Unmanned Aircraft Systems:

Identifying and Mitigating Hazards

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Introduction

The Unmanned Aircraft System (UAS)[1] industry is fast becoming one of the most prolific and useful industries in aviation today. Unmanned Aircraft (UA) provide a platform for many missions, not only for the military, but also for many other government agencies in the United States (U.S.) and other countries. Many people do not appreciate the scope of the UAS industry. Currently, there are UAs larger and faster than a Boeing 737. There are more than 500 unmanned aircraft systems built by over 200 manufacturers and supporting an industry found in 43 countries.[2] The endurance and remote capabilities of UAS technology can advance many national priorities, including homeland protection, atmospheric measurement, firefighting, pipeline and nuclear facility monitoring, and local law enforcement. As technology advances, it is anticipated that UAs will come to perform

[1] According to the United States Radio Technical Commission for Aeronautics, and as adopted by the U.S. Federal Aviation Administration, an Unmanned Aircraft System is defined as "an unmanned aircraft and its associated elements required for operation." An unmanned aircraft is defined as "an aircraft operated without the possibility of direct human intervention from within or on the aircraft."
[2] Kevin W. Williams, FAA AAM-510. Briefing at the National Transportation Safety Board UAS Forum, April 2008, "UAS Control Station Human Factors: Sensory Information."

more missions, such as crop dusting, cargo transport and perhaps even emergency medical transport, now performed only by manned aircraft.

In order to reap the full benefits of UAs, however, the safety of UAS operations will need to be addressed. UAs are reported to have a high mishap rate — by some counts a rate 100 times higher than that of manned aircraft.[3]

Background

The first UA accident formally investigated by the U.S. National Transportation Safety Board (NTSB) occurred in April 2006 and resulted in the NTSB issuing 22 safety recommendations to the UA operator or the U.S. Federal Aviation Administration (FAA), addressing a wide range of safety issues related to the civilian use of unmanned aircraft. These recommendations are summarized in this paper. In the accident, a turboprop-powered 10,000-pound General Atomics Predator B UA operating on a surveillance mission by the U.S Customs and Border Protection (CPB) agency crashed in a sparsely populated residential area near Nogales, Arizona.

Fortunately, the UA did not collide with another aircraft during its accident descent, and no one on the ground was injured. However, the aircraft crashed less than 100 yards from a large house (see photo below). The NTSB determined that the probable cause of the accident was "the pilot's failure to use checklist procedures when switching operational control from a console that had become inoperable due to a 'lockup' condition, which resulted in the fuel valve inadvertently being shut

[3] Jackson, P. (Ed.). (2003). *Jane's all the World's Aircraft 2003-2004*. Alexandria, VA: Janes Information Group.

offand the subsequent total loss of engine power, and a lack of a flight instructor in the GCS [Ground Control Station].”[4]

Photograph 1: Predator B UA Accident Site in Nogales, Arizona

The investigation raised questions about the different standards for manned and unmanned aircraft and the safety implications of this discrepancy. Why, for example, were numerous unresolved lock-ups of the pilot's control console even possible when such conditions would never be tolerated in the cockpit of a manned aircraft?

Investigators with the NTSB have been closely monitoring the development and flight testing of a number of UASs. In a short time, there have been several interesting UA crashes. For example, one UA breached its test boundaries before crashing near a highway. In another case, Bell Helicopter crashed a UA tilt rotor inside its test range. In July 2004, the engine of a U.S. Coast Guard-operated Altair UA, which is very similar to the Predator B, inadvertently shut down after the crew switched

[4] More information about the accident, CHI06MA121, is available on the NTSB’s Web site at <http://www.ntsb.gov>. The final report is available at http://www.ntsb.gov/ntsb/brief.asp?ev_id=20060509X00531&key=1.

operating positions and the fuel was cut off. In that incident, the crew was able to restart the engine. And finally, in late July of this year, the NTSB initiated an investigation into an experimental Raytheon Cobra UA that collided with a light pole while maneuvering for a pre-programmed landing near Colorado Springs, Colorado. The UA had departed from a road paralleling one of the athletic fields on the grounds of the U.S. Air Force Academy and was returning to that location when the accident occurred.[5]

In addition to the efforts involved in the Nogales investigation, and given the growing importance of UAs, the NTSB held a two-day forum in April 2008 on the safety issues associated with them. The forum provided an opportunity for the NTSB and interested parties from the United States and other countries to understand and discuss the safety implications of the increasing presence of UAS in the world's crowded airspace.[6] The FAA and subject matter experts from the aviation community presented and discussed information related to the safe integration of UAs into the U.S. National Airspace System (NAS) and the policies, practices and procedures in use today and planned for the future.[7] Forum participants provided perspectives that are also summarized in this paper.

Defining the Challenge and Setting Standards

In the United States, UAs are considered aircraft and, therefore, must conform to the applicable rules of 14 Code of Federal Regulations Part 91. The FAA has denied both public and civil UAs free access to the NAS because UAs cannot yet comply with certain Federal Aviation Regulations, including CFR 91.113, which includes "see and avoid" requirements. Unmanned Aircraft are not yet

[5] More information about the accident, DEN08FA130, is available on the NTSB's Web site at <http://www.ntsb.gov>. The final report is available at http://www.ntsb.gov/ntsb/GenPDF.asp?id=DEN08FA130&rpt=p.

[6] The issues addressed in the forum included regulatory standards; integration in the national airspace system; perspectives of current UAS operators; aircraft design, certification and airworthiness; human factors; future UAS applications; and a case study of the NASA Ikhana mission.

[7] The materials generated from this forum are available for review at http://www.ntsb.gov/events/symp_UAS/symp_unmanned_aircraft.htm.

able to sense other aircraft in flight and autonomously maneuver to avoid them as a manned aircraft can. This limitation means that UAs could be hazardous to other users of the NAS, especially manned aircraft without transponders.

Until detect, sense and avoid capability is certified and available, and appropriate rules have been established, a UAS operator can gain access into the NAS only by obtaining a certificate of authorization (COA) or an experimental airworthiness certificate in the experimental category. Currently, the FAA is only approving COAs for public-use missions, and approval of civil for-profit uses is not expected in the near term.

To address the lack of detect, sense and avoid capability, the FAA has tasked the U.S. Radio Technical Commission for Aeronautics (RTCA)[8] to develop a minimum aviation system performance standard for UA systems; UAS command, control and communication systems; and UAS sense-and-avoid systems. The RTCA Special Committee (SC)-203 was formed on October 19, 2004, to develop these standards and continues to work on these products. During the NTSB's UAS Forum, the FAA indicated that the effort to produce viable standards for avionics design and production will take years, perhaps stretching through 2015 or beyond, given the current rate of progress. Until such standards are in place, the FAA intends to maintain strict controls to ensure the safety of the NAS.

Work is under way, however. The RTCA has issued Department Order (DO)-304, which defines a "UAS Hazard" as any hazard associated with the operation of an UAS that leads to one of three "worst credible potential outcomes":

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[8] RTCA is a not-for-profit corporation that develops consensus-based recommendations regarding communications, navigation, surveillance and air traffic management system issues. It functions as a Federal Advisory Committee, and the FAA uses its recommendations as the basis for policy, program and regulatory decisions.

- ✈ A midair collision with another aircraft, manned or unmanned
- ✈ Impact with the ground or any structure resulting in death, injury or property damage
- ✈ Loss of the UA

DO-304 also defines the mitigation of these hazards as "… the practices, procedures or design features that reduce the severity or eliminate the occurrence of identified hazards." According to Tom Farrier, in his presentation at the 2008 FAA UAS Conference, three main concepts associated with mitigation of UAS hazards are (1) The more mitigations, the better; (2) The earlier in the system safety process a mitigation can be inserted, the better; and (3) Sometimes, the best mitigation is avoiding the situation where a hazard is most likely to be encountered. Farrier also presented a list common UAS hazards, shown in table 1 below.

Table 1: Generic UAS Hazards[9]

- Sustained loss of control link (up to the aircraft)
- ✈ Sustained loss of data link (down from the aircraft)
- ✈ Sustained loss of required voice communications
- ✈ UA system malfunctions affecting control or requiring immediate landing
- ✈ Position reported error (horizontal or vertical)
- ✈ Control latency (delayed response to inputs or ATC direction)
- ✈ Meaconing, intrusion, jamming or interference (MIJI)
- ✈ Lost visual contact with the UA
- ✈ Inability of UA to react to visual cues (lights, markings, signage, etc.)
- ✈ Inability of other aircraft to visually acquire the UA
- ✈ Wake turbulence vulnerability
- ✈ Unqualified/inadequately trained UA pilots sharing airspace w/manned aircraft.
- ✈ Unrecognized/unexpected weather change (including entry into clouds)
- ✈ Human performance issues unique to UA operations

[9] Farrier, Thomas. *Unmanned Aircraft Systems: Hazards and Mitigations*. Presented to the FAA 2008 UAS Conference, January 16, 2008.

Other domestic and international efforts are under way to improve UAS safety. Since early 2003, UAS industry representatives and government agencies have been working with the American Society of Testing and Materials (ASTM) to develop UAS-related standards for small, light, unmanned aircraft. The work, conducted by the ASTM F38 Committee, includes the development of standards in airworthiness, flight operations and operator qualifications. According to the ASTM, the of the standards will be to provide the FAA Administrator with a means to approve appliances and UASs defined as small and light for routine operations.

In Europe, the European Organisation for Civil Aviation Equipment Working Group 73 is conducting work similar to that of the RTCA SC-203, and focusing on UASs weighing more than 330 pounds. The International Civil Aviation Organization (ICAO) is also grappling with the development of standards and policies for UAS operations. ICAO has created a UAS Study Group, and meetings on global UAS standards have begun.

Unmanned Aircraft System Design and Equipment

Perhaps the most obvious way to identify and mitigate hazards is to consider UA hardware. The development of design standards and requirements for UAS detect, sense and avoid capability; command and control data links; and the UASs themselves is essential. Manufacturers need these standards in order to design and build UASs that aviation authorities can approve for unrestricted flight in airspace shared by manned aircraft.

During the NTSB forum, U.S. military UAS operators recommended that UAS designs be evaluated using the same processes used for manned aircraft and that UASs not be operated without an airworthiness release that ensures subsequent design changes are properly evaluated, tracked and approved.

It was also noted that UASs not originally designed using airworthiness standards for manned civil aircraft may be difficult to modify for redeployment into civil airspace and may need additional, operationally based risk mitigation. The experiences of the U.S. Department of Defense suggests that large UASs designed using applicable manned-aircraft airworthiness standards can rely on that design to help mitigate risk, whereas small UASs can be safely managed through a rigorous operational risk assessment process.

In the NTSB's investigation of the April 2006 Nogales accident, several specific UAS design deficiencies were noted, including the following.

Inadvertent Engine Shutdown

The ground control station (GCS) of the Predator B that crashed in Nogales, like many UAS GCSs, contains two nearly identical control consoles: Pilot Payload Operator-1 (PPO-1) and PPO-2. When the UA is controlled via engine controls on PPO-1, the engine condition lever at the PPO-2 console controls the camera's iris setting. Moving the lever forward increases the camera's iris opening, moving the lever to the middle position locks the iris setting and moving the lever aft decreases the opening. Typically, the lever is set in the middle position. Operational control of the UA can be transferred from PPO-1 to PPO-2 in the event of a malfunction of PPO-1. Console lockup checklist procedures indicate that, before switching operational control between the two consoles, the pilot must match the control positions on PPO-2 to those on PPO-1 by moving the PPO-2 condition lever from the middle position to the forward position, which keeps the engine operating.

The accident pilot stated in a post-accident interview that, during the accident flight, the console at PPO-1 "locked up," which prompted him to switch control of the UA to PPO-2, as allowed by the system design. However, he did not consult the console lockup checklist. He stated that he did not position the PPO-2 levers to match the PPO-1 levers before the transfer of control, as indicated in the console lockup checklist. As a result, the condition lever of PPO-2 was in the middle position when the transfer of control occurred, and the engine fuel shutoff valve was commanded to close when control was transferred to PPO-2. NTSB investigators later confirmed, through a review of parameters recorded during the event, that the condition lever of PPO-2 was in the fuel cutoff position when the switch from PPO-1 to PPO-2 occurred. Thus, fuel to the UA's engine was cut off, and its engine stopped operating.

Findings in the Nogales investigation and information about the similar aforementioned U.S. Coast Guard event demonstrate that the current design of the control consoles and in particular the dual functions assigned to a single lever can cause an unsafe condition that can result in an unintended engine shutdown if proper procedures are not followed. As a result, the NTSB recommended to the CBP that should require a modification to the UAS to ensure that inadvertent engine shutdowns do not occur.

Visual and Aural Alerting System

The Nogales accident pilot stated that, after switching to the PPO-2 console, he noticed that the UA was not maintaining altitude, but he did not know why. The investigation revealed that although engine data and fault annunciations are normally displayed on the PPO-1 and PPO-2 consoles, a significant amount of information is presented, including several highlighted warnings other than engine performance data, that is not prioritized; therefore, it may be difficult to sort information quickly in an emergency situation. Adding to this difficulty is the absence of a unique aural annunciation associated with an engine-out indication; only one tone is used to signal all fault conditions. Without an obvious indication of the engine-out condition, the pilot was unable to quickly evaluate the situation and recognize that the fuel had been cut off.

The pilot also stated that it was difficult for him to assess if PPO-2 was also locked up, most likely because its head-up display was blank and control inputs to the UA were not readily apparent on the overhead tracking display. Post-accident evaluation of the telemetry data indicated that the PPO-2 console was not locked up and that, if the pilot had been able to quickly diagnose the engine failure, he should have been able to restart the engine.

The reasons for console lockups are varied, and, when a lockup occurs, the cues may not be readily apparent to the pilot. The system does not diagnose the nature, cause or extent of a lockup and does not display a fault message to the pilot. Similar to a personal computer that slows down and freezes, the system leaves the user unaware of the extent of the problem or what functions are affected. In the event of a lockup, the pilot may become aware of the problem because some parameters are not updating as frequently as expected or because all visual cues may freeze. The pilot may lose some or all situational awareness of the aircraft. Furthermore, as previously mentioned, the system does not adequately prioritize fault warnings to facilitate identification during an emergency situation. As a result, the NTSB concluded that the accident UAS lacked adequate visual and aural indications for safety-critical fault conditions, such as an engine-out condition or console lockup. Therefore, they recommended that the CBP require modification to the UAS to provide adequate visual and aural indications of safety-critical faults, such as engine-out conditions and console lockups, and present them in order of priority, based on the urgency for pilot awareness and response.

Loss of Essential Electrical Power

The NTSB investigation revealed that, after the console lockup and transfer of control to PPO-2, the engine shut down and the UA's functionality degraded quickly as it began to operate on battery power. On battery power, the UA automatically shuts down some systems to conserve electrical power. The UA shut down several functions, including the satellite communication system and the transponder. At that point, the pilot likely had a blank head-up display screen on PPO-2 and no visual cues to determine if he could control the UA from PPO-2. He initiated a procedure to send the UA to its lost-link mission profile.

Analysis of recorded telemetry and radar data showed that the UA began flying the lost-link mission profile. However, with no engine power, the UA continued to descend below line-of-sight (LOS) communications, and further attempts to re-establish the data link with the UA were not successful. In addition, having shed electrical power to its transponder as a result of the loss of engine power, the aircraft could no longer be tracked by Air Traffic Control (ATC). As a result of these findings, the NTSB recommended that the CPB require that the UAS be modified to ensure that the transponder continues to provide beacon code and altitude information to ATC even if an engine shuts down in flight and that the pilot is provided a clear indication if transponder function is lost. Also, the NTSB recommended that the CBP review all UAS functions and require necessary design changes to CPB's UASs to ensure that electrical power is available for an appropriate amount of time to all systems essential to UA control following loss of engine power.

Engine Restart Capability

Although the UAS is programmed to control certain functions without pilot-initiated commands, it is not programmed to autonomously control the position of the fuel shutoff valve and enable selfinitiated engine restart after an inadvertent engine shutdown, entry into the lost-link mission profile and descent below LOS control, such as occurred in this case. If the UA engine shuts down while operating in an area where LOS control is lost, there is inadequate redundancy to restart the engine. Therefore, the NTSB recommended that the CBP should develop a means of restarting the UA engine during the lost-link emergency mission profile that does not rely on LOS control, for example, through an autonomous capability in the UAS's control system or through use of control functions enabled via a backup satellite communication system available to the pilot on the ground.

UA Maintenance, Troubleshooting and Minimum Equipment Lists

A review of UAS maintenance processes and records in the Nogales accident revealed several deficiencies, some of which were a factor in this accident. The first link in the chain of events that led to the accident involved a fault in the GCS, which caused PPO-1 to lock up. Review of a computer logbook kept in the GCS showed 9 lockups in a three-month period before the accident, including two lockups on the day of the accident before takeoff and another lockup six days before the accident. Review of a maintenance logbook revealed no entries describing any corrective action to address the control console lockup that occurred six days earlier. The operator accepted the repeated console lockups as routine, correcting the fault by cycling power to the system, without identifying the source of the lockups or rectifying the problems before further flight.

Because the source of the lockup events had not been traced to any particular component or element in the system, the full effect that lockups could have on the UAS's function was likely not fully understood. The failure to eliminate repetitive lockups invited the possibility of a more severe consequence to UA operation. Further, although system redundancy was provided by the ability to manually switch to backup systems, such as the PPO-2 console or the mobile GCS, continued reliance on backup systems to mitigate repeated failures reduces safety margins, diminishes the functional capability of the UAS and, in some cases, may increase pilot workload.

Investigators also noted that there did not appear to be any process by which the UAS could be functionally tested and returned to service in a reliable manner. Typically, complex systems require in-depth troubleshooting, repair and verification procedures for return to service. Neither the CPB nor its contractors had a documented maintenance program that ensured that maintenance tasks were performed correctly and that comprehensive root-cause analyses and corrective action procedures were required when failures, such as console lockups, occurred repeatedly. As a result, maintenance actions could not be relied upon to be effective or repeatable, which is a critical factor in ensuring airworthiness. Therefore, the NTSB recommended that the CBP identify and correct the causes of the console lockups, and that they implement a documented maintenance and inspection program that identifies, tracks and resolves the root cause of systemic deficiencies and that includes steps for in-depth troubleshooting, repair and verification of functionality before returning aircraft to service.

The investigation also revealed that the CBP lacked a plan to manage the potential risks associated with operating a UAS with inoperative components. The CBP's system lacked a minimum equipment list (MEL) and dispatch deviations guide that could have been used to determine if an acceptable level of safety or reliability had been achieved for the flight. An MEL and dispatch deviations program would provide a standardized process to guide maintenance personnel to determine if a UA should be dispatched with an inoperative component. MELs and dispatch deviation guides also prevent aircraft with certain inoperative components to fly without alternate plans to safely and reliably complete a mission. Without such specific guidance, UAs may be dispatched with known inoperative components, which could lead to accidents, especially if other critical components fail unexpectedly in flight.

The development of an MEL and dispatch deviation guide would also help to define spare-parts requirements. The NTSB investigation discovered that spare parts were virtually nonexistent at the UAS facility. Although neither the lack of a MEL nor the lack of spare parts was a factor in this accident, these findings highlight a weakness in the operation of the UAS. Therefore, the NTSB recommended that CBP develop MELs and dispatch deviation guides for its UAS operations, and also assess the spare-parts requirements for its UAS operations to ensure the availability of parts critical to UA launch, as defined by the MEL requirements.

Air Traffic Control Issues

While it may be relatively easy to identify and mitigate hazards related to UA hardware, much more difficult to assess and correct are the hazards associated with the integration of UAs into a country's regulated airspace through ATC.

During the Nogales investigation, and again during forum discussions, the NTSB discovered that most air traffic controllers are not fully aware of all UAS applications, their effects on the NAS, their integration into the NAS or ways to mitigate UAS-associated risks. Standardized procedures for normal situations — and abnormal ones such as for lost-link operations — will help all involved, including air traffic controllers, UAS pilots and manned-aircraft pilots, to anticipate UAS performance. In the United States, the FAA is developing procedures and training for its air traffic controllers on how to work with and manage UASs.

In the NTSB's investigation of the Nogales UA accident, the following ATC deficiencies were noted.

Unmanned Aircraft System Lost-Link Mission Profile

In the event of a lost data link between a GCS and UA, the accident UA was designed and programmed to fly a flight path known as the lost-link mission profile, which was a predetermined autonomous flight path, until the GCS operation could be restored and LOS data link transmissions can be reestablished.

The NTSB found that the lost-link procedure only provided for the UA to crash along the lost-link route. NTSB recommended that future lost-link procedures should include provisions for the UA to proceed to a safe zone for a crash landing. Proper training of UA pilots on use of lost-link profiles during operation and a thorough review of the procedures for developing lost-link mission profiles would minimize the potential hazards to people on the ground and maximize the chances of recovering the data link.

Lost Transponder

As previously mentioned, the transponder was not operating on the accident flight following the loss of electrical power. The transponder is vitally important to ATC because it provides an enhanced electronic signature, an identification code and altitude information presented on the controller's radar display. During a lost-link event with an operating transponder, ATC would be able to track the UA, confirm that the UA was proceeding autonomously to predetermined points, continue to ensure separation from other aircraft, and, if required, assist with the search for a missing UA. Without the transponder or primary radar returns, ATC was unable to track the aircraft or provide assistance.

An operating transponder on a UA provides critical safety information. Unlike manned aircraft, the UA does not have a human backup to provide such information in the event of a failed transponder. Therefore, the NTSB recommended that the FAA require that UA transponders provide beacon code and altitude information to ATC and to aircraft equipped with Traffic-Alert and Collision Avoidance Systems at all times while airborne by ensuring that the transponder is powered by the emergency or battery bus.

Coordination with Air Traffic Control

In the United States, operators of aircraft are required to coordinate with ATC to ensure separation of aircraft operating in the NAS while flying in controlled airspace under instrument conditions. Thus, the pilot, while piloting the UA, was required to coordinate with ATC to minimize the risk of collision. The UA was authorized to operate in temporarily restricted airspace. Other aircraft were required to contact ATC before operating in this airspace. In this accident, the UA could not maintain altitude, breached the lower limit of the restricted airspace and was operating autonomously in unprotected airspace until it glided to the ground. The ATC transcript revealed that ATC contacted the pilot after it lost contact with the UA and after the UA transponder stopped working following engine shutdown. The pilot did not indicate that the UA had descended below the temporarily restricted airspace altitude.

At that point, the pilot or ATC should have declared an emergency to initiate better surveillance of the UA, if possible, and ATC advisories to other aircraft at risk for a collision. Had an emergency been declared, controllers in adjacent facilities and pilots operating in the area would be alert to a missing aircraft and vigilant in helping to locate it. Moreover, any changes to the lost-link profiles developed by the CBP and contained in the COA were supposed to have been shared with the FAA and ATC to allow coordination between the operator and ATC in the event of a lost-link emergency. However, the investigation revealed that the CBP had changed the profiles contained in the COA but did not share these revisions with ATC.

The NTSB concluded that the lack of advance planning between the CBP and ATC to define responsibilities in the event of a UAS emergency creates a hazard for users of the NAS. Although there was no in-flight collision and no one on the ground was injured in this accident, there is concern about the potential for loss of life or more extensive property damage stemming from such hazards. Therefore, the NTSB recommended that the CBP participate in periodic operational reviews between the UAS operations team and local ATC facilities, with specific emphasis on face-to face coordination between the working-level controller and UA pilot(s), to clearly define responsibilities and actions required for standard and nonstandard UA operations. The NTSB stated that these operational reviews should include, but not be limited to, discussion of lost-link profiles and procedures, the potential for unique emergency situations and methods to mitigate them, platform-specific aircraft characteristics and airspace management procedures.

Recurring Operational Reviews of Nonstandard Operations

Interviews with air traffic controllers indicated a lack of awareness of the UA's lost-link profile. The lost-link profile was defined in the COA. It specified that the UA was to proceed to a predetermined location and hold until the link was re-established. ATC personnel indicated that previous UA lost-link occurrences resulted in the UA autonomously returning to the departure airport; in some of those cases, controllers were not aware that the UA had been recovered at the departure airport until the UA pilot advised them. For the accident flight, the lost-link profile did not include a return to the departure airport, nor did it match the profile defined in the FAA COA.

The air traffic controller could have declared an emergency once he knew that the aircraft was in distress and no longer under the UA pilot's control. Although the controller stated that he considered this an emergency, he had never declared an emergency as long as he had been a controller. He left that up to his supervisor. His supervisor expected the UA to return autonomously to the departure airport and, about 45 minutes after the link was lost, expected to hear from the UA pilot that the UA had landed, as had occurred in similar situations in the past. After 45 minutes passed, the supervisor did not know how to handle the situation. Monitoring UAs is a new ATC responsibility that presents new challenges.

During the lost-link descent, the UA did not fly in accordance with any flight track that ATC had become accustomed to or with the flight track specified in the FAA COA or any other previously known to the ATC. This meant the possibility of an autonomous UA with a maximum gross weight of 10,000 pounds, a ceiling potential of 50,000 feet mean sea level, potential airspeed of 220 knots and an overall flight duration capability in excess of 30 hours in the NAS without ATC knowing where it was or where it might end up. Clearly, this created a potential hazard to other users of the NAS and people and property on the ground.

Given the likelihood of increased UAS operations worldwide, it is critical that UA operators be familiar with ATC procedures and that ATC be familiar with UAS procedures and related system capabilities. Controllers especially need to know how UASs and related systems affect ATC services. Accordingly, the NTSB recommended that the FAA require the periodic operational reviews that the NTSB asked the CFB to hold between the UAS operations teams and local ATC facilities.

Requirements and Considerations for Pilots of UAs

The participants in the NTSB UAS Safety Forum agreed that UAS pilots' certification should require them to have knowledge of the airspace consistent with an operation's intended scope. Additionally, early human systems integration in the UAS design process could reduce the opportunities for design-induced human error and ideally would draw from existing design standards and knowledge about human factors learned from manned aviation.

Nancy Cooke[10] provided this list of UA pilot training and certification issues and research questions:

- ✈ Determine knowledge, skills and abilities necessary for UAS operation.
- ✈ Identify common ground across services, platforms, airspace and mission
- ✈ Identify most effective training method or hybrid of methods
- ✈ Determine empirically whether manned flight experience is a necessary prerequisite to UAS training, and if so, the type and extent of ground school/ flight training necessary
- ✈ Determine value of prior experience operating remote-controlled airplanes
- ✈ Determine importance of video gaming experience
- ✈ How should performance be assessed?
- ✈ How instructors should be trained?

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[10] Nancy J. Cooke, Ph.D., Arizona State University and Cognitive Engineering Research Institute

- ✈ What distinguishes competency from expertise?

The NTSB UA accident investigation showed the importance of addressing these questions and developing more effective training for UA pilots.

During the accident investigation, the CBP's training records showed that the accident pilot was experienced in flying Predator A UAs, having flown 519 hours; however, he had logged only 27 hours in a Predator B UA. This is significant because the Predator B has a different engine and more complex engine controls than the Predator A. For example, the control console for the Predator A does not have a condition lever, and it was the positioning of this lever which caused the engine to be inadvertently shut down in this accident.

The NTSB's investigation revealed that the CBP's pilot experience requirements were general: 200 manned aircraft hours and 200 hours of UAS time. No model-specific flight time requirements exist for UASs. A syllabus from the accident pilot's training referenced emergency procedures, but neither the syllabus nor the pilot's flying training record specified which emergency procedures were reviewed or practiced.

As previously discussed, the pilot did not correctly transfer control from the PPO-1 console to the PPO-2 console. In addition, the COA outlined operational procedures to notify and coordinate with ATC in response to an emergency. The investigation found that the pilot did not perform many of the defined actions. Based on the accident pilot's response to the emergency, the NTSB concluded that the pilot was not proficient in the performance of emergency procedures.

Human Factors Issues

During the NTSB's UAS Safety Forum, an interesting statistic was presented: 33 to 43 percent of all UA mishaps were caused by human factors issues.[11] It was noted[12] that one of the main human factors issues for UA operations involves the fact that the pilot's perception occurs through sensor displays, rather than his or her own physical experience. It was noted that the visual experience of a UA pilot is like "looking at the world through a soda straw," with no motion or tactile feedback. There are also significant delays in vehicle response to the controls. As a result, the following difficulties occur:

- ✈ Landing difficulties (example: Predator nose-mounted flight camera is not on a gimbal, so the pilot loses sight of the runway until the UA lands)
- ✈ Limited ability to perceive weather changes
- ✈ See-and-avoid difficulties
- ✈ No "seat-of-the-pants" flying
- ✈ Loss of situation awareness, spatial disorientation

Displays and systems used in UASs that compensate for UAS pilots' lack of sensory input would help pilots detect anomalous events affecting safety of flight in a timely manner. Research is ongoing in these areas and is greatly needed.

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[11] Schmidt, J. & Parker, R. (1995). *Development of a UAV mishap factors database.* Proceedings of the 1995 Association for Autonomous Vehicle Systems International Symposium, 310-315.
[12] Nancy J. Cooke, Ph.D., Arizona State University and Cognitive Engineering Research Institute.

Additionally, as forum participants highlighted, UAS operations typically involve teams, so efforts to ensure clear communication and effective coordination would decrease the opportunity for human error.

Finally, like manned operations, fatigue management systems are important in UAS operations. UAS operators often work long shifts and experience environmental stressors. They also can be challenged by high workload, vigilance tasks, interruption of circadian rhythms and lack of sleep. These challenges are often greater for UA pilots than manned aircraft pilots because of the unique missions of UAs and because one pilot typically controls numerous UAs as required.

Unmanned Aircraft System Safety Risk Management

During its investigation, the NTSB evaluated the CBP's safety control plans, which include equipment design features, operational procedures, pilot training and proficiency, and maintenance. Overall, investigators found that, although the CBP had implemented some operational safety controls, these controls did not prevent a console lockup from leading to an accident. Also, given the frequency of Predator B UAS console lockups, the occurrence of the two lockup-induced engine shutdowns, and previously noted deficiencies with the system's human interface, the NTSB expressed concern that a single pilot may not be able to ensure safe operation of the UAS.

For example, flight testing of remotely piloted vehicles at various flight test ranges commonly requires two pilots, a range safety officer and a flight safety officer. Although UA operations such as those conducted by the CBP are generally routine and a single pilot may be able to adequately manage the routine operations, an emergency or unusual operational situation may quickly overload a single pilot, as was demonstrated in this accident. Therefore, the NTSB recommended that the CBP require that a backup pilot or another person who can provide an equivalent level of safety as a backup pilot be readily available during the operation of a UAS.

Tracking and Analyzing Unmanned Aircraft Incidents and Events That Affect Safety

UAS operation is an evolving activity. The FAA informed NTSB staff that public-use UAS operations in the United States have more than doubled over the past year. All public-use aircraft operations (both manned and unmanned) are exempt from certain aviation safety regulations, and, therefore, operators supervise their own flight operations without oversight from the FAA.

In the case of the Nogales investigation, the FAA COA included a set of requirements under which the CBP should operate its Predator B UAS. Many of these requirements, such as requiring the aircraft to be equipped with a transponder and restricting flight over populated or congested areas, were aimed at controlling the risk of a midair collision with other users in the NAS or of injury or damage to people or property on the ground. These requirements, combined with existing FAA ATC procedures, policies and requirements for air traffic management of manned aircraft, provide additional controls to ensure the safety of the NAS during UAS operations. Ensuring that all of these safety controls are being properly executed is fundamental to an effective safety management system and is critical in preventing future accidents.

In manned aircraft operations, tracking and analyzing operational failures and malfunctions of aircraft or ground systems has provided valuable insight into and has improved the effectiveness of both design and operational safety controls; it also has aided in the discovery of root causes for accidents. For example, FAA and NTSB investigators frequently use service difficulty reports to evaluate the frequency and effects of safety-related equipment failures. Likewise, safety feedback systems, such as aviation safety action programs, provide objective data used to evaluate the effectiveness of operational safety controls, such as training, procedures and checklists. At the time of this accident, the FAA did not require the CBP to provide reports of or analyze significant operational safety incidents or malfunctions involving Predator B operations.

The GCS lockups uncovered during the Nogales accident investigation represented a potential safety concern because they could result in the momentary loss of control of a UA. However, despite the repeated lockup events, the CBP continued to fly the UA without identifying the root cause of the lockups or analyzing whether these events could lead to flights out of the approved operating area of the NAS. The NTSB concluded that data-tracking and analysis programs for UAs could help identify deficiencies in the safety control plans or their implementation before they lead to an accident. NTSB also concluded that periodic review and analysis of these data by the UA operator, whether government or civilian, with oversight by the FAA, is critical to ensure that safety controls for UAS operations work as intended and to ensure that UA operators and ATC take timely corrective action when the controls are shown to be ineffective.

Effective events monitoring is critical, given the increase in UAS operations in the NAS and the future likelihood of their direct integration with manned aircraft throughout the NAS. In fact, the absence of a proven track record for UAS operations in the NAS reinforces the need to collect operational data to verify the adequacy and effectiveness of planned safety controls. NTSB believes that now, while operations are conducted only in sparsely populated locations, is the time to build critical knowledge on how to safely operate UASs in the NAS; and, a program for monitoring safety assurance is imperative to achieve that end. Therefore, the NTSB recommended that the FAA require that all UAS operators report to the FAA, in writing within 30 days of occurrence, all incidents and malfunctions that affect safety, and further require that operators are analyzing these data in an effort to improve safety; and evaluate these data to determine whether programs and procedures, including those under ATC, remain effective in mitigating safety risks.

Aircraft Accident and Incident Definitions, Notification and Reporting

In the Nogales investigation, it was discovered that air traffic controllers and managers did not believe the event qualified as an aircraft accident because, as with all UASs, no one boarded the aircraft. According to Annex 13 to the Convention on International Civil Aviation (ICAO), *Aircraft Accident and Incident Investigation*, Chapter 1, “Definitions,” an aircraft accident is “an occurrence associated with the operation of an aircraft which takes place between the time any person boards the aircraft with the intention of flight until such time as all such persons have disembarked.” The NTSB’s rules at 49 Code of Federal Regulations (CFR) 830.2, “Definitions,” similarly define an aircraft accident as “an occurrence associated with the operation of an aircraft which takes place between the time any person boards the aircraft with the intention of flight and all such persons have disembarked, and in which any person suffers death or serious injury, or in which the aircraft receives substantial damage.”

The existence of UASs clearly was not contemplated when these definitions of “accident” were developed. The definitions must, therefore, be updated and formal guidance for handling UAS accidents must be developed. Efforts are ongoing to address the definition of aircraft accident in ICAO Annex 13 and 49 CFR 830.2.[13] Meanwhile, the NTSB recommended that the FAA should require that established procedures for handling piloted aircraft emergencies be applied to UASs.

[13] On March 31, 2008, a U.S. government “Notice of Proposed Rulemaking” (NPRM) was published for public comment regarding a proposal to modify the NTSB’s definition of a reportable accident. The NPRM can be found in the U.S. Federal Register, Volume 73, number 62, page 16826.

Recording of Communications Between UA Pilots and Air Traffic Controllers, Other UA Pilots, and Other Assets

Aviation safety investigators have long recognized the value of cockpit voice recorders (CVR) and recordings of ATC radio communications to accurately determine the facts of an accident or incident and have used that information to improve the safety of aircraft operations. During the investigation of the Arizona UA accident, investigators found that routine radio communications between the UA pilot and ATC controllers were recorded by ATC and did provide valuable information. However, after radar contact was lost and the search for the UA ensued, additional communications by the UA pilot with ATC and other assets involved in supporting the UA operation were conducted by telephone. The telephone conversations were not recorded. The lack of such recordings hampered the investigation because investigators could not evaluate the effectiveness of critical communications between the UA pilot, air traffic controllers and other assets.

Further, the communications between UA pilot(s) and other personnel within the GCS were not recorded. The value of recording conversations between pilots in a cockpit is well known. Recorded conversations between a UA pilot at the GCS and other operational support personnel would also be of value. A CVR or similar technology in the GCS would enable more complete post-accident and post-incident evaluation and reconstruction. Therefore, the NTSB recommended a requirement that all conversations, including telephone conversations, between UA pilots and ATC, other UA pilots, and other assets that provide operational support to UAS operations, be recorded and retained.

Summary of NTSB Recommendations from the Nogales Accident

- ✈ UA manufacturers should ensure that inadvertent engine shutdowns do not occur.
- ✈ UA manufacturers should provide adequate visual and aural indications of safety-critical faults, such as engine-out conditions and console lockups, and present them in order of priority, based on the urgency for pilot awareness and response.
- ✈ UAS operators' methods of developing lost-link mission profiles should ensure that lost-link mission profile routes minimize the potential safety impact to persons on the ground, optimize the ability to recover the data link and, in the absence of data-link recovery, provide the capability to proceed to a safe zone for a crash landing.
- ✈ Pilots of UAs should be trained concerning the expected performance and flight path of the unmanned aircraft during a lost-link mission.
- ✈ The transponder of a UA should continue to provide beacon code and altitude information to air traffic control even if an engine shuts down in flight and that the pilot is provided a clear indication if transponder function is lost for any reason.
- ✈ UAS functions that require necessary design changes should be reviewed to ensure that electrical power is available for an appropriate amount of time to all systems essential to unmanned aircraft control following loss of engine power.

- ✈ A means of restarting a UA engine during the lost-link emergency mission profile should be required that does not rely on line-of-sight control, for example, through an autonomous capability in the UAS control system or through use of control functions enabled via a backup satellite communication system.
- ✈ Participate in periodic operational reviews between the UAS operations team and local air traffic control facilities, with specific emphasis on face-to-face coordination between the working-level controller and pilots, to clearly define responsibilities and actions required for standard and nonstandard UA operations.
- ✈ All conversations, including telephone conversations, between unmanned aircraft (UA) pilots and air traffic control, other UA pilots, and other assets that provide operational support to UA operations, should be recorded and retained to support accident investigations.
- ✈ Identify and correct the causes of GCU console lockups.
- ✈ Ensure the implementation of a documented maintenance and inspection program that identifies, tracks and resolves the root cause of systemic deficiencies and that includes steps for in-depth troubleshooting, repair and verification of functionality before returning aircraft to service.
- ✈ Aviation engineering and maintenance experts should oversee the definition of maintenance tasks, establishment of inspection criteria, and the implementation of such programs. Also, ensure oversight of contractor(s) implementing such programs.

- ✈ Minimum equipment lists and dispatch deviation guides should be developed for UAS operations.
- ✈ UA pilot training programs should ensure pilot proficiency in executing emergency procedures.
- ✈ A backup UA pilot or another person who can provide an equivalent level of safety as a backup pilot should be readily available during the operation of a UAS.
- ✈ A safety plan should be developed which ensures that hazards to users of the airspace and persons on the ground introduced by UAS operations are identified and that necessary actions are taken to mitigate the corresponding safety risks to the public over the life of the program. The plan should include, as a minimum, design requirements, emergency procedures and maintenance program requirements to minimize the safety impact of UAS malfunctions in flight, continuous monitoring of the UAS operation, analysis of malfunctions and incidents, and lessons learned from other operators of similar UAS designs.
- ✈ Established procedures for handling piloted aircraft emergencies should be applied to UAS operations.
- ✈ UAS operators should report to the airworthiness authority, in writing within 30 days of occurrence, all incidents and malfunctions that affect safety; require that operators are analyzing these data in an effort to improve safety; and evaluate these data to determine whether programs and procedures, including those under air traffic control, remain effective in mitigating safety risks.

Conclusion

Integrating UASs within the existing safety framework for a nation's airspace, without imposing new airspace restrictions on other users, is ideal. The goal for UAS equipment and operations is to live up to the high standards for certification, pilot qualification and training set for manned applications. Given the lack of UAS equipment certification standards and the inability for UAs to see and avoid other traffic, planned UAS operations should undergo a detailed safety risk assessment before flying to consider the potential hazards that they may introduce to people flying in the airspace and on the ground. The safety risk assessment is also needed when the UA is flying above and below altitudes normally used by airline operations.

UAS operations can be integrated more effectively when stakeholders who manage the operation, such as air traffic controllers and airspace users, communicate early and often during the planning stage. Hazard analyses performed first by UAS manufacturers during the system design phase, then by operators using the systems, are critical to identifying and managing safety risks. The results of these analyses will affect system design, the mission plan and rules, and contingency plans and form the basis for determining flight readiness. An operational risk assessment can be used to help determine how to safely conduct UAS operations in a nation's shared airspace and is especially beneficial when conducting operations with UASs designed for military purposes. In addition, the use of data tracking and analysis programs to continually evaluate the efficacy of the existing safety management controls, up to and including an accident and incident investigation protocol, is a necessary step to achieve safe operation of UAS in civil airspace.

Efforts to ensure UAS safety should not be delayed. Unmanned aircraft are critical to many missions and interests. Regulatory bodies, militaries, UAS manufacturers and all airspace users should work together so that the necessary expertise and logistical resources are made available to integrate UAS into the world's airspace in a reasonable timeframe—and without compromising safety.

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