UNMANNED AIRCRAFT SYSTEM ACCIDENTS: LEARNING TO PREDICT THE UNPREDICTABLE

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Introduction

Unmanned aircraft systems (UAS) are becoming the subject of steadily growing interest on the part of both entrepreneurs (who are coming up with more and more innovative ideas as to how to make money with them) and regulators (who are becoming increasingly engaged in trying to figure out how to bring them safely into the existing aviation system). For the latter, so-called "UAS integration" is not a trivial problem, despite the interest of many in portraying it as such.

In some respects, the emerging UAS sector has followed the evolutionary path blazed by prior technological innovations in aviation, such as the introduction of commercial jet airliners in the 1950s. But, it has done so with unprecedented speed, and with the huge advantage of a century's experience with the basic challenges of aviation to inform their developmental efforts. The number of unmanned aircraft likely to be conducting civil operations in just a few years is completely out of proportion with the body of experience-based knowledge that has been assembled about the hazards associated with them to date.

Previous aviation safety lessons were hard won and incrementally learned; today, the UAS generation of safety challenges has arrived at the aviation community's doorstep as a potentially unruly teenager instead of a newborn infant. At the same time, UAS advocates mindful of the inherent limitations of unmanned aircraft are lobbying hard to carve out various regulatory exemptions for their operations. Such demands represent a desire for permanent *accommodation* of UAS rather than true integration, since they would result in a system to which different users are held to different standards and, in effect, different levels of safety.

Widespread deployment of at least some unmanned aircraft into airspace currently used by manned aircraft to conduct both visual flight rules (VFR) and instrument flight rules (IFR) operations now seems likely in the near term, at least in the United States. Therefore, it is a matter of some urgency to understand their potential impact on the aviation system as a whole under both normal and adverse circumstances, and to be as ready as possible to address a new set of investigative and prevention challenges.

With respect to unmanned aircraft systems as a whole, the air safety investigator community has three challenges: how to investigate UAS accidents and incidents; how to apply the fruits of those investigations to reduce the likelihood of similar events in the future; and, how to make informed judgments regarding the most critical UAS-related hazards requiring both investigation and mitigation, as opposed to those which simply are the most commonly encountered. It is the last of these issues that is the focus of this paper.

Historical Perspectives on Aircraft Accident Investigation

From the start of heavier-than-air flight more than a century ago, the aviation community has had to address a vast array of safety challenges, all of which necessitated the development of investigative processes and procedures suitable to identifying and remedying them. There is a stark logic associated with how these activities progressed over time.

The table on the following page shows how one fundamental technological problem after another had to be addressed as aviation's horizons expanded. In the early years of powered flight, engine reliability and the structural strength of aircraft components were literally life-and-death issues that had to be resolved to move forward. As they were, confidence in the aerial medium grew, and with that greater confidence came a greater desire to exploit its untapped potential to maximum advantage. Air mail operations drove a need for greater night and adverse weather capabilities; growing numbers of passengers obliged operators and regulators to find means of protecting them as well as making them comfortable. Since every one of these advancements required investment, the art and science of air safety investigation itself had to become increasingly more sophisticated to be able to define the requirements and justify the expenditures.

Unmanned aviation is not charting the same path, and cannot be expected to proceed with the same degree of caution as early aviation pioneers exercised, simply because (a) UAS operators are not putting the lives of passengers or their own employees at risk; and (b) their commercial interests (as opposed to safety) are being accorded priority in the creation of enabling regulations, driven by the multitude of business models envisioned for UAS applications. Theirs is a more calculated approach to the costs and benefits of aviation, made with due consideration for potential liability, but also made with the great advantage of involving aircraft orders of magnitude less expensive than manned aircraft.

	Safety Focus Areas	Landmark Accidents	Major U.S. Prevention Efforts
1910	Engine Reliability		
	Airframe Strength		
1920	Night/All-Weather Operations		
	Basic Flying Regulations		
1930	Passenger Safety	T&WA (Kansas)	Insurance Industry
	Air Traffic Safety	T&WA (Missouri)	(Jerry Lederer)
1940	Aerospace Physiology		Creation of CAA/CAB
	Aviation Weather		
1950	Crashworthiness	NA 101 (EWR)	Flight Safety Foundation
	Route Structure	TW2/UA718 (Grand Canyon)	
1960	Jet Airliner Safety	UA736/USAF F-100F (LAS)	Creation of FAA/NTSB
	Radar Surveillance	TW266/UA826 (NYC)	
1970	Design/Maintenance Practices	TK981 (France) KL4805/PA1736 (Tenerife)	NTSB Midair Collision Studies
	Crew Resource Management	UA173 (PDX)	
1980	Airspace Management Hazardous Weather	PS182 (SAN), AM498 (Cerritos) DL191 (DFW)	
1990	Runway Incursions	NW1482/299 (DTW)	
	Controlled Flt into Terrain	AA965 (Cali)	Commercial Aviation
2000	Approach/Landing Loss of Control	AA 1420 (LIT)	Safety Team
2010		AF447 (South Atlantic)	

Figure 1. Chronology of Air Safety Advancements and Their Catalysts

In addition, if you look at Figure 1 closely, it becomes evident that it wasn't until relatively recently that broad safety concerns affecting the bulk of the operating community and the flying public started being replaced by more focused issues associated with the completion of individual flights. To date, UAS manufacturers generally do not appear to be working together to address broad-based reliability issues that should be of mutual concern, especially those associated with making UAS integration into the National Airspace System (NAS) safe rather than simply minimally permissible. Their energies are being expended on making their own systems more efficient (endurance being one of the most desirable properties of unmanned aircraft), and they have little interest in imposing any increased payload or on-board power requirements on themselves.

This apparent blind spot is in part due to the reluctance of some aviation stakeholders to require unmanned aircraft and their pilots to meet the same standards as those expected of manned aircraft and their pilots, which in turn is based on the different priorities they have with respect to aircraft capabilities, mission accomplishment and risk tolerance. However, it also is traceable to a lack of manned aviation experience on the part of many UAS manufacturers, as well as a lack of hard data regarding broad UAS-specific safety issues. All of these challenges must be confronted if unmanned aircraft systems are to be successfully brought into wider use for commercial and public safety purposes.

Determining UAS Investigative and Record-Keeping Requirements

Investigators unfamiliar with how unmanned aircraft systems work might ask, "Why do some UAS occurrences deserve focused investigative attention, while others warrant formal tracking for statistical and reliability purposes, and a few can safely be disregarded?" The short answer is that some kinds of events are the result of systemic issues associated with the design or operation of unmanned aircraft, while others involve operational or equipage issues where the manned and unmanned aviation sectors intersect. These are the events worth capturing and in some cases delving into in detail.

Unmanned aircraft that malfunction with no resulting effect on manned aircraft around them, and which do not offer lessons learned beyond the immediate UAS involved, for now should be accorded the lowest investigative and record-keeping priority possible to avoid a completely unmanageable influx of new and difficult-to-exploit data. The following brief discussion should help readers understand the distinction between critical and non-critical UAS occurrences from a systems perspective.

More than five years ago, RTCA Special Committee 203 developed the conceptual diagram below, identifying the three basic components ("segments") of unmanned aircraft systems: the "aircraft segment" that flies, the "control segment" from which the pilot in command flies the aircraft, and the "airspace system" segment within which the aircraft flies and the pilot interacts with air traffic control as necessary.

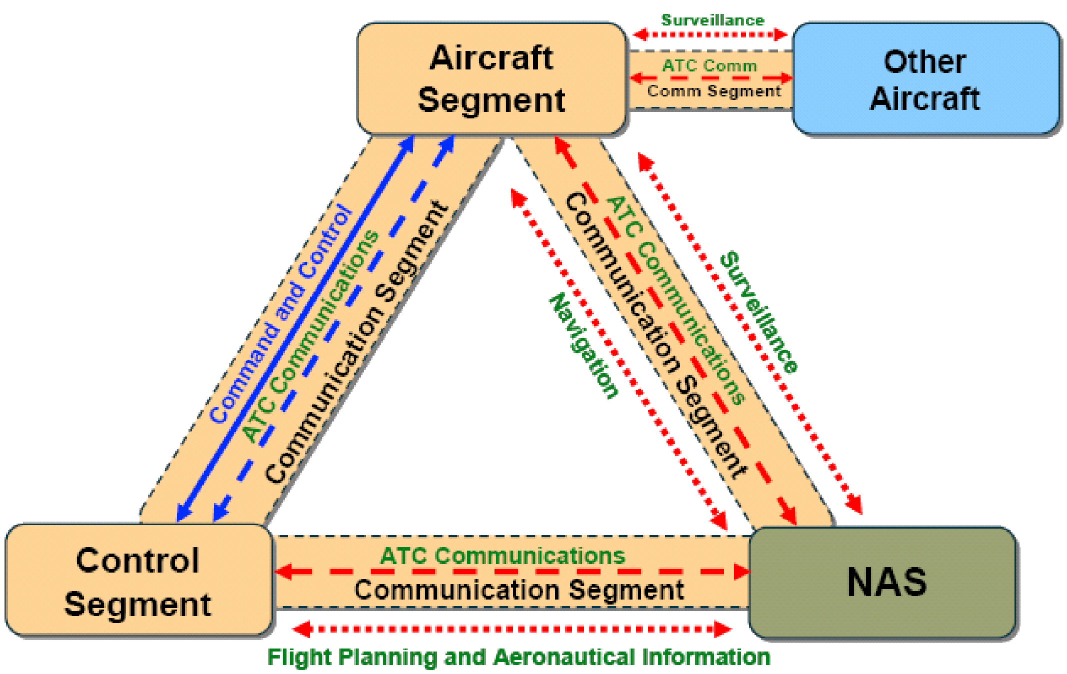

Figure 2. Common Components of an Unmanned Aircraft System.[1]

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[1] RTCA SC-203, DO-304, *Guidance Material and Considerations for Unmanned Aircraft Systems* (Washington, DC: RTCA, Inc., March 22, 2007), page 5.

In addition, each of the three principal segments in the SC-203 model is connected to the others through so-called “communications segments,” which deliberately were kept generic because of the vast differences in how they operate from one system to the next. This model has withstood the test of time, to the extent that any UAS in existence may be overlaid upon it and each segment described by SC-203 will have a recognizable analogue. However, it does not completely describe the full environment within which the system operates in terms of interrelationships between all of the segments and other aircraft, which is necessary to understand the nature of UAS-related hazards and possible accidents.

The modified model below – referred to as the “UAS Kite” – allows the introduction and impact of hazards to be more easily visualized.

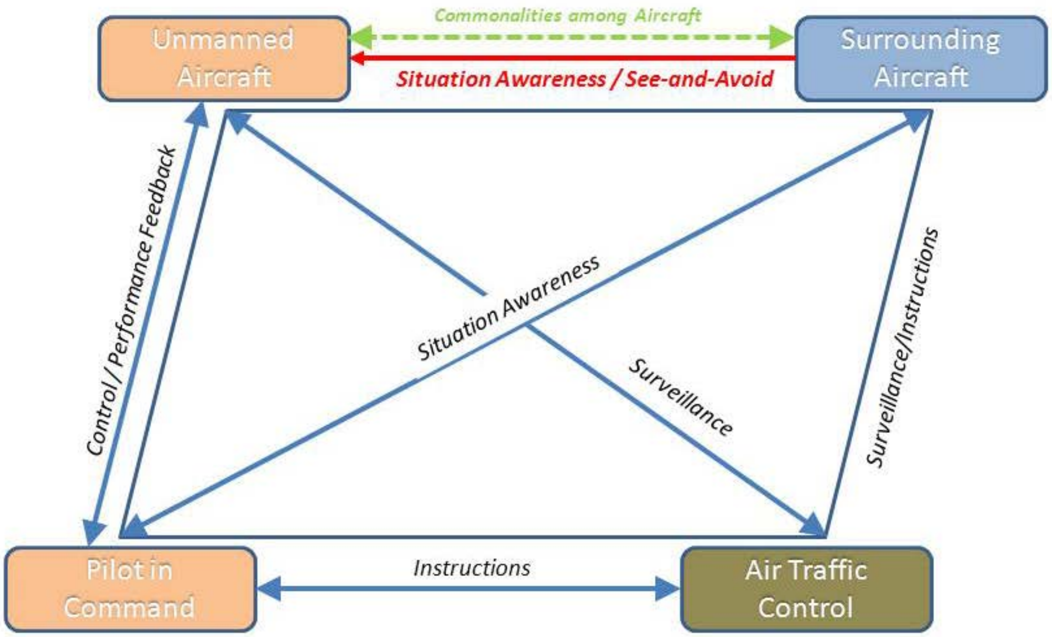

Figure 3. The “UAS Kite” Model for Hazard and Risk Assessment

From a top-level perspective, a UAS-related hazard occurs in controlled airspace when anything affects the normal operation of any of the four vertices of the unmanned aircraft/PIC/ATC/other aircraft parallelogram so as to create the potential for an undesired outcome. In addition, anything that disrupts any of the communications segments similarly may result in increased risk. The criticality of the communications segment between an unmanned aircraft and those surrounding it is evident because it is the only potentially one-way segment; other aircraft may see and react to the unmanned aircraft (assuming it is large enough to be readily observed), but most UAs cannot do likewise.

The UAS Kite also can be applied to illustrate the different safety issues associated with UAS operations in uncontrolled airspace. By removing the ATC vertex (as opposed to simply disabling it as in the event of an “ATC-Zero” scenario), it is clear that the entire model becomes unbalanced; the UAS PIC has few means available to become aware of surrounding aircraft, and there is no ATC segment to monitor the flight path of the UA and provide advisories to other aircraft.

Finally, the UAS Kite provides clues regarding the *criticality* of hazards with respect to how they may affect its vertices. If the operation of any segment is degraded (including where manned aircraft pilots operate in the vicinity of unmanned aircraft in shared airspace without awareness of the latter), risk increases. This includes the added line at the top of the Kite, identifying “commonalities among aircraft” as an additional “segment” for the purpose of hazard identification and assessment.

From a regulator’s and investigator’s perspective, the UAS Kite offers a starting point for setting priorities for rulemaking and information-gathering. These activities may be based on the unmanned aircraft systems and operating environments for which safety officials are responsible, and may be tailored through assessment of the basic nature of the segments’ in-service interactions and interrelationships in a given State. However, this starting point must be further refined to maximize the effectiveness of the scarce ASI resource.

Setting UAS Investigative Priorities for Air Safety Investigators

Apart from the rapidity with which a variety of unmanned aircraft concepts have been developed and a corresponding scarcity of hard data regarding their limitations in actual use due to their short operational history, the vast differences in performance and on-board capabilities among different types of UAS have introduced significant complications into the regulatory equation. For example, with respect to accident and incident investigations, a number of issues have yet to be satisfactorily addressed, such as:

- To what extent is it desirable or practical to investigate accidents and incidents of UAS of different sizes?
- What types of UAS accidents and incidents warrant in-depth investigation?
- Does it make sense to expend investigative resources on small UAS accidents? If so, under what circumstances?

Answering these and similar questions on a case-by-case basis requires addressing three aspects of unmanned aircraft and their operations: the commonalities among UAS that lead to similar types of accidents, incidents, and unusual occurrences; commonalities between manned and unmanned components; and, expected interactions between manned and unmanned aircraft operations. Through advance consideration of these factors, their incorporation into appropriate regulations and future interpretation of them in the context of specific accident and incident scenarios, investigators should be able to prioritize scarce resources toward those inquiries most likely to generate information usable to improve the safety of UAS operations across their size, performance and capability spectra.

Commonalities among Unmanned Aircraft System Attributes

Rethinking unmanned aircraft system safety in the context of investigative priorities first requires concentrating on three key UAS attributes:

- Lack of on-board see and avoid capability;
- Vulnerability to pilot loss of control due to electronic link failures; and
- Vulnerability to local or system-wide failure of Global Position Satellite (GPS) system.[2]

The basic difference between manned and unmanned aircraft is, of course, the remote location of the unmanned aircraft's pilot. This difference is why these three serious and recurring hazards associated with UA operations must be not only acknowledged, but directly confronted. The inability of a UAS pilot in command (PIC) to conform to right-of-way rules has long been recognized as a significant threat in any aviation system where VFR and IFR aircraft share airspace, but technologies specifically intended to routinely mitigate this threat are literally years away, and are unlikely to be capable of being installed in any but a handful of the largest and most sophisticated unmanned aircraft.[3]

By the same token, control link failures – perhaps even a greater hazard than the lack of see-and-avoid or a viable alternate means of compliance for it – are known to occur with varying degrees of frequency from system to system, but conversations about them are routinely avoided despite the potential unpredictability they bring to unmanned aircraft operations, especially in controlled airspace. Given that the entire concept of unmanned aviation hinges on reliable means of keeping pilots and their aircraft connected, it is somewhat surprising that this issue receives as little high-level attention and concern as it does; if the regulators don't force the issue, the operators and manufacturers definitely have no incentive to engage on it.

Finally, virtually all unmanned aircraft systems that exceed modelers' radio-controlled aircraft in basic capabilities incorporate some application of GPS technology to report the unmanned aircraft's position, to enable some kind of preprogrammed response to a loss of their control link, or both. However, as proponents of future air navigation systems are belatedly discovering, the failure of part or all of the GPS constellation can constitute a significant and perhaps intolerable single-point failure mode. An unmanned aircraft of any type that is out of its PIC's direct line of sight and then loses GPS functionality has the potential to become both autonomous *and* directionless… a very bad combination.

There are variables associated with how different unmanned aircraft systems of differing size and complexity manage each of these issues, but these rarely are explored in detail due to the tendency of many observers to lump all UAS under a single umbrella. Regardless, the

[2] On the UAS Kite, these are depicted as (1) the one-way segment between unmanned and surrounding aircraft; (2) failure of the PIC-to-UA "control" segment; and (3) failure of the UA-to-PIC "performance feedback" segment.

[3] Some UAS proponents have suggested that the solution to the size and weight problem of "sense and avoid" systems for smaller unmanned aircraft is to develop ground-based sense and avoid (GBSAA) capabilities to provide surveillance and warning of collision risks in specific volumes of airspace, perhaps coinciding with established classes of airspace where aviation operations are densest. While such proposals are being explored, they bring with them significant cost, technology and operational concept questions that as a minimum put their deployment on a mid- to long-term timeline similar to that expected for dedicated, aircraft-based sense and avoid (ABSAA) systems.

system states under which different unmanned aircraft systems encounter see-and-avoid, lost link or GPS-related problems have a significant bearing on the severity of possible outcomes when they occur. This is partly because of how UAS pilots in command (PIC) interact with their and other aircraft in different modes of operation, and partly because of the options – or lack of options – available to the PIC when problems are encountered.[4]

There are three system states relevant to this proposition: line of sight, beyond visual range, and beyond line of sight. "Line of sight" operations are those conducted with the unmanned aircraft in view of its pilot in command at all time. "Beyond visual range" operations are those where the aircraft remains within electronic line of sight of its ground control station but is too far away to be seen by the PIC, who must rely on information passed back from the aircraft via data downlink (e.g., GPS location, camera view) to maneuver and navigate the aircraft. "Beyond line of sight" operations are those where the unmanned aircraft is beyond the electronic horizon – far enough away that the curve of the Earth prevents straight-line electronic communications with it – and command, control and communications links with its ground control station must be relayed through a satellite, repeater or similar intermediate retransmission system.[5]

How does understanding the effects of different combinations of UAS and system state help investigators know where they should focus their efforts? If one unmanned aircraft system is involved in accidents or incidents whose causes have been anticipated and designed out or otherwise controlled in others, it becomes much easier to justify requiring a more uniform feature or procedure for all UAS likely to encounter the same circumstances. Thus, any accident or serious incident involving a given unmanned aircraft system must be documented and compared with similar systems operating in the same system state. While the hazard encountered may drive a uniform risk shared by all, it also could be that a lesser-severity outcome is an indicator that something much worse might have occurred if a less capable UAS had been involved.

The bottom line of this discussion is that regardless of the physical or technical differences among individual unmanned aircraft or unmanned aircraft systems, the hazards associated with them are essentially identical in comparable system states. The existing mitigations for these hazards vary widely from one UAS to the next, but that diversity of solutions actually can form the basis for identifying best practices and best equipage concepts for

[4] At the same time, the conditions under which a UAS accident or incident occurs may significantly complicate one of the most basic of investigative requirements, namely, confirming the continuity of the flight control system from pilot to control surface. While the process (as opposed to the need) of investigating unmanned aircraft is a subject for another paper, the complexity of this challenge is illuminated by the following two passages from SAE Aerospace Recommended Practice (ARP) 5707, *Pilot Training Recommendations for Unmanned Aircraft Systems (UAS) Civil Operations*: "The presence of data link in the system requires that the pilot become aware of communication protocols between the ground station and the aircraft. The pilot needs to know how to establish the links and how those links could be broken. If the links are broken, the pilot must know what the effects are on the system… Control handoffs are unique in the sense that a transfer of control of the aircraft takes place over a distance. The procedures involved in the transfer of control from one control station to another are not found in manned aircraft operations. Even when control is transferred from one control station position to another, the procedure is more complex than simply acknowledging that control has been transferred." (Page 17)

[5] The three system states, and the ways the three attributes present themselves differently in each, are explained in detail in the Appendix.

preventing them. The only way to know why some systems are more (or less) susceptible to certain types or severities of occurrences is to individually investigate them as they happen. To avoid being completely overwhelmed by events, investigators should concentrate on those involving see-and-avoid breakdowns, control (uplink) and data (downlink) failures, and GPS-related malfunctions, along with the failure of any system intended to provide an alternate means of compliance with existing see-and-avoid rules.

Commonalities between Manned and Unmanned Aircraft Equipment

The second investigative priority for UAS-involved accidents and incidents is where a powerplant or avionics common to both manned and unmanned aircraft malfunctions. (This would be identified as a degradation of the "commonalities among aircraft" segment on the UAS Kite.) While a full-up investigation of each occurrence most likely would not be necessary in most cases, the consequences of such malfunctions in *unmanned* aircraft might be less severe than could be the case in *manned* applications. A certain amount of advance and ongoing self-education will be necessary to recognize which systems might incorporate such shared equipment, and to ensure that the unmanned/manned connection is clearly identified for each UAS overseen by the investigative authority.

One of the many unusual aspects of unmanned aircraft is that part of the cost savings they are expected to realize will be achieved by their not being required to incorporate very much in the way of "aviation-certified" components. That is, UAS certification in the U.S. will for the most part be based upon conformity with consensus standards rather than adherence to technical standard orders (TSO). This is justifiable, and indeed logical, with respect to those aspects of manned aircraft required by certification regulations on the basis of the need to protect the lives of those on board.[6]

By the same token, certain key UAS components, such as radios and transponders, must be expected to function within the same tolerances and with the same degree of reliability required of those meeting TSO requirements. As such, it is likely that at least some unmanned aircraft systems will incorporate off-the-shelf – i.e., certified – avionics for these purposes. Therefore, failures of all such components must be scrutinized carefully, regardless of the aircraft or system within which they are installed, and reporting and investigation requirements identical to those required for comparable failures in manned aircraft should be established for them accordingly.

Another peculiarity of unmanned aircraft is that some are designed around existing powerplants, including some currently used in manned aviation as well as non-aviation variants of the aviation-approved models. The nominal lines between engines used in aircraft and those not suitable for such use blurred considerably with the advent of "light sport aircraft," and homebuilt experimental aircraft often go even farther in applying light-weight, efficient engines to aviation purposes.

[6] It has yet to be determined whether similar concerns for possible death, injury or property loss resulting from inadequately reliable UAS-specific subsystems will drive a reconsideration of the consensus standard approach.

Whenever UAS engine failures are reported, the responsible air safety investigators will need to dig into the specifics of the *exact* type of engine in use. In some cases it is relatively easy to determine if a specific engine model, such as one built by an established company like Rotax or Wankel, has been certified for manned aircraft, and word needs to be circulated through manned channels if a failure involving a certified engine takes place in an unmanned aircraft.

In many cases, however, the challenge may be to determine if an observed failure in a non-aviation certified powerplant with parts commonality with an aviation model could reasonably affect manned aircraft. This is not currently a priority for most investigation authorities, but it actually represents an opportunity to improve manned aircraft safety based on unmanned aircraft experience. As such, it should be explored whenever practical as unmanned aircraft become more numerous and the use of off-the-shelf components to build and equip them continues to expand.

Interactions between Manned and Unmanned Aircraft Operations

The final priority for investigators should be to ensure all possible avenues are open to them to become aware of every instance where manned and unmanned aircraft come into conflict with each other. This means ensuring a close ongoing relationship with air navigation service providers and airport operators, as well as establishing a trusted anonymous reporting system for both manned and unmanned pilots if one does not already exist.

While statistical tracking of both midair and near midair collisions involving UAS will be essential, it will be equally important to dig deeper into both – especially the latter – wherever practical to validate or cast doubt on many assumptions being made in conjunction with granting unmanned aircraft greater freedom to operate.

There is natural concern about the possibility of controlled flight into terrain and loss of control accidents involving unmanned aircraft, but most observers tend to concentrate on the midair collision (MAC) threat as being the most pressing. Indeed, the growing calls for UAS "integration" into the NAS – deliberately placing aircraft with no onboard see-and-avoid capability in the midst of manned aircraft operating under both VFR and IFR – require serious consideration of the likelihood of MACs between manned and unmanned aircraft and the few ways they realistically may be prevented.

Part of the challenge of bringing focused attention to the MAC threat in the context of unmanned aircraft operations is the same as has been experienced with manned aviation: relating near midair collision (NMAC) circumstances to those that actually result in collisions. MAC and NMAC events often are reported and investigated through two entirely different processes, with the former investigated as accidents and the latter as air traffic events.

NMAC reporting and investigating tends to be somewhat skewed because it often is done in response to suspected or objectively measured violations of separation minima rather than actual or perceived close calls. As such, NMAC reports are good at measuring the effectiveness with which controlled airspace is managed and operated within required tolerances, but rarely do they delve into the kinds of issues often seen in actual midair collisions – distraction, sun angles, undetected convergence, etc.

The toll of the midairs that do occur (in the U.S., seven out of ten were fatal in 2009, while only about one out of every six other types of accidents was fatal[7]) makes it imperative to understand the circumstances under which both MACs and NMACs are likely to occur in detail, and to gauge the risk of UAs being involved in both accordingly. In particular, it means documenting the aviation environments within which they take place – in terms of both location and system state – to ensure existing safety margins are not inadvertently compromised in an effort to expand UAS commercial opportunities, and to be positioned to exhaustively examine every MAC involving a manned and an unmanned aircraft regardless of the cost or extent of damage suffered by either.

A generally unspoken but fairly obvious expectation regarding manned and unmanned operations in shared airspace is that there are going to be a lot of unwanted encounters between the two, and many have the potential to occur in airspace that has been extremely safe for decades. According to the FAA, "Recent studies of midair collisions involving aircraft by the National Transportation Safety Board (NTSB) determined that… [the] vast majority of accidents occurred at or near uncontrolled airports and at altitudes below 1000 feet."[8] This can be attributed at least in part to the strict limitations imposed on pilots flying in denser aviation environments, especially Class B and C airspace.

Those very locations are likely to become some of the most desirable for unmanned aircraft operations in the near future, in part for electronic news gathering and commercial purposes but far more frequently in support of public safety missions. Such increased activity certainly is justifiable, and much if not most of it could be argued as being in the public's interest. But, when matched against the growing calls for relief from the regulatory requirements mandating transponders and two-way radio communications with ATC – the same rules that have made midairs almost non-existent anywhere except uncontrolled airspace – the wisdom of having separate sets of safety rules for manned and unmanned aircraft becomes suspect.

This final type of investigative activity is likely to become the most politically charged, especially if it documents a pattern of dangerous activity involving unmanned aircraft. However, given the fact that the smallest unmanned aircraft are both the least likely to be equipped for radar detection by ATC and the most likely to escape visual detection by manned aircraft pilots, the entire aviation community needs better information regarding the likelihood of MACs with unmanned aircraft, as well as the outcomes of all such occurrences. While a collision with a small unmanned aircraft may be less likely to result in a fatality than a similar collision with a second manned aircraft, remember that it only took a few geese to bring down an A320 just a few short years ago.

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[7] Aircraft Owners and Pilots Association, *2010 Nall Report: The Joseph T. Nall Report of Accident Trends and Factors.* Frederick, MD: AOPA, 2010, pp. 15-17 *passim*.
[8] "Midair Collision Avoidance: Your Role in Collision Avoidance" -- http://www.faa.gov/about/office_org/headquarters_offices/ato/tracon/anchorage/pilots_info/mca/.

The Feasibility of Preventing Future Occurrences

Having determined the three sets of circumstances under which given UAS-related events should be formally investigated, analyzed and statistically tracked, or simply recorded – commonalities among UAS, commonalities between manned and unmanned aircraft components and hazardous interactions between manned and unmanned aircraft operations – one final consideration rarely of concern to investigators inquiring into manned aircraft occurrences must be taken into account: the likelihood that effective recommendations for future prevention actually can be made or, if made, will be implemented.

Air safety investigators may consider this a somewhat cynical element to include in this discussion, but it is unavoidable. Investigations can be expensive affairs, and unmanned aircraft accident and incident investigations often have the potential to be significantly more complex than their typical manned aircraft counterparts. In-depth inquiries into events where similar unmanned aircraft systems – or manned aircraft with common powerplants – could encounter significantly worse outcomes under similar conditions might be the best predictive tools possible. But, unless blood is shed, they simply may not be considered worth the cost.

Proponents of system safety-based approaches to controlling risk typically identify five opportunities in the life cycle of a given system to address identified hazards (also known as “design order precedence”):

- As the system is being designed;
- Through modifications to established designs;
- Through incorporation of “engineered features” to actively interrupt accident sequences and reduce risk;
- Through incorporation of subsystems designed to warn of an imminent hazard, if modification is not practical; and
- Through development of procedures and training intended to avoid encountering a hazard or to manage its effects.[9]

In a perfect world, these principles would be universally applicable at the earliest point in time possible. For most unmanned aircraft systems, that should mean there is ample opportunity to ensure that known hazards are designed out, and the currently small numbers of most UA fleets should simplify the modification of those currently in service.

Unfortunately, the greatest hazards associated with unmanned aircraft systems relate to their intrinsic limitations in seeing and avoiding other aircraft and their reliance on continuous electronic connectivity between the pilot in command and his/her unmanned aircraft. Secondarily, the autonomous response to the loss of a control link relied upon by the vast majority of unmanned aircraft is utterly dependent on the reliability of the GPS constellation and its local reception. These must be understood to be fundamental attributes of the concept of unmanned aircraft themselves. At best they can be mitigated, but they never can be eliminated.

[9] Adapted from Military Standard (MIL-STD) 882E, *Department of Defense Standard Practice: System Safety* (11 May 2012), paragraph 4.3.4.

The question of whether aircraft subject to such predictable and potentially dire vulnerabilities should be allowed into the sky already has been decided. Many regulators are not being permitted the opportunity to consider the wisdom of allowing broadly-based unmanned aircraft operations in shared airspace. Instead, they are being pressed on a variety of fronts to move forward. So, the challenge in many if not most future UAS investigations is likely to be finding feasible and defensible strategies for protecting other aircraft and the public from the consequences of inadequate or absent alternatives to on-board see-and-avoid, disruptions in pilot/aircraft connectivity, and GPS-related failures. Removing the threats themselves is unlikely to be an acceptable option.

Detailed exploration of this latter issue will be the subject of a future paper. However, the stark choice many investigators will have to face for the foreseeable future is to determine if the consequences or provable threat associated with a given UAS-related event will justify confronting likely resistance to most or all of the possible recommendations that could best prevent its recurrence. While this often is part of the challenge at the conclusion of a major investigation, for unmanned aircraft systems it must, for now, be a consideration as to whether or not even to initiate an inquiry in the first place. If the payoff won't warrant the overall costs – be they financial or political – it may not be worth doing any more than simply documenting the occurrence for future information, and then moving on.

UAS Safety: From Reactive to Predictive?

This year's ISASI Annual Seminar theme is "Evolution of Aviation Safety – From Reactive to Predictive." Earlier in this paper, that evolution was characterized as movement from generalized safety concerns associated with flying itself toward focused attention on recurring factors in specific types of aviation accidents. Building as it has on the lessons of the first century of aviation, the UAS sector is in a strange middle ground, with some fundamental issues regarding the safety of unmanned aircraft operations still to be resolved while it already is possible to identify specific areas requiring improvement as well.

As stated in the title of this paper, the challenge with unmanned aircraft systems – just as with manned aircraft – is "learning to predict the unpredictable." To some extent, the advent of unmanned aircraft systems requires hitting "reset" on a century of progress in the field of aircraft accident investigation, especially with respect to the crucial linkage between *discovering* causes and *acting* to prevent their recurrence. An ongoing frustration facing many aviation safety professionals in unmanned aircraft circles is the unwillingness or inability of both operators and regulators to do what has become standard practice in the aviation safety domain: extrapolating the larger lessons that need to be learned from individual accidents and applying them broadly, rather than only to the involved operator or airframe.

So, how does the current state of the UAS sector, from the standpoint of both the maturity of the technologies and the experience base necessary for safe operations, bode for moving from "reactive" to "predictive"? The author's estimate of the prevailing climate is that UAS are in the curious position of being subject to an array of new but readily anticipated hazards, but that there is a lack of will on the part of virtually all of the sector's stakeholders to proactively address them in a systematic manner. What for now is far less predictable is the relative value and effectiveness of the different mitigations that different manufacturers have developed to deal with these predictable hazards.

There appears to be only one real advantage that the accelerated pace of UAS development and deployment has brought into the safety domain. Awareness of the newness of the UAS sector has been accompanied by a degree of caution regarding moving too quickly to implement new operational concepts or technologies. That has translated into more forethought regarding foreseeable hazards and possible mitigations for them. To that extent, UAS regulators and investigators already are doing their best to leverage "reactive" solutions identified through past manned aircraft accidents into predictive, or at least risk-based approaches to the prevention of future unmanned aircraft accidents.

Summary

The purpose of any safety investigation is to identify ways to prevent the occurrence of a similar accident in the future. From that perspective, it is always desirable to investigate any out-of-the-ordinary event involving an aircraft in operation, regardless of the severity of the outcome. However, it is impractical to expend significant time and resources on low-consequence events unless those events:

- Involve an actual failure of procedures or design features intended to prevent undesirable interactions between manned and unmanned aircraft;
- Could reasonably be assumed to result in a far worse outcome under similar circumstances based on the absence of relevant mitigations or the ineffectiveness of those already in place; or
- Might have different outcomes if different aircraft or participants were involved, or if they occurred in different system states.

In keeping with the above, it is clear that *any* undesired interaction between a manned and an unmanned aircraft warrants an investigative response. However, as discussed throughout this paper, there are a variety of factors investigators must weigh before committing scarce resources to investigations where the return on investment would be questionable. The midair collision threat is the greatest, in terms of both potential consequences and the public's likely concern following any such occurrence. Therefore, any collision or significant disruption of normal operations in controlled airspace involving an unmanned aircraft will warrant a visible, aggressive investigative response.

It is likely that the air safety investigator community will learn to anticipate the vulnerabilities and hazards associated with unmanned aircraft systems and their operation at the same accelerated rate that the sector itself is advancing. In the meantime, it is essential that air safety investigators help regulators gather as much relevant data as possible regarding UAS hazards and risks as quickly as possible. Investigators need a basis upon which to be able to make useful UAS-related recommendations (and to be prepared to investigate potentially new types of accidents), and regulators need hard information upon which to develop meaningful boundaries for UAS operations in airspace shared with manned aircraft. Beyond safer UAS operations in the future, one other reward is likely to accrue from these efforts: a risk-driven approach to data accumulation also will naturally lead to safer *manned* operations wherever safety efforts for manned and unmanned aircraft can be applied to positively influence one another.

APPENDIX

System States Associated with Unmanned Aircraft System Operations

The following briefly summarizes each of the system states within which unmanned aircraft systems operate and the variability each offers relative to the three key aspects of their design and operations (i.e., hazards) identified in this paper. Any given unmanned aircraft flight might encounter one, two or all three of these states at various points throughout its mission, depending on the capabilities of the overall system conducting it.

While reading the description of each system state, bear in mind that different unmanned aircraft systems may be more or less capable of providing effective mitigations for the various hazards as they are encountered in each. Thus, the specific capabilities of each system must be taken into consideration when assessing the possible applicability of a lesson learned – or a recommendation – stemming from a given system's experience with a given accident or incident.

"Beyond Line of Sight" (BLOS) Operations

Beyond line of sight UAS operations are those conducted by UA sufficiently distant from their PIC and ground control station (GCS) that their datalink must be maintained via satellite.[10] This arrangement presents a number of technology-based challenges (including loss of signal due to aircraft maneuvering or aircraft structure masking the satellite antenna, changeover failures during the switch from line of sight (LOS) to BLOS due to hardware or software problems or crew coordination issues, etc.) However, it offers one great advantage: the presence of two independent circuits through which the aircraft can be controlled. Should one fail, in many cases the other can be brought on line to support recapture of the aircraft.[11]

U.S. "public use" BLOS UAS operations most commonly are conducted in Class A airspace, where the rules-based structure and comprehensive radar surveillance accorded high altitude IFR operations can to some extent compensate for the UAS PIC's inability to see and avoid other aircraft under visual meteorological conditions (VMC). Unfortunately, a lengthy FAA engineering evaluation of traffic alert and collision avoidance systems (TCAS), which are common aboard the majority of civil aircraft at Class A altitudes, concluded that they are not safe for use in unmanned aircraft.

[10] At least one UAS reportedly uses repeater technology to extend an unmanned aircraft's range from its PIC by retransmitting line-of-sight command signals. There are a few operational concepts examining the feasibility of exercising long-range control of unmanned aircraft through surface-based telecommunication systems, but these are not yet practical and are not likely to become so in at least the near- to mid-term. However, in general it is fair to equate BLOS operations with a supporting satellite communications requirement.

[11] Dual control links often are advocated as a means of greatly reducing the lost link threat. However, they bring with them a host of complications. For example, the AAI RQ-7 *Shadow* has such redundancy, and indeed appears to have significantly fewer instances of control link failure-related mishaps in U.S. Army service. By the same token, the *Shadow* is a robust aircraft with ample electrical power and payload capacity to accommodate twin systems, and crews are required to ensure there is sufficient spectrum available in the desired operating area to accommodate two links… and link failures still occur anyway.

Satellite coverage is for the most part excellent over the bulk of the continental United States, meaning loss of control link is a relatively rare event. When it does occur, the current small number of high-altitude long-endurance (HALE) unmanned aircraft in U.S. airspace usually makes clearing an autonomous flight to a recovery location a relatively straightforward proposition, provided the aircraft's intentions (for lack of a better term) are known. However, since loss of control link often is accompanied by loss of voice communications between the PIC and air traffic control (ATC),[12] there can be delayed recognition of a lost link occurrence, accompanied by a period of significant uncertainty regarding the aircraft's initial response to the loss.

At least one documented GPS disruption is known to have affected an unmanned aircraft during BLOS operations in the U.S. National Airspace System (NAS). The system involved was a Northrop Grumman RQ-4 *Global Hawk*, the largest and most capable platform currently in regular service. The RQ-4's unique advantage in the event of GPS failure is its incorporation of an independent inertial navigation system as well as GPS, which meant that after a short period of confusion, the PIC was able to switch over to an alternate navigation system to complete his mission. No other current-generation or proposed new HALE UAS is so equipped, meaning a future GPS-related malfunction or loss of signal is likely to have a far less uneventful outcome unless it becomes a certification requirement for redundant navigation systems – either inertial or terrestrially based – to be a mandatory part of any HALE unmanned aircraft.

"Line of Sight" (LOS) Operations

Line of sight UAS operations make up the vast majority of U.S. unmanned aircraft flights, and that likely will be the case for the foreseeable future. The three UAS attributes cited above – lack of on-board see and avoid capability, vulnerability to loss of control link and vulnerability to local or system-wide GPS failures – manifest themselves differently in this system state.

In the first instance, two major issues appear to be emerging with respect to see-and-avoid mitigation in how LOS operations actually are conducted:

- Pilots in command tend to want to act as their own observers, as they would if they were flying model radio-controlled aircraft as a hobby. This significantly simplifies their crew coordination needs, although it increases the likelihood that they will lose visual contact with their aircraft and along with it the means of clearing their own flight path; *but*:
- The ground-centered nature of the vast majority of line-of-sight UAS operations means that PICs not supported by observers must fly their aircraft heads-down a significant percentage of the time to remain over the surface feature of interest to them.

[12] The most common arrangement for maintaining PIC contact with ATC involves running a parallel communications signal up to the same satellite as is used for the control link. Both signals then come down to the aircraft, which uses an aviation radio to retransmit PIC-to-ATC communications. This has the virtue of providing the PIC the same awareness of surrounding traffic as enjoyed by manned aircraft pilots, but means the voice link can be just as fragile as the control link, if not moreso.

Unauthorized LOS operations are becoming more and more common, almost always with aerial photography as the primary purpose of the flight; the obligation to see and avoid other aircraft virtually never occurs to these pilots, and in any event they are ill-equipped to carry it out responsibly.

Vulnerability to lost link usually is not a problem in true LOS operations, simply because command signals almost always can travel at least as far as the aircraft can be seen. However, link problems do arise when "line of sight" operations are pushed beyond true line of sight limitations, as described below.

Finally, GPS capability is a highly desirable adjunct to LOS operations, since it allows for easy re-acquiring of a temporarily unseen aircraft and can enable an automated return to a pre-designated point in space on command or if a lost link occurs.

"Beyond Visual Range" (BVR) Operations

Many UAS authorities only distinguish between LOS and BLOS UAS operations. However, those two operating environments do not reflect the possibility of a third option, namely, a UA flown with reference to a GPS-supported navigational display, pilotage, or both while out of the PIC or other visual observers' view. These may be the most hazardous of small UAS operations; the PIC has no idea if other aircraft are in the vicinity of the unmanned aircraft, and by relying on a control link that depends on a straight line between the GCS and the UA, he or she greatly increases the likelihood that they will lose control of the aircraft as it approaches its effective maximum range (if such even has been reliably determined).

The lack of onboard see-and-avoid capability is particularly troubling in BVR operations. They are not typically authorized by the U.S. Federal Aviation Administration (FAA) for this very reason. Some operators have suggested that placing visual observers along the aircraft's route of flight offers a suitable alternative, but coordinating their efforts is a complex proposition that few are willing to undertake. It also complicates the already problematic operational issue of crew coordination, especially in the event the range from the PIC becomes so great that a second GCS – and a second pilot – becomes necessary.

Similarly, since safe BVR operations are dependent on quality datalinks in both directions (up to the aircraft for control; down from the aircraft for positional information), a failure of either link can easily result in the loss of the aircraft, perhaps with collateral injury or damage to persons or structures on the ground in the process. While "lost link" is most commonly associated with a breach on the control side, the criticality of the downlink is most evident in BVR operations.

Finally, a GPS anomaly occurring during BVR operations almost certainly will result in the loss of the aircraft, unless it is immediately recognized and reacted to by a pilot with the means to recover the aircraft via direct observation of its route of flight over the ground, i.e., pilotage. If an aircraft at the limits of its effective range from its GCS cannot be contained within a specific area, it is at the greatest risk of becoming a "flyaway" – an unmanned aircraft not under the control of its PIC and not responding to preprogrammed lost link instructions.

The increasing complexity and bandwidth requirements associated with LOS, BVR and BLOS operations – and the concomitant potential for a necessary component of the PIC's command and control capability to be disrupted – are illustrated below.

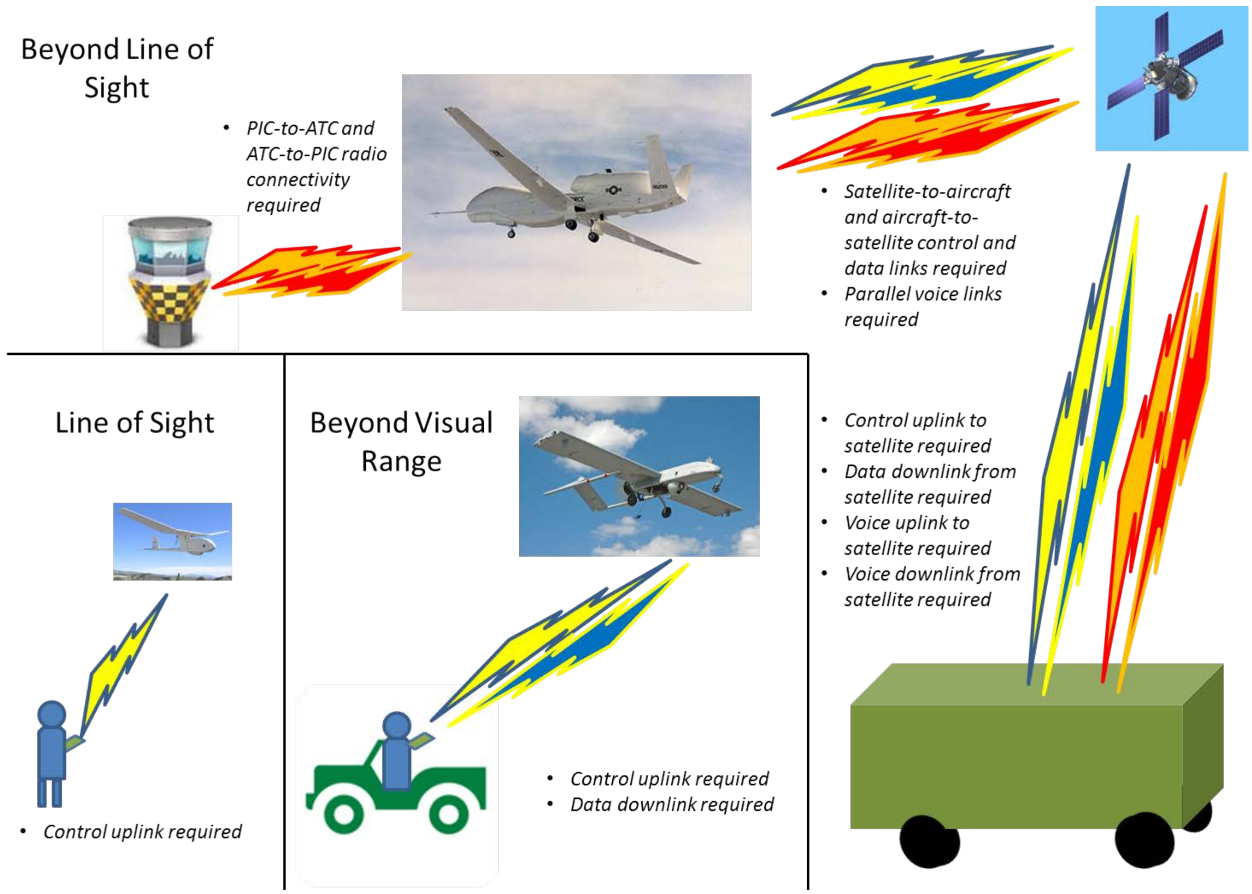

Figure A1. Increasing Potential for Command and Control Disruption by System State