Remotely Piloted Aircraft Systems

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1. INTRODUCTION

Remotely piloted (or unmanned) aircraft are rapidly emerging as a new sector of civil aviation. As regulatory agencies work to integrate these aircraft into the existing aviation system, they must contend with a unique set of human factors that are not yet fully identified or understood.

These aircraft are sometimes referred to as drones, uninhabited aircraft, or unmanned aerial vehicles (UAVs). Throughout this chapter, the terminology of the International Civil Aviation Organization (2015) will be used. The term "remotely piloted aircraft" (RPA) will be used to refer to the aircraft, in both the singular and plural. The term "remotely piloted aircraft system" (RPAS) will be used when the intent is to refer to the entire system, comprising the aircraft, its control station, communication links and other elements. The workstation of the remote pilot will be referred to as the "remote pilot station" (RPS) or control station.

Any discussion of RPAS is complicated by the diversity of the sector and the rapid rate at which it is developing. RPA range from micro air vehicles the size of insects, to large jet aircraft such as the Global Hawk. In between are electric rotorcraft, numerous fixed-wing aircraft, and balloons that can remain aloft for extended periods, climbing and descending as necessary to take advantage of prevailing winds. To further complicate matters, many RPAS include features not typical of conventional aviation, such as catapult launch systems, electric engines, and solar cells (see Figure 1).

Figure 1. Three examples of remotely piloted aircraft. (1) The 18 kg, catapult-launched Insitu ScanEagle; (2) 6,700 kg High Altitude Long Endurance (HALE) Global Hawk; (3) AeroVironment Helios Prototype, a solar powered flying wing designed for long-duration, high-altitude missions in the stratosphere.

Much of the recent growth of this sector has involved small electric rotorcraft used for aerial photography, site surveys, and inspections of buildings and infrastructure (Association for Unmanned Vehicle Systems International, 2016). The FAA (2016) has released regulations that allow lightweight RPA to be flown near the ground within sight of the pilot. Currently, however, no regulations are in place to allow larger, more capable RPA to routinely fly beyond pilot line-of-sight, in airspace shared with conventional aircraft. This chapter focuses on the human challenges that must be addressed before these RPA can be fully integrated into the civil airspace system[1].

The potential uses of these aircraft include pipeline and rail track inspection, police and firefighting, mineral exploration, agriculture, mapping, wildfire monitoring, and environmental research. Long-endurance fixed-wing systems and free balloons have potential as High Altitude Platforms (HAPs) for telecommunications or remote sensing tasks that might otherwise have required a satellite. In the not-too-distant future, converted airline aircraft may operate as unmanned freighters (Smith, 2010).

Despite the diversity of designs and missions, all RPAS have features in common, notably the physical separation of the pilot from the aircraft, control via radio signals, and a remote control interface. These characteristics, in turn, introduce a set of human factors that are not typical of conventional aviation, some of which have not yet been the focus of extensive research. A key objective of this chapter is to raise questions and identify areas in need of research.

2. HUMAN FACTORS OF REMOTELY PILOTED AIRCRAFT SYSTEMS

RPA have experienced a significantly higher accident rate than conventionally piloted aircraft. In the early 2000s, accident rates for some RPA were between 30 and 300 times higher than the comparable rate for general aviation (Tvaryanas, Thompson, & Constable, 2006). In the years 2006-2010, MQ-9 RPA operated by US Customs and Border Protection had an accident rate of 53 per 100,000 hours, although this figure must be interpreted with caution as it was based on a relatively small total of flying hours (Kalinowski & Allen, 2010). The US Army has reported an accident rate of 49.3 per 100,000 flying hours for its RPA, compared with 4.4 for its manned aircraft. The army acknowledges, however, that the rate for RPA may be a low estimate due to significant underreporting of RPA mishaps (Prather, 2013). Statistics for accidents in

[1] The FAA (2013) has stated that future integration of RPA into civil airspace will require that each RPA be under the control of a pilot who will comply with all ATC instructions, no pilot will control more than one RPA at a time, RPA will be capable of flight under instrument flight rules, and autonomous operations will not be permitted.

which the aircraft is destroyed enable more reliable comparisons to be made between RPA and manned aircraft as there is less potential for under-reporting or differences in definitions. In 2015, the most recent year for which data are available, MQ-9 operated by the US Air Force (USAF) were destroyed at the rate of 4.0 per 100,000 hours flown. This is a significant improvement over earlier years, yet is still markedly higher than the figure for the USAF's manned aircraft, which were destroyed in accidents at the rate of 0.41 per 100,000 flying hours (USAF, 2015).

The higher accident rate for RPA can be partly explained by technological factors such as the use of non-certificated components and a lack of system redundancy. However, inadequate consideration of human factors by system designers has also contributed to the accident record (Tvaryanas, 2004; Williams, 2004).

The following sections contain an overview of the human challenges of remotely piloted aircraft, with a focus on the points of difference between this sector and conventional aviation. The illustrative quotes throughout the text are from remote pilots who participated in focus groups conducted by Hobbs, Cardoza, and Null (2016). Pilots were asked to recall a hazardous event or error that had occurred when operating an RPA. As well as revealing human-system integration challenges, their reports also illustrate the positive contribution that humans make to the performance of highly-automated, remotely operated systems.

2.1. Reduced sensory cues

Lacking the ability to hear the sound of hail on the fuselage, smell an onboard fire, feel turbulence, or notice ice accumulating on a windshield, the remote pilot relies almost entirely on visual displays to monitor the state of the aircraft. Even when the RPA is equipped with a camera, the image quality may be limited, and the field of view may be reduced to a narrow "soda straw" picture.

The sensory isolation of the remote pilot may make it more difficult to identify and recover from threats and errors, a function that is performed routinely by the pilot of a manned aircraft (Helmreich, 2000). For example, one remote pilot was apparently unaware that the aircraft was flying upside down shortly before it crashed (Whitlock, 2014). In many cases, these displays present data in textual form, which may further impede the flow of information to the pilot. In the following example, the pilot was unaware that the RPA had a stuck throttle until it failed to level off:

> "We fly based on digital gauges. We don't hear or feel anything, like RPM changes …. The aircraft is supposed to level off, at say, 5,000', and there is a delay due to data link to know if it actually leveled off. … As opposed to a real aircraft [where] you can feel the airplane leveling off, I couldn't determine if it was still climbing until I noticed it was 300' past its command altitude."

A solution may be to provide the remote pilot with a greater variety of sensory inputs, including haptic or aural cues (Arrabito et al., 2013; Giang & Burns, 2012) and graphical displays (e.g., Kaliardos & Lyall, 2015; McCarley & Wickens, 2005). Research is needed to identify the sensory cues that will be most useful to the remote pilot, and then to make the case that the benefits would justify the added cost and complexity.

2.2 Control via radio link

Unlike the mechanical control cables or fly-by-wire systems of a conventional aircraft, the RPAS fly-by-wireless control link introduces control latencies and the possibility of complete interruption in some circumstances. RPAS technology and pilot procedures must each be designed to accommodate these limitations. Figure 2 shows the elements of a typical RPAS, including the RPA, the control station, and the communication links. Two distinct links are shown: a ground-based link that is used when the RPA is operating within line-of-sight of a ground antenna, and a satellite link that provides communication over greater distances.

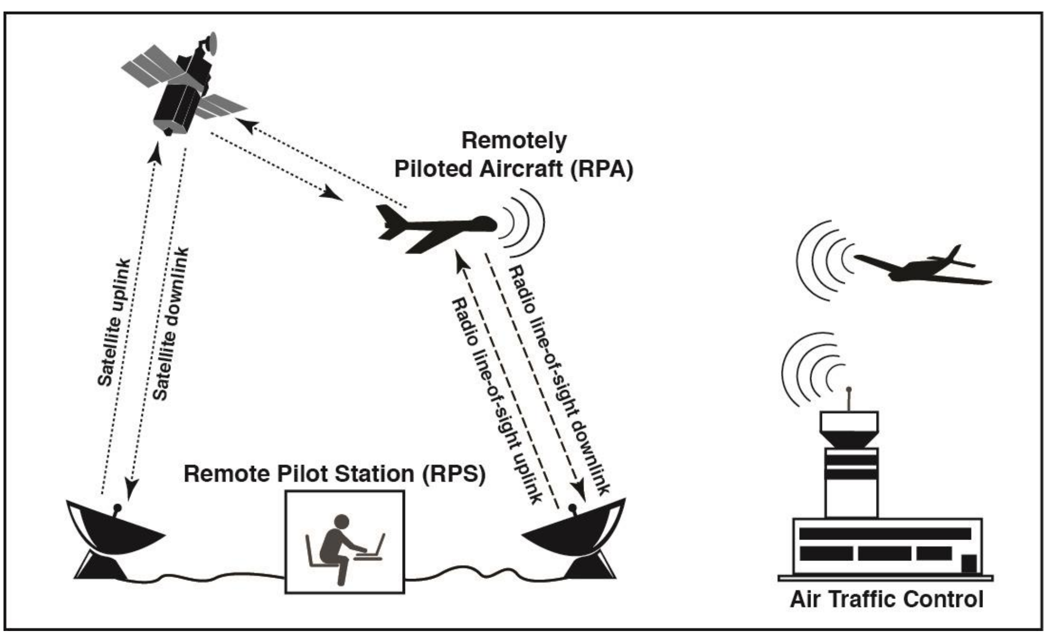

Figure 2. The Remotely Piloted Aircraft System (RPAS) consists of the Remotely Piloted Aircraft (RPA), the Remote Pilot Station (RPS), and the associated communications systems.

A pilot command from the control station can take around 100 ms to be uplinked to the RPA if the signal is transmitted from a nearby ground antenna. Most of this delay is the result of signal processing at either end rather than the time it takes radio waves, traveling at the speed of light, to reach the aircraft. With an equivalent delay on the downlink, the total round-trip latency between a command and the response observed on the pilot's display can become noticeable. If control is via satellite, additional processing steps and the distance that must be traveled by the signal can produce round-trip latencies of 1000 ms or more (Tvaryanas, 2006a). Unlike a hobbyist flying a radio-controlled aircraft, whose commands are delayed on the uplink, but who can directly observe the aircraft response in real time, the RPA pilot must contend with the sum of the uplink and the downlink delays.

Tracking tasks can be impacted by command-response delays of less than 100ms. Longer delays and variable latencies increase the difficulty of these tasks even further (Wickens, 1986). An RPA that relied on continuous pilot control inputs to maintain stable flight would be difficult to control via a satellite link, and would also be unable to tolerate link interruptions. For these reasons, virtually all RPA require some level of on-board automation, and the role of the pilot becomes that of a supervisory controller rather than a human-in-the-loop manual controller.

The introduction of highly-automated airline aircraft in the 1980s led to improvements in safety and efficiency (Orlady & Orlady, 1999) but was also accompanied by new challenges as pilots transitioned to the role of managers of automated systems. Data entry errors and loss of situational awareness became areas of increasing concern, and terms such as *mode confusion*, *automation surprise*, and *automation complacency* were coined to express the emerging issues. The RPAS sector is currently experiencing some of the same problems with systems that were developed with little apparent regard for human factors principles. It remains to be seen whether remote operation via radio link will make it more difficult for the pilot to manage automated systems, possibly exacerbating the impact of clumsy automation. In the following case, the behavior of the RPA surprised the remote pilot, who was nevertheless able to intervene and recover the situation.

> "I … put the airplane into a holding pattern. …The aircraft turned in the opposite direction than what I wanted it to do. To correct the situation, I over-rode the aircraft. I had the aircraft go into the hold again and the aircraft did it again."
> [The aircraft was successfully re-directed on a second attempt].

2.2.1. Link management

In addition to managing systems on-board the aircraft, the remote pilot must also manage the control link. Before the flight commences, the pilot may be assigned control frequencies to use throughout the flight, and may be required to check that unrelated transmissions are not occurring on the assigned channels. With the control system reliant on radio signals, the standard preflight control check becomes particularly important. During flight planning the pilot must take into account the predicted strength of the link throughout the intended flight and develop a three-dimensional picture of the link strength at various altitudes and distances from an antenna located on the ground. A signal coverage map may show this information in a 2D format, typically displaying shadows where the signal will be blocked by terrain or obstructions. As the distance between the aircraft and the ground antenna increases, the aircraft may need to fly higher to maintain a link with the ground station. A link strength indicator is a critical display in the RPS, although pilots report sometimes using less precise cues, such as a “snowy” camera image to warn of an impending loss of link. There appears to be no published research examining how best to support pilot awareness of actual and predicted link status.

2.2.2. Loss of link: Implications for the remote pilot

No radio control link can be guaranteed to be 100% reliable, and there will be occasions when the link will be unavailable. A pre-programmed lost link procedure enables the RPA to continue flight in a predictable manner until the link is resumed. The procedure may involve either a simple maneuver such as climbing to re-gain a signal, or a more complex plan, such as flying to a pre-determined position. Rather than being perceived as an emergency, the activation of the lost link procedure can be seen as a response to a non-normal situation, analogous to a diversion or a go-around in a conventional aircraft.

A lost link event can consist of three stages, as shown in Figure 3. In stage 1, the link has been interrupted, but the aircraft continues to fly in accordance with the last command received from the pilot. Some link outages will last a few milliseconds (ms), whereas others may extend for minutes or even hours. It would be disruptive if the RPA started to fly its lost link procedure each time a brief link interruption occurred. Therefore, an on-board timer is needed to measure the duration of the outage, and activate the lost link procedure after a pre-set interval has elapsed. In the terminal area, the lost link procedure may need to commence after an outage of a few seconds. Elsewhere, the RPA may be able to safely continue along its planned flightpath for an extended period before entering its lost link procedure.

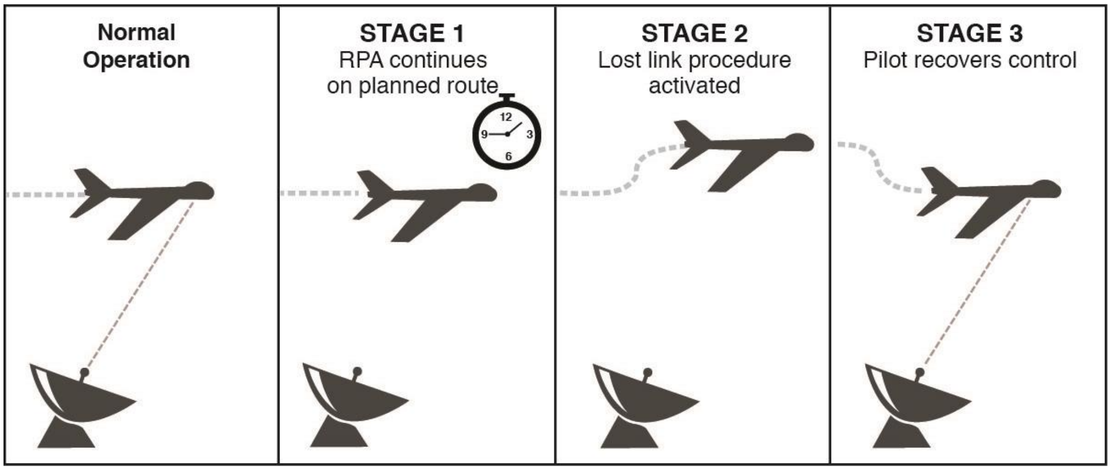

Figure 3. Stages of a lost link event.

“Nuisance” lost link events have sometimes prompted remote pilots to delay the activation of the lost link procedure, or inhibit it until the aircraft has reached a certain location. In this example, the pilot used a workaround to extend the duration of stage 1, to prevent the RPA from repeatedly turning for home:

> “The airplane … made many turnarounds due to it being out of link then … it would reacquire and … return on mission. This affected fuel burn. [So I] set time-out feature just short of the actual mission duration.”

If the aircraft will remain in stage 1 for a significant time, the pilot must be aware that each command sent to the aircraft could be the last, if a link interruption were to occur. For example, a temporary turn towards rising terrain may become irreversible if the link is interrupted before a follow-up command can be sent to the aircraft.

In stage 2 of a lost link event, the RPA’s pre-programmed lost link procedure is activated. Different lost link procedures will be appropriate according to the location of the aircraft and the stage of flight. The RPA pilot must therefore remain aware of the current lost link procedure, updating it as frequently as every 10 minutes to ensure that it has not become stale, or would not create a hazardous situation if activated (Neville, Blickensderfer, Archer, Kaste, & Luxion, 2012). In the following example, a problem with the lost link procedure was detected during a control handover:

> "At the beginning of the flight, the lost link procedure was valid, but the procedure was not updated later in the flight. At one point, had the lost link procedure been activated, it would've had the aircraft fly through terrain in an attempt to reach the next waypoint. However, the aircraft didn't lose link and the error was caught in the handover to the next set of operators."

In the third stage of the lost link sequence, the link is re-established and the aircraft transitions back to pilot control. The pilot must ensure that any control inputs made while the link was interrupted do not result in sudden changes in aircraft state when the link is reestablished. Depending upon the length of the outage, and the location and state of the aircraft, the pilot may need to evaluate whether the original flight plan can be resumed.

Loss of link can occur for a variety of technical and human reasons. The pilot of a conventional aircraft cannot accidently disconnect the cockpit from the rest of the aircraft. The remote pilot however, can make errors that will inadvertently achieve this effect. Potential human causes of lost link include flying beyond the range of the ground station, flying into an area where the signal is masked by terrain, frequency selection errors, abrupt aircraft maneuvers, physical disruptions to plugs and cables, and electronic lock-outs in which a screen lock or security system prevents access. In addition, the pilot must be alert to radio frequency interference, whether from malicious or unintentional sources. At the time of writing, the author was aware of no studies examining the human causes of lost links.

2.2.3. Loss of link: Implications for Air Traffic Control

The behavior of the aircraft in the event of a lost link must be predictable not only to the pilot, but also to air traffic control (ATC). Controllers must be able to determine how and when each RPA will respond during a lost link event. A simple programmed maneuver, such as a climb or a turn towards a specific location, may be easily included in the flight plan. However, more complex maneuvers that change throughout the flight may be more difficult to present to ATC. On occasions, common cause failures have resulted in multiple RPA losing link simultaneously (ICAO, 2015). Although this would hopefully be a rare event, it could present ATC with a complicated traffic picture.

To prevent the RPA from executing a lost link procedure that contradicts an ATC instruction received before the link interruption, there may be occasions where ATC will ask the pilot to inhibit the lost link procedure for a set time, or until the aircraft has reached a particular location. As well as a pre-assigned squawk code to indicate a lost link, ATC may need to know the time remaining until the RPA will commence its lost link maneuver. A countdown timer could conceivably be included in the aircraft's data block on the controller's scope.

2.2.4. The relay of voice communications via the control link

Voice communication between the remote pilot and ATC is typically relayed from the control station to the RPA via the command link, and then re-transmitted by an on-board radio (RTCA, 2007). In a similar way, transmissions from ATC and other pilots in the vicinity are received by the radio on board the RPA and then relayed to the remote pilot via the downlink. An advantage of this system is that the remote pilot can participate in the "party line" communications of pilots and ATC, but this may come at the cost of noticeable delays. Voice latencies can increase the likelihood of step-ons, in which two people attempt to transmit simultaneously. RPAS voice latencies are likely to be most problematic when a satellite link is involved, as illustrated by the following report:

> "There is a delay between clicking the press-to-talk and talking. This is very difficult to manage when in very busy airspace, and listening for a gap to talk. Sometimes by the time we press the talk button, with the satellite delay, the gap is gone and we step on other aircraft."

Telecommunications research has found that 250 ms one-way delays can significantly disrupt phone conversations (Kitawaki & Itoh, 1991). Consistent with this finding, FAA policy requires that communications systems deliver an average one-way delay between pilot and ATC voice communications of less than 250 ms (FAA, 2012). Several studies have examined the impact of controller voice latencies that might be introduced by future communications networks (e.g., Sollenberger et al., 2003; Zingale, McAnulty, & Kerns, 2003). These studies have generally found that one-way latencies in controller transmissions of up to 350 ms are tolerable. In a simulation study, Vu et al. (2015) found that remote pilot voice delays of 1.5 and 5 seconds produced comparable rates of step-ons; however further research is required to identify the dividing line between tolerable and disruptive voice latencies for remote pilot voice communications.

A further implication of the RPAS voice relay system is that a loss of link will not only prevent the pilot from sending commands to the RPA, but it will also interrupt voice communication at this critical time. Future communication systems are likely to solve this problem. For now, the pilot must rely on a telephone to regain communication with ATC, as described by a remote pilot:

> ‘We were constantly … talking to ATC via VHF to keep them updated and coordinated. We lost link. Then we realized that we didn’t have ATC’s phone number. We were able to finally call ATC, but it took a few minutes to find the number.”

2.3. Implications for “see and avoid”

Before RPAS can be integrated seamlessly into civil airspace, the remote pilot must have a means to “see and avoid” other aircraft whenever conditions permit (14 CFR 91.113; ICAO, 2011) and to comply with other air traffic requirements that rely on human vision. Detect and Avoid (DAA) systems for RPAS have been a major focus of recent human factors research, including work by NASA to support the development of industry standards for DAA displays (Fern, Rorie, & Shively, 2014; Rorie & Fern, 2015). Detecting and avoiding other aircraft is generally considered to consist of two related concepts, (1) remain well clear and (2) collision avoidance. To remain well clear of other aircraft, the remote pilot must maintain an awareness of surrounding traffic and make any necessary separation maneuvers before the intruder aircraft poses an imminent threat. In controlled airspace, the pilot would be expected to coordinate with ATC before maneuvering, as illustrated by the following report:

> “I was flying on a heading assigned by ATC. We have a display that shows traffic. On this display I was watching a flight block coming towards my aircraft. I realized that we were on a converging course so I queried ATC, and they had no info on it. We found the traffic through swinging the ball [pointing the on-board camera]. The pilot of the converging [aircraft] was completely oblivious to us. He was on a different frequency. I had to maneuver to avoid him.”

The rules of the air currently leave it to the pilots of conventional aircraft to judge what it means to remain well clear of other aircraft. The introduction of DAA technology requires that the term be defined precisely. An advisory committee developing standards for DAA systems has defined “well clear” as meaning that the RPA and the threat aircraft do not come within 4000 ft horizontally and 450 ft vertically when operating away from terminal areas. A time based-metric, broadly equivalent to 35 seconds to closest point of approach, is also included in the definition (RTCA, 2016).

Keeping RPA well clear of other aircraft is not only a matter of safety, but will also ensure that the addition of RPA to the civil airspace system does not cause concern for conventional pilots, that Traffic Alert and Collision Avoidance System (TCAS) alerts and resolution advisories are not triggered excessively, and that ATC workload is not increased.

Displays to assist the pilot in remaining well clear can be *informative*, *suggestive* or *directive*. An informative display provides traffic information but provides no further guidance to the pilot. A suggestive display provides the pilot with a range of possible maneuvers and may also display “no-fly” areas, leaving the pilot free to formulate a course of action. Directive displays give the pilot a single recommended maneuver to remain well clear. Directive guidance has been found to produce more rapid pilot response times than informative or suggestive displays; however the certification requirements for a directive system are too great for them to be considered a ‘minimum requirement’ (Rorie, Fern, & Shively, 2016). In simulation trials comparing informative and suggestive displays, Rorie et al. (2016) found that suggestive displays reduced the time it took the remote pilot to initiate a maneuver to remain well clear, reduced the size of the maneuver, and resulted in fewer and less severe losses of well clear.

If the RPA fails to remain well clear of traffic, it may be necessary to make a collision avoidance maneuver. The Airborne Collision Avoidance System for unmanned aircraft (ACAS Xu), currently under development, will provide a collision avoidance system specifically for RPA that will be interoperable with the TCAS of manned aircraft. Given the possibility of link outages, and the need for a rapid pilot response, it is likely that future RPA equipped with ACAS Xu will need to be capable of making an autonomous response to a resolution advisory.

Given the long-recognized limitations of the see-and-avoid principle (Hobbs, 1991), a remote pilot with a well-designed DAA display will almost certainly have a better awareness of traffic than the pilot of a conventional aircraft whose only traffic information comes from the view out the window. Furthermore, if the system is capable of detecting aircraft that are not equipped with transponders, the remote pilot may be aware of traffic that does not appear on the controller’s scope. Consequently, DAA systems could change the patterns of communication between pilots and controllers. For example, the workload of controllers could be raised by remote pilots calling with concerns about nearby traffic.

2.4. Control transfer

A unique feature of RPAS is that control may be transferred in-flight between adjacent consoles, or between geographically separated control stations. Transfers can also involve a change of control link, such as from satellite to terrestrial radio communications. Handovers produce an elevated risk of human error in many task environments, including air traffic control, aircraft maintenance, and medicine (Parke & Kanki, 2008). This also appears to be true for RPAS. Tvaryanas (2006a) notes that the control of a long-endurance aircraft may be transferred multiple times during the course of a single flight, with each transfer contributing to a cumulative risk of error or misunderstanding.

Control transfers require careful briefings and checklist discipline. Several RPA accidents and incidents have involved failures to match the control settings on the receiving control station with that of the relinquishing control station, as illustrated by the following example involving a transfer during ground checks:

> "… we had the aircraft engine at idle with the parking brake set, but when the radio handover switched to XXX, he didn't have the parking brake set and the power was set at 80% …. The result was the engine revving up, and the aircraft jumping its chocks."

Three possible styles of inter-control station transfer can be identified (see Figure 4). A seamless transfer would involve the instantaneous switching of control from one control station to the next. In a "make before you break" transfer there is an overlap in command authority between the receiving and relinquishing control station, which is analogous to having two cockpits connected simultaneously to the aircraft. If both control stations have the ability to transmit commands to the RPA, there is clearly a need for careful coordination to ensure that both pilots do not attempt to uplink commands simultaneously. The "break before you make" style requires that the relinquishing control station shuts off its command link to the aircraft before the receiving control station establishes its command link, although both control stations may continue to receive the downlink from the RPA during the process. During the transfer gap, which could last several seconds or longer, neither pilot will be able to send commands to the aircraft or speak with ATC via the aircraft's on-board radio. Although this style of transfer is currently used by some RPAS, the FAA (2013) has stated that it will not be acceptable for future operations in civil airspace. Despite the criticality of RPAS control transfers, many questions remain unanswered. For example:

What design features are needed in the RPS to facilitate transfers? How should pilots confirm that control settings are consistent between the RPS before transferring control?

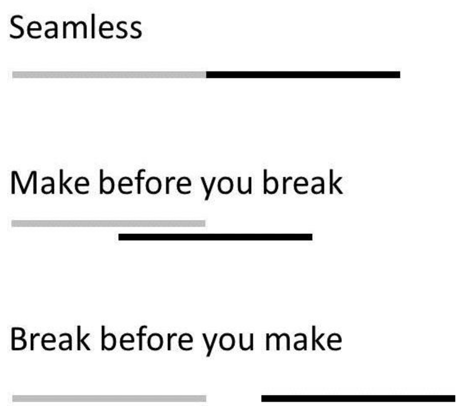

Figure 4. Three potential styles of control transfer.

2.5. The control station environment

The control stations of sophisticated RPAS increasingly resemble industrial control rooms or office workstations (see Figure 5). The space may need to accommodate not only pilots, but also technicians, payload operators, and maintenance personnel[2]. As a remote pilot has noted: “People come and go, opening and closing doors and holding casual conversations. Ringing telephones, whispered remarks, and other disturbances can interrupt critical operations - such as approach and landing maneuvers that demand silence and concentration.” (Merlin, 2013, p.132).

Figure 5. Control station for General Atomics MQ-9 (left), NASA’s Global Hawk, and Raytheon’s advanced Common Ground Station System (CGCS).

[2] Additionally, there may be no reason why the RPS should not be wheelchair accessible.

Anecdotal reports indicate that during critical in-flight events, operational personnel will sometimes gather at the control station to observe or offer support. It is unclear how the presence of additional personnel affects crew resource management. One remote pilot expressed it this way:

> "In manned aircraft it is clear who is in command, but with UAS operations, there are multiple people who have a sense of responsibility for the aircraft. So when there is something that needs attention many people run to the GCS [Ground Control Station]."

Applying a blanket "sterile cockpit" policy to the control station may create other problems. Maintaining vigilance during periods of task under-load may emerge as one of the greatest human factors challenges for RPAS (Cummings, Mastracchio, Thornburg, & Mkrtchyan, 2013). Thompson et al. (2006) found high levels of boredom, reduced mood and chronic fatigue among United States Air Force MQ-1 Predator pilots. They identified the control station environment as a major contributor to boredom. Well-meaning efforts to control distraction, such as eliminating windows or prohibiting visitors may only serve to increase the monotony of the piloting task. Furthermore, comfortable, un-stimulating environments can unmask fatigue, making it especially difficult for personnel to remain alert (Moore-Ede, 1993). In future, control stations must be designed to maximize pilot alertness. Solutions could include allowing pilots to work in a standing position, or vigilance monitoring devices similar to those found in the cabs of locomotives.

A final observation concerns the implications of the RPS environment for maintenance personnel. Unlike the cockpit of a conventional aircraft, the RPS is accessible to maintainers while the aircraft is in-flight. Scheduled maintenance, such as software updates, should probably never occur while the RPA is airborne. However, non-scheduled corrective maintenance may sometimes be necessary. Examples are diagnosing and rectifying console lock-ups, re-booting computer systems, and troubleshooting problems with cable connections. Maintenance error is a significant threat to the reliability of aviation systems, especially when the system is in an operational mode while maintenance is occurring (Reason & Hobbs, 2003). If corrective maintenance is to be performed on ground-based elements of the RPAS while the RPA is airborne, the prevention and management of maintenance error will be especially important (Hobbs, 2010).

2.6. Controls and displays

The cockpits of conventional aircraft evolved gradually over decades, incorporating principles learned from accidents and incidents. Standard features such as the "Basic T" arrangement of primary flight instruments, and controls that can be distinguished by touch, have helped to ease workload and reduce pilot error. Current-generation control station interfaces rarely comply with aviation standards, and they frequently contain an assortment of consumer electronics including computer monitors, pull-down menus, keyboards, and "point-and-click" input devices (Waraich, Mazzuchi, Sarkani, & Rico, 2013).

The human factors deficiencies of control stations have been widely described (e.g., Cooke, Pringle, Pedersen, & Connor, 2006). Physical ergonomics problems include controls that cannot be reached from the pilot's seat, difficult-to-read fonts and color schemes, and unguarded controls that are susceptible to bumping or inadvertent activation (Hobbs & Lyall, 2016a; Hopcroft, Burchat, & Vince, 2006; Pedersen, Cooke, Pringle & Connor, 2006).

Control stations have also suffered from more subtle deficiencies in cognitive ergonomics. A well-designed RPS would include features such as feedback to the pilot to confirm that a command has been received, consistency across controls and displays, appropriate prioritization of information provided by alarms and displays, and control interfaces that minimize the need for complex sequences of inputs to perform routine or time-critical tasks (Hobbs & Lyall, 2016b). Yet these principles have not always been applied in practice. For example, Pestana (2012) describes the process that must be performed by the pilot of NASA's Ikhana RPA to respond to an ATC request to "ident", a routine action that will highlight the aircraft's return on the ATC radar screen. The pilot must perform a sequence of seven steps using a trackball to navigate pull-down menu options. The same task in a manned aircraft can be performed in a single step.

In the following example, a display presented information in a form that was not easily useable by the remote pilot:

> "Pitch and roll indicators are digital, not analog. Makes it difficult to capture the trend of what the aircraft is doing. … We sometimes write down numbers so we can keep track, and that adds to our workload."

The same interfaces that make it difficult for the pilot to perform a task correctly can also make it easy to make errors. Keyboard or menu-based controls may be especially subject to skill-based slips when pilots have developed well-learned action sequences that can be triggered unintentionally:

> “When I activated the gear extension, I turned off the engine by mistake. … I accidentally pressed the engine shutdown switch with my left hand because the gear engage button is next to the engine shutdown switch and I was in a hurry due to time pressure.”

The list below gives a flavor of design deficiencies that have been identified in current RPS:

- Presentation of non-integrated or raw data that require the pilot to perform additional cognitive processing to extract meaning (Tvaryanas & Thompson, 2008; Neville et al., 2012).
- Lack of design consistency across controls and displays (Gawron, 1998).
- Complicated, multi-step sequences required to perform routine or time-critical tasks, often involving menu trees (Cooke, et al., 2006; Pestana, 2012).
- Reliance on text displays to the exclusion of other sources of information, potentially introducing a foveal bottleneck that restricts the flow of information to the pilot (Hobbs & Lyall, 2016b; Tvaraynas, 2006b).
- Use of non-standard or counterintuitive language in text messages (Hobbs & Lyall, 201b).
- Non-intuitive automation and inadequate mode annunciation (Cooke, et al., 2006; Williams, 2007).
- Lack of feedback on pilot control inputs or system states (Tvaryanas & Thompson, 2008).
- Heavy reliance on memory to keep track of system status and flight plan details (Neville et al., 2012).
- Multi-function displays and controls, particularly where a control may perform both a critical and a non-critical function (Tvaryanas & Thompson, 2008; Hobbs & Lyall, 2016b; Neville et al., 2012).
- Need for complex instrument scans (Tvaryanas & Thompson, 2008).
- Difficulty in detecting and correcting errors (Neville et al., 2012).
- Poor hierarchy of presentation. e.g. critical displays that can be obscured by non-critical pop-up windows, and a proliferation of display screens (Hobbs & Lyall, 2016b).

- Reliance on keypress sequences and shortcuts, increasing the risk of skill-based slips and muscle memory errors (Neville et al., 2012).
- Single auditory alarm tones with multiple meanings, and alarms that lose their impact due to repeated activation (Hobbs, 2010; Arrabito et al., 2010).

Some of the design deficiencies in RPS might have been avoided had existing human factors standards been applied. In other cases, the problems reflect a lack of RPAS-specific standards. Several human factors guides for military RPAS currently exist (Under Secretary of Defense, 2012; NATO, 2007, 2009). However, there are currently no human factors standards for non-military RPAS operating in civilian airspace. In order to avoid a piecemeal approach to guidelines development, Hobbs and Lyall (2016a) have proposed that future guidelines for civil RPAS should (a) supplement existing human factors guidelines by focusing on the unique requirements of unmanned aviation, and (b) should be based on a systematic analysis of the tasks that the pilot must perform via the RPS.

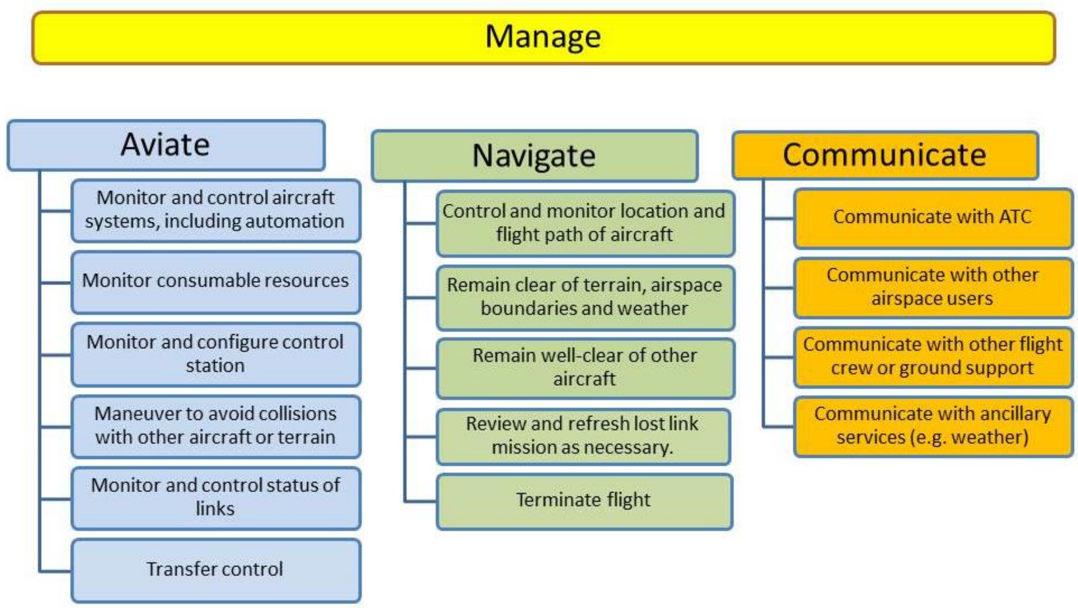

Figure 6. Responsibilities of the remote pilot.

Figure 6 shows the primary safety-related tasks of the remote pilot when operating in airspace shared with conventional aircraft. Some of these tasks are common across aviation but are especially challenging for the remote pilot, perhaps due to the lack of direct sensory cues or communication latencies. In other cases, the remote pilot has unique responsibilities. These include monitoring the status of control links, control transfers, and flight termination. The draft RPS guidelines proposed by Hobbs and Lyall

(2016b) are structured around the tasks shown in figure 6, with a focus on displays and controls that would be unique to RPAS.

2.7. Emergencies and flight termination

Faced with a serious on-board problem, such as an engine failure, the pilot of a conventional aircraft will first consider whether a landing can be made at a nearby airport. If that is not possible, an off-airport emergency landing may be necessary. Even if the aircraft sustains damage, an emergency landing can be considered a success if the occupants are unscathed. The absence of human life on board an RPA markedly changes the nature of emergency decision-making for the remote pilot. In essence, the "manned mindset" that leads a pilot to attempt to save the aircraft and its occupants may not transfer to unmanned aviation, where the safety risks are borne by the occupants of other aircraft and uninvolved individuals on the ground. In an emergency, the remote pilot may be faced with the following options:

- attempt a landing at a suitable airfield,
- attempt a controlled off-airport landing or ditching,
- activate a parachute system, or
- activate a flight termination system that will cause the aircraft to descend to a controlled impact, while minimizing risk.

Flight termination systems introduce the risk of inadvertent activation. It is worth noting that the first loss of a Global Hawk RPA occurred when a flight termination message was sent by mistake (Hobbs, 2010). The guidelines of Hobbs and Lyall (201b) recommend a range of precautions for parachute or flight termination systems. These include a requirement for two distinct and dissimilar actions to initiate a flight termination, aural and visual warnings to the crew before the final activation of the system, and controls designed to minimize the likelihood of unintentional activation.

The flight planning for a large RPA can be expected to include the identification of suitable sites for flight termination. For example, in 2007, NASA successfully used its Ikhana RPA to monitor wildfires in the western United States (Buoni & Howell, 2008). As part of the risk management plan for this mission, NASA identified a large number of potential sites for emergency landings or crashes, as shown in Figure 7.

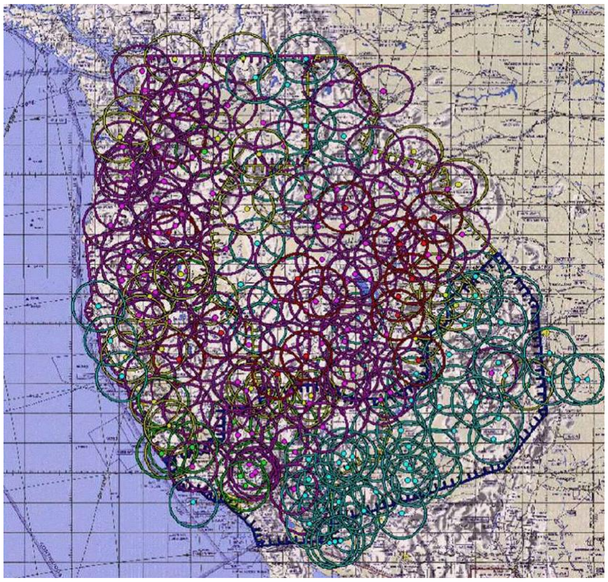

Figure 7. Over 280 emergency landing sites were identified for NASA's Ikhana wildfire monitoring missions. The aircraft could have been directed to glide to one of these sites in the event of a complete and irreversible engine failure.

Even if potential sites for flight termination have been pre-selected, in the event of an emergency, it may be necessary to confirm that the selected site is clear of people and property. If the link is likely to be interrupted as the aircraft descends, the pilot may have to act quickly to interpret sensor data from the RPA, select a suitable site, and send the necessary commands to the RPA at early stage in the descent. Automated decision-support aids that recommend a site after analyzing sensor data may assist the pilot in these time-critical situations (Patterson, McClean, Morrow, & Parr, 2012).

2.8. Required competencies of flight crew

The FAA (2013) has stated that RPAS capable of operating in the US National Airspace System must have a pilot in command, however it is not clear what qualifications this person will need to possess. Despite the diversity of RPAS, there are likely to be core competencies that will apply across systems, related to the pilot responsibilities shown in Figure 6. Recommended training requirements for non-military remote pilots operating in civil airspace have been produced by SAE (2011). These requirements cover the unique issues such as control transfer and link management, as well as identifying syllabus items from manned aviation that would no longer be relevant to RPAS. Although SAE assumes that manned experience will not be necessary to operate an RPAS, this issue is far from settled. Some military RPAS are operated by personnel with no flying experience, yet it seems likely that conventional piloting experience will provide the remote pilot with insights or attitudes that contribute to safe operations. Remote pilots may also require non-technical skills training focusing on unique issues such as flight termination decisions, communication and coordination with remote crew members, control transfers, and the impact of reduced sensory cues on threat and error management.

Finally, it should be noted that, with the pilot no longer co-located with the aircraft, the task of piloting could be outsourced to virtually anywhere in the world, just as airline maintenance tasks have been outsourced to low cost locations. One advantage could be a reduced need for pilots to work during the night, if control can be transferred between control stations in different time zones.

3. CONCLUDING COMMENTS

In conclusion, the safe and efficient integration of RPAS into civil airspace will require thorough human factors input into their design and operation. In many cases, existing human factors knowledge from aviation and other industries can be applied directly to RPAS. For example, cockpit design standards could help to improve some control station interfaces. In other cases, RPAS operations introduce a unique set of human factors that have not yet been clearly identified or examined.

Much of this chapter has been focused on unanswered questions. Virtually every aspect of RPAS, from interface design, interaction with ATC, and pilot decision-making demands attention from the human factors profession. For example, what will be the RPAS equivalent of the “Basic T” flight instruments? Is decision-making affected by the lack of shared fate between the remote pilot and the aircraft? How can we make best use of the positive contribution that humans make to the performance of remotely operated systems?

Some of the emerging RPAS issues considered in this chapter will increasingly apply to conventional aircraft as the divide between remotely piloted and conventional aircraft becomes less distinct. Modern airline aircraft are already equipped with communication links that enable technical personnel on the ground to receive real-time performance data from engines and other systems. Recent airline crashes resulting from pilot incapacitation or malicious acts may accelerate the development of systems that will enable flight crew on the ground to take control of an airliner in an emergency. The act of transferring control from the cockpit to the ground would instantly transform a conventional aircraft into a passenger-carrying RPAS. Researchers have only just begun to examine the numerous human factors and security considerations of this concept (Comerford et al., 2013).

Throughout the 20th century, developments in aviation human factors often occurred in response to accidents, an approach sometimes referred to as "tombstone safety." In the years ahead, we must glean every available lesson from RPA accidents. However, we must also aim to identify RPAS human factors in a less costly manner. Incident investigations, simulations and applied research will be essential to ensure that the integration of RPAS into civil airspace can occur safely and efficiently.

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