knowledge base needed to effectively understand and investigate unmanned aircraft-involved accidents. Nevertheless, first-hand UAS experience should be considered either mandatory or highly desirable for anyone running a UAS-involved investigation. If such cannot be reasonably obtained in advance of an investigation, the participation of a subject matter expert specifically qualified in the involved system and personally familiar with the ground control station arrangement in use during the accident sequence should be considered mandatory.

18- An example of this would be where a requirement for all UAS to be transponder-equipped, even for VFR operations in uncontrolled airspace, subsequently allowed a UA to be successfully tracked and separated from following CNPC failure.

19- Investigators always should be open to the possibility that an unexplained manned or unmanned aircraft accident might have been the result of a midair collision with an unmanned aircraft. The lack of unexplained physical remains or an unrelated overdue aircraft can make such an event more difficult to recognize, as can the fact that the operators of smaller systems may not even be aware that their aircraft has gone missing due to a collision if it was not in sight at the time of the event. The time-tested practice of identifying “too many parts” in wreckage may be complicated by the involvement of smaller unmanned aircraft, which might leave less physical evidence of their presence but still could have imparted a significant amount of force to a critical component (engine, control surface) or to the cockpit itself.

20- Heavy model aircraft (20 – 150 kg) operations must be conducted pursuant to annually renewed authorization letters from ENAC in designated areas only (which are treated as “segregated areas” for the purpose of this regulation), but may go up to 150 meters AGL and are not subject to propulsion system size limits.

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