Human Challenges in the Maintenance of Unmanned Aircraft Systems

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Executive Summary

Human error will pose a threat to the operation of Unmanned Aerial Vehicles (UAVs), just as it does in other fields of aviation. If UAVs are to be permitted to operate in the National Airspace System (NAS), it will be necessary to understand the human factors associated with these vehicles. Rather than eliminating the potential for human error, the removal of the on-board pilot may transfer some of the risk of human error from pilots to maintenance personnel. The objective of this study was to identify human factors that will apply in the maintenance of UAV systems. The study was focused on UAVs weighing less than 500 lbs.

Unlike conventional aircraft maintenance, UAV maintenance personnel must ensure the reliability of an entire system that comprises the vehicle, the ground station, and communication equipment. At present, there are no published studies of the human factor issues relevant to UAV maintenance. In addition to a literature review and site visits, thirty-one structured interviews were conducted with personnel experienced in the operation of mini- to medium-sized UAVs. The researchers gathered information on critical UAV maintenance tasks including tasks unique to UAV operations, and the facilities and personnel involved in maintenance. The researchers identified issues and grouped them into four categories: hardware; software/documentation; personnel, and environment.

Hardware issues included the frequent assembly and disassembly of systems, and a lack of information on component failure patterns that would enable maintenance personnel to plan maintenance effectively. The risks associated with certain types of batteries emerged as a potential major hardware maintenance issue. Software/documentation issues included the need to maintain computer systems, and difficulties associated with absent or poor maintenance documentation. Environmental issues include the extreme operational conditions that can be experienced in UAV operations. Personnel issues included the influence of the remote controlled aircraft culture and the skill requirements for maintenance personnel.

UAV systems rely on computer technology, autopilots, radio transmission and allied fields to a greater extent than conventional general aviation airplanes. For this reason, many of the skill and knowledge requirements critical to UAV maintenance will lie in the avionics field. In addition, an emerging distinction between field maintenance and major shop maintenance has implications for the skill and knowledge requirements for UAV maintainers. Personnel who perform field maintenance on UAV systems may require less specialized knowledge and skills than shop personnel who perform major repairs or major preventative servicing tasks. The diversity of UAV designs presents a regulatory challenge for the FAA. Ultimately, decisions concerning the regulation of skill and experience requirements for UAV maintenance personnel will need to be informed by risk judgments.

List of Abbreviations

AMT	Aviation Maintenance Technician
ASAP	Aviation Safety Action Program
ASRS	Aviation Safety Reporting System
ATA	Air Transport Association
COTS	Commercial Off The Shelf
EASA	European Aviation Safety Agency
EMF	Electro Magnetic Field
EMI	Electro Magnetic Interference
FIM	Fault Isolation Manual
GCS	Ground Control Station
GPS	Global Positioning System
ICAO	International Civil Aviation Organization
LOL	Loss of Link
LRU	Line Replaceable Unit
MOS	Military Occupation Specialty
MTOW	Maximum Take-Off Weight
NAS	National Airspace System
NTSB	National Transportation Safety Board
RC	Radio Controlled
SHEL	Software, Hardware, Liveware, Environment
SSR	Secondary Surveillance Radar
UAV	Unmanned Aerial Vehicle

Introduction

To enable the operation of Unmanned Aerial Vehicles (UAVs) in the National Airspace System (NAS), it is necessary to understand the human factors of unmanned aviation. The objective of this study was to identify human factors that will apply in the maintenance of UAV systems.

The history of unmanned aviation can be traced back at least as far as World War I (Newcome, 2004). Recent technological advances, including the miniaturization of components and other developments in the fields of electronics, navigation and telemetry, are creating new possibilities for UAVs. As sensors and other payloads become smaller and lighter, tasks which once required a manned aircraft can now be performed with a small unmanned aircraft (Office of Secretary of Defense, 2002). Potential civil and commercial applications include, communication relay linkages, surveillance, traffic monitoring, search-and-rescue, emergency first responses, forest fire fighting, transport of goods, and remote sensing for precision agriculture (Herwitz et al., 2004; Herwitz, Dolci, Berthold & Tiffany, 2005).

A rapid expansion of non-military UAV applications is expected to emerge once airspace regulations are defined (Frost & Sullivan, 2001). A recent study projected a UAV market for both military and non-military applications as high as $7.5 billion in the next 10 years (Ramsey, 2005). A range of safety considerations must be addressed to permit UAVs to operate in the National Airspace System (NAS) (Weibel & Hansman, 2004; DeGarmo, 2004), particularly the maintenance challenges that involve human activity

There are different views about the precise definition of UAVs (Newcome, 2004). For the purpose of this study, the definition provided by ASTM International was adopted. UAVs are here defined as “an airplane, airship, powered lift, or rotorcraft that operates with the pilot in command off-board, for purposes other than sport or recreation … UAVs are designed to be recovered and reused…” (ASTM, 2005).

Several different classification systems have been proposed for UAVs (ASTM, 2005; Joint Airworthiness Authories/Eurocontrol, 2004; Civil Aviation Safety Authority, 1998). UAVs range in size from micro vehicles measuring inches in size and ounces in weight to large aircraft weighing more than 30,000 pounds. In this study, the categorization system shown in Table 1 was used. These weight categories encompass fixed-wing, rotorcraft and lighter-than-air vehicles. These vehicles have a range of propulsion systems including electric and gas powered engines. Cost, complexity and capability generally increase with weight. Recognizing that there is a significant interest in unmanned aircraft for civil and commercial applications, our study focused on mini to medium sized UAVs (weights ranging from 1 to 500 lbs.) because of their long-term affordability, in contrast to larger UAVs such as Global Hawk and Predator that have been developed for defense applications.

Table 1. Size class groups for UAVs

ROA Class	Weight (lbs)	Range (miles)
Micro	Less than 1	1-2
Mini	1 - 15	A few
Small	15 - 100	100s
Medium	100 - 500	100s to 1,000s
Large	500 - 32,000	1,000s

The diversity of UAV systems suggests that maintenance issues will be significantly different across UAV class groups. The maintenance of a 25,600 lb Global Hawk is likely to have very little in common with the maintenance associated with a micro aircraft such as the hand-sized electric powered Black Widow which weights less than 1 lb (Grasmeyer & Keennon, 2001). Even within weight class groups, the variability of aircraft design presents a regulatory challenge for the FAA.

Key elements of UAV systems

A key difference between a UAV and a conventional aircraft is that the UAV is part of a total system comprising the air vehicle, a ground control station (GCS), the communications data link and other ground-based components, each with specific maintenance requirements. Air vehicles can be categorized as fixed wing, rotary wing, ducted fan, or lighter-than-air. In addition to the airframe, the airborne part of the air vehicle includes the propulsion unit, the flight controls, the electric power system, and the payload.

Figure 1. The SoLong UAV developed by AC Propulsion has an electric motor powered by lithium-ion batteries. Solar panels on the wings charge the batteries. In June 2005, the SoLong stayed aloft for 48 hours.

The engine types commonly used to propel UAVs are four-cycle and two-cycle reciprocating internal combustion engines, rotary engines, and increasingly, electric motors. In some cases, gas turbines are used in UAVs (Fahlstrom & Gleason, 1998). Electric motors in combination with solar panels have the potential for extremely long duration flights. In 2005 a solar powered UAV remained aloft for 48 hours, see Figure 1 (Dornheim, 2005).

The GCS is a critical element of the UAV system because it is the operational center for command-and-control links for air vehicle and payload operations. The GCS transmits guidance and payload commands, and receives flight status information (e.g., GPS location; altitude; speed; direction) and mission payload data (e.g., video imagery). In larger UAV operations, the GCS is sheltered for housing the computer workstations, the associated control and display consoles, the ground-based data communications instrumentation, signal processing components, and environmental control equipment (i.e., heaters/air conditioners). For long duration missions, the environmental control equipment is important for ensuring workable conditions for UAV operators. In the case of smaller UAV operations, the GCS may be located in the open, with only rudimentary protection against the weather.

Embedded in the UAV system are the ground-based and airborne components of the autopilot system. Some autopilot systems have the capability of flying more than one UAV. UAV flights out of visual range are extremely reliant on GPS precision. Autopilot systems vary as a function of size and capability. One of the more widely used autopilot systems that has been integrated with small and mini UAVs, measures less than 6 inches along any axis (Fig. 2).

Fig. 2 Airborne component of an autopilot system measuring 4.8" x 2.4" x 1.5" and weighing less than 240 grams.

A critical component of UAV systems is the data link providing two-way communication between the aircraft and the GCS. The ground-based data receiving station enables line-of-sight or satellite communication links between the GCS and the UAV. Data receiving stations are usually located in close proximity to the GCS. In the case of a remotely positioned data receiving station, connections to the GCS may be wireless, although fiber-optic cables are preferred. The uplink provides control of the UAV flight path and commands to its payload. The downlink acknowledges commands and transmits status information about the UAV (e.g., UAV GPS position and elevation). This information is used to assist navigation and accurately determine the UAV location for modifying flight plans and addressing sense-and-avoid challenges. The risks of EMI (electromagnetic interference) and deliberate jamming are critically important issues.

Launch and recovery equipment may involve different methods ranging from conventional take-off and landings on prepared sites to a vertical descent using rotary wing or fan systems (Fahlstrom & Gleason, 1998). Catapults (e.g., pyrotechnic rocket-type or a combination of pneumatic/hydraulic methods) are also used. Nets and arresting gear are used to capture fixed wing UAVs in small areas. Parachutes and parafoils are also used. In contrast to manned aircraft, many UAVs have a flight termination system. Flight termination may involve an engine kill system, or a system to end the flight by using flight control surfaces. The flight termination system is generally considered a fail safe that, at the very least, provides a means of recovery at a predefined location.

Human factors in UAV operations

Throughout the development of aviation, human error has presented a significant challenge to safe and reliable operation (Hobbs, 2004). Although UAVs do not carry an onboard pilot, operational experience is demonstrating that human error presents a hazard to the operation of UAVs (McCarley & Wickens, 2005). At some future stage, even the ground-based pilot may be superseded by a fully autonomous flight system. Nevertheless, there is little question that human tasking will be a critical element in the maintenance of UAVs in terms of post-flight assessments and pre-flight preparations.

The accident rate for UAVs is higher than that of manned aircraft (Tvaryanas, Thompson, & Constable, 2005; Defense Science Board, 2004). The loss of operational unmanned military surveillance aircraft exceeds the loss of manned combat aircraft by a factor of 10 (Johnson, 2003). Although Johnson recognized that the losses were attributable in part to the danger of the UAV missions, human error was viewed as a contributing factor given the fact that UAV operators have less real-time information and fewer fault recovery options.

Williams (2004) studied US military data on UAV accidents. Maintenance factors were involved in 2-17% of the reported accidents, depending on the type of UAV. For most of the UAV systems examined by Williams, electromechanical failure was more common in accidents than operator error. In a study of US Army UAV accidents, Manning et al. (2004) determined that 32% of accidents involved human error, whereas 45% involved materiel failure either alone or in combination with other factors. Tvaryanas et al. and Williams, in contrast, found that a higher proportion of accidents involved human factors. These studies suggest that system reliability may be emerging as a greater threat to UAVs than it currently is to conventional aircraft. This trend may serve to increase the criticality of maintenance, particularly given the limited system redundancy in most small UAVs.

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McCarley & Wickens (2005) reviewed the literature on human factors of unmanned aviation and identified a range of issues related to automation, control and interface issues, air traffic management, and qualification issues for UAV operators. At present, however, no studies have focused specifically on the maintenance human factors of UAV systems.

Human factors in maintenance

Maintenance is one of the most critical and time consuming activities conducted in aviation. Within the airline industry, it has been estimated that for every hour of flight, 12 man-hours of maintenance occur. Maintenance was defined as any activity performed on the ground before or after flight to ensure the successful and safe operation of an aerial vehicle. Under this broad definition, maintenance includes assembly, fuelling, pre-flight inspections, repairs, and software updates. Maintenance activities may involve the vehicle as well as equipment such as the UAV ground control station.

Maintenance activities can be classified broadly as either corrective or preventative. Corrective maintenance involves the repair or replacement of systems that have experienced wear or damage. In many cases, corrective maintenance is non-routine and is performed in response to an operational event such as a hard landing or a system failure. Non-routine tasks are more likely to require fault diagnosis, problem solving and special skills. Preventative maintenance tasks are performed before a problem occurs, and may involve tasks such as inspections, lubrication or the replacement of components at pre-determined intervals. Preventative maintenance tasks are typically routine, and tend to require a more limited range of skills and knowledge than corrective maintenance tasks.

Each disturbance of an otherwise functioning system for maintenance introduces the risk of a maintenance-induced failure (Kletz, 2001). In a range of industries, deficient maintenance is recognized as one of the most common causes of system failure (Reason & Hobbs, 2003). Preventative maintenance involves a trade-off between this risk and the expected benefits of the maintenance procedure. When information on component failure history is available, preventative maintenance schedules can be tailored to ensure that maintenance-related system disturbances are minimized.

Pilot factors have been identified in approximately 70% of aviation accidents (Hawkins, 1993). It has been estimated that deficient maintenance and inspection is involved in around 15% of major airline accidents, although this proportion appears to be growing (Reason & Hobbs, 2003; Hobbs, 1999). Rather than eliminating the potential for human error, the removal of the on-board pilot may accentuate the importance of ground based support activities for UAV operations by transferring some of the risk of human error from pilots to maintenance personnel. It is likely, therefore, that the human factor in maintenance will be a particularly important part of UAV operations.

Method

Three methods of data collection were used in the current study: (1) literature review; (2) site visits; and (3) structured interviews. Each method was used to gather qualitative information on human factor issues. Given that the field of UAV maintenance human factors is largely unexplored, the intent of the research was to identify broad issues, rather than engage in quantitative research. A literature review was conducted to identify issues of relevance to UAV maintenance. Information was gathered from academic publications, public reports, and conference papers as part of the literature review. However, it is important to emphasize that the amount of published literature on the subject was and continues to be very limited.

A total of ten on-site visits were made to UAV operators and manufacturers. These visits provided valuable opportunities for first-hand observations of UAV operations and a chance to observe the challenges associated with UAV maintenance. Some of the interviews were conducted face-to-face in association with site visits. In most cases, however, telephone interviews were used. Interviewees were asked a series of questions designed to reveal human factor issues associated with UAV maintenance. The interview questions are listed in Appendix A.

The interviews involved authorities in commercial and military UAV operations. The sample groups featured experts directly involved with the maintenance of the UAV. Particular attention was directed to what type of human factors training would be required to maintain unmanned aircraft.

Interview participants

A total of 31 structured interviews were conducted with UAV users from commercial, academic and military operations.

Of the potential interviewees approached, approximately 10% declined to be interviewed. It appeared that refusals were due to concerns about commercial confidentiality and, in some cases, a concern that participation may lead to unwanted attention from the FAA. In order to allay concerns about confidentiality, interviewees were assured that their identities would not be revealed unless they gave specific authorization to do so. Of the interviewees willing to participate in the study, 58% were working with more than one UAV type and 55% were involved with military applications. More than 50% of the interviewees were involved with the manufacturing of UAVs. A distinction was made between manufacturers who fly and maintain their UAVs, and customers who purchased UAVs. Of the sample group, all of the manufacturers were operators of their own UAVs. Most of the UAVs operated or constructed by the interviewees were in the 15-100 lb (small) weight class or smaller (Fig. 3). Although the focus of this study was on UAVs weighing less than 500lb, in order to gain a complete perspective on the industry, a limited number of discussions were held with operators of large UAVs weighing greater than 500 lbs.

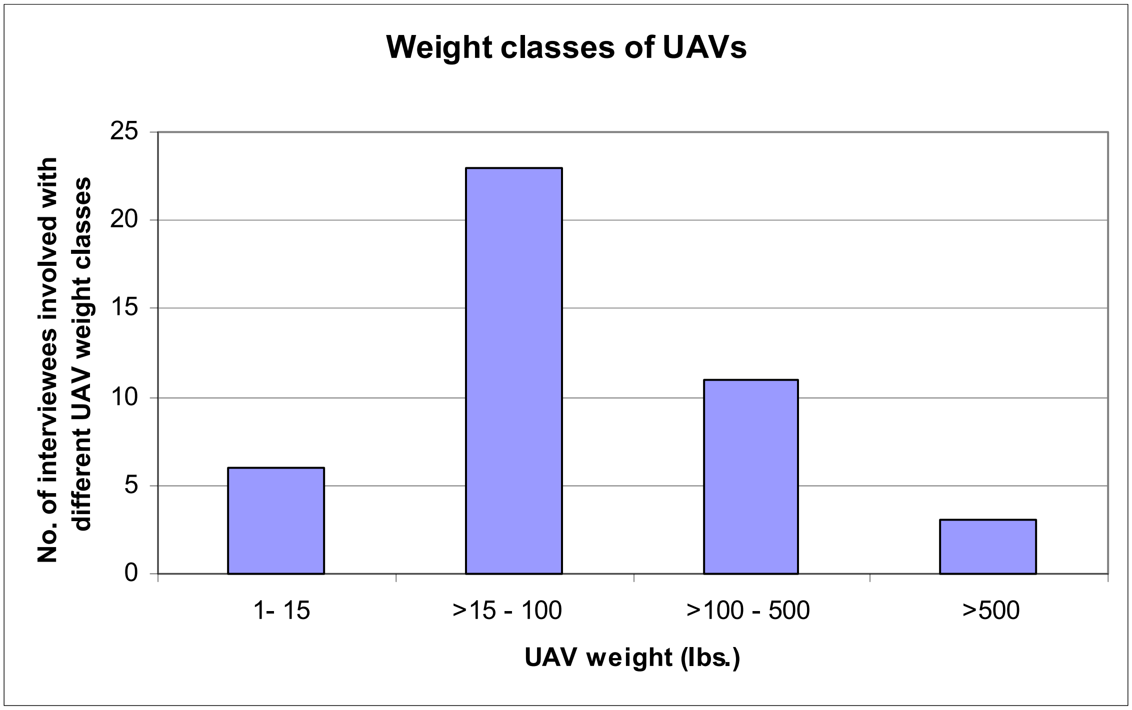

Figure 3. Number of interviewees involved with the mini (1-15 lb), small (<5-100 l.), medium (>100-500 lb) and large (>500 lb) UAV weight classes.

Results

The results chapter is divided into two sections. In the first section, differences between UAV maintenance and conventional aviation maintenance are described. The second section deals with the issue of UAV maintenance technician qualifications and training requirements.

Differences between UAV maintenance and conventional aviation maintenance

Issues that emerged from the structured interviews are arranged in sections based on the SHEL model as illustrated in Figure 4. The SHEL model is a human factors analysis framework originally proposed in the 1970s by Edwards and now formally recommended by ICAO (1992).

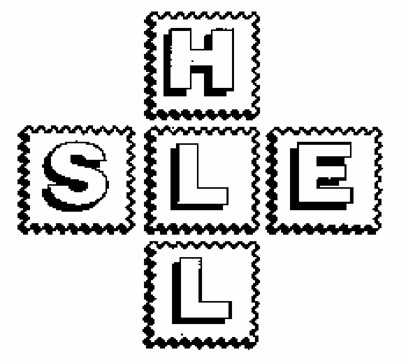

Figure 4. The SHEL model of human factors.

The SHEL model divides human factors issues into four broad areas with which the human must interact. These are the areas of "Software", "Hardware", "Environment" and "Liveware". The Liveware/Software interface represents the interaction between people (or liveware) and soft aspects of the task such as procedures, documentation, computer software and manuals. The term "software" as used in the SHEL model is not limited to computer software, but applies generally to information management aspects of the task. The second element of the model is the interaction between people and hardware, such as tools, equipment and the physical structure of the UAV. The third element of the model represents the personal interactions in the system, and includes issues such as communication, teamwork and group interactions. In this report the word "personnel" is used in preference to the term "liveware". Knowledge and skill issues are also included in this element. The last element of the model represents the interaction between people and the environment, such as lighting and weather extremes.

Software/documentation

Availability of flight history data

In many cases, the ground control station records extensive information, such as flight history and engine performance. This information can be used to monitor the functioning of systems and identify anomalous conditions. This information makes it possible to conduct an extensive post-flight review, which will have significant implications for the way maintenance is conducted. The need for maintenance personnel to be comfortable with the use of computers for the recovery of archived data clearly is an important requirement.

Lack of maintenance documentation

Several operators reported that UAVs were delivered with operating manuals, but no maintenance manual or maintenance checklists. As a result, the operators developed their own maintenance procedures and documentation. Other UAV operators reported that their UAVs were delivered without technical information such as wiring diagrams, making it difficult to troubleshoot problems or repair electrical systems.

Poor standard of maintenance documentation

In cases where a UAV was delivered with maintenance documentation, maintenance personnel were sometimes dissatisfied with the quality of documentation. For example, UAV maintenance documents rarely conform to the Air Transport Association (ATA) chapter numbering system. In the course of the interviews, examples were given of poor procedures including poorly conceived Fault Isolation Manual (FIM) documents. One of the most common recommendations was the need to keep careful log books that document all tasks performed on the UAV.

Lack of reporting systems

Unmanned aviation is at an early stage of development and the safety issues affecting the industry have not yet been clearly identified. Incident reporting schemes such as the NASA Aviation Safety Reporting System (ASRS), Aviation Safety Action Programs (ASAP) maintenance reporting programs, and manufacturer-specific reporting systems have helped to identify safety deficiencies related to components, maintenance practices and documentation. Without systems to gather incident information for the benefit of operators, manufacturers and the FAA, it will be difficult for the UAV industry as a whole to learn lessons from maintenance incidents.

Need for familiarity with computer software

Thirty five percent of the interviewees discussed software maintenance as a human factors issue. Given the importance of computer components in most UAV systems, several UAV owners require maintenance personnel to have an understanding of computers and the capability to make software updates. Maintenance personnel may need to update UAV autopilot system software, and then verify and clearly document the software versions being operated. It is critical that the on-board software revision matches that loaded on the ground station. One interviewee considered that it was easier to train computer-literate people in aviation than to train aviation people in computer skills. Several interviewees mentioned that they had received no training in the use of computer software.

Hardware

Whole-of-system approach

In conventional aviation, the AMT is responsible for the airworthiness of an aircraft. In UAV operations, the maintainer is concerned with the reliable operation of an entire system, comprising not only the aircraft, but also ground-based support equipment. Ground-based system elements may include launch systems, ground control station, transmission equipment and in some cases, landing systems. The broad scope of UAV maintenance has implications for the skill and knowledge requirements for maintenance personnel. These implications will be addressed in later sections.

Extensive use of computer hardware

Virtually all UAV systems rely on standard off the shelf laptop computers to run flight control software, monitor the progress of the flight, and collect data from the aircraft in flight. In some cases, the laptop may be housed in a building or trailer; in other cases, however, it is used outdoors on battery power, perhaps with a hood to enable the screen to be seen in daylight. The laptop essentially functions as a “glass cockpit” from which the flight is controlled. A computer failure, virus or even a depleted battery could threaten the success of the flight if the aircraft is being flown through the laptop. Ensuring the functioning of the laptop is an airworthiness issue. Some UAV operators reported that they maintained a second laptop on standby in case of a failure.

Packing and transport

The handling of UAVs is similar to sailplanes that are typically moved in trailers. One UAV manufacturer used the maximum size of a UPS box as a point of reference for designing their UAVs. A Sports Utility Vehicle or van may be used for the smaller UAVs, but when wing spans start to exceed the dimensions of such a ground vehicle, then new packaging and human factors must be addressed. Operators reported that transport and handling damage "ramp rash" are significant issues due to the need to move and assemble UAVs. Carrying UAVs into and out of vehicles and through doorways creates numerous opportunities for damage. Smaller UAVs in particular tend to be constructed with the aim of minimizing mass, with a consequent reduction in robustness. One operator considered that the forces involved in routine handling could exceed those experienced by the UAV in flight.

Assembly

Small- and medium-sized UAVs are generally disassembled between flights for transport and storage, whereas a conventional aircraft may be assembled in the factory and then largely spend the rest of its service life intact. The repeated assembly and disassembly of UAV systems introduces certain human performance related vulnerabilities. A particular concern is the frequent connection and disconnection of electrical and other systems, which can increase the chances of damage and maintenance errors. Bent and damaged pins in plug connectors, or mis-mated connectors are a common source of airworthiness problems in aviation. In the nuclear power industry, the probability of improperly mating a connector has been estimated at 0.003 (Swain & Guttmann, 1983). While this may appear to be a low number, it implies that one out of every 300 cable connections can be expected to be made in error. Clearly, the more frequently this task is performed, the greater chance that an error will occur. The chance of error may be higher under the influence of performance shaping factors such as time pressure, poor lighting or fatigue. Weight and balance calculations taking payload into account must also be made once the aircraft has been assembled.

UAV-specific elements

UAV systems may include components such as launch catapults, computer hardware, autonomous landing systems, sense-and-avoid instrumentation (ground-based or airborne) and flight termination systems (e.g. parachute release; engine kill systems). These components are not typical features of general aviation aircraft, and their maintenance will require a specific set of skills and knowledge. These systems also present opportunities for specific forms of maintenance error. For example, there have been occasions where UAV parachute release systems have deployed on the ground due to the actions of maintenance personnel. Compared with conventional aircraft, most UAVs have less redundancy built into the aircraft (Bolkcom, 2005). A consequence for maintenance personnel is that there may be less margin for error in maintaining a UAV system.

Criticality of maintaining communication systems

A conventional manned aircraft can continue to operate despite a loss of communications. Although a manned aircraft can operate in the absence of a communication link, the loss of communication with a UAV can result in the loss of the aircraft. Therefore, the maintenance of a data link between the ground control station and the aircraft is a critical airworthiness issue. The UAV may be programmed with a sequence of steps to be performed in case of a loss of link (LOL), such as returning to the last point at which communication was made, or in extreme cases terminating the flight. In 2003, loss of signal was identified as a causal factor in 11% of US military UAV failures (Office of Secretary of Defense, 2003).

Loss of link was raised by interviewees in 32% of the interviews, but in general, interviewees did not provide detail on the maintenance steps needed to ensure uninterrupted wireless communication links. Certification of the ground control and radio link to the UAV (Dornheim, 2004) is a critical issue. It may also be necessary to maintain a communication link with Air Traffic Control. The command and control link is critically important along with the need for navigational precision which means properly certified GPS data sources.

Battery maintenance requirements

In recent years there have been significant developments in battery performance driven by the consumer electronics industry. Whereas electric powered aircraft formerly had flight times measured in minutes, endurances of over an hour can now be achieved (Bland, Coronado, Miles & Bretthauer, 2005). Electric motors are being used on fixed wing, rotary wing and lighter than air vehicles. In such vehicles, monitoring the performance and charge of batteries is as important as checking the fuel system of a gasoline fuelled aircraft. Monitoring the condition of batteries takes special care and may involve running computer analysis to assess battery condition.

During interviews, batteries were noted as the cause of a high proportion of mishaps, both with airborne and ground-based systems. Careful attention needs to be directed to battery charging/discharging cycles.

Some types of batteries, particularly those containing lithium, can be dangerous if correct procedures are not followed. These batteries may catch fire if abused, short circuited, overcharged, damaged or exposed to water. A particular danger is that the fire may not start immediately, but may start minutes or hours after the damage has occurred. During the interviews, an example was given of a radio control aircraft owner having a lithium polymer battery catch fire in the trunk of his car after the battery had been used earlier in the day in a model aircraft.

> “Rechargeable LI-Ion batteries must be charged in accordance with the manufacturers specifications. Care must be taken specifically to avoid overcharging, as doing so can cause the cells to bloat, burst, and catch fire. Puncture or other seal failure is the other primary cause of lithium battery problems/fires. During a crash, the batteries can be bent, stressed, punctured, or sheared and may not exhibit immediate symptoms of a problem. We did, however, have an accidental puncture occur when a technician was trying to mount a camera pod in a bird that still had a battery pack in. The fire was immediate and the airframe was lost. Quickly”. (Reported by M. J. Logan, 2006).

UAV batteries could be particularly dangerous if shipped by air freight. The National Transportation Safety Board (NTSB) has investigated several cargo fires involving lithium batteries. In 1999, a pallet of non-rechargeable lithium batteries caught fire shortly after being offloaded from an international flight at Los Angeles. The NTSB issued a series of recommendations concerning the transport of lithium batteries after this incident (National Transportation Safety Board, 1999). In 2004, a package of rechargeable lithium-ion batteries caught fire as they were being loaded on board a freighter aircraft for a trans Atlantic flight (National Transportation Safety Board, 2005). The research and special programs administration of the Department of Transportation (2002) noted:

> “With the growing consumer demand for portable powered devices that have increasing capacity to operate for long periods, more and more batteries that have very large reserves of electrical energy are being shipped. If not properly protected from short circuiting or prevented from accidental activation, these batteries can generate a large quantity of sparks and/or heat for an extended period”. (p. 75210).

The increasing use of re-chargeable lithium batteries in UAV operations raises the potential that maintenance personnel will be required to ship batteries, perhaps to return a faulty battery to the manufacturer. UAV maintenance personnel should have an awareness of battery hazards.

Composite materials

UAVs tend to make extensive use of composite materials. Repair of these materials requires special expertise and equipment as well as attention to hazardous materials. Some interviewees reported that repairs to composite materials would require the component to be returned to the manufacturer. The failure modes of composite structures are different to the failure modes of traditional metal structures. Visual inspection and auditory tap tests are commonly used methods to detecting damage in composite materials, yet the human factors of composite inspection are not well understood (Ostrom

& Wilhelmsen, 2005). The inspection of UAV airframe may also be particularly difficult due to the small size and access difficulties.

Distinguishing between payload and aircraft

Conventional aircraft are typically used to transport passengers or cargo. UAVs are most commonly used as platforms for sensors. In contrast to conventional aircraft, the payload on board a UAV is more likely to be integrated with the UAV structure and power supply and be capable of transmitting data during the flight. There is not necessarily a clear distinction between the payload and the aircraft; however, maintenance personnel are generally expected to work not only with the aircraft, but also with onboard equipment such as cameras or other sensing devices.

The close proximity and integration of payloads increases the chances that the payload will have an impact on the operation of aircraft propulsion, navigation or communication systems. Electro magnetic (EMF) interference between payloads and aircraft systems is a relatively common issue in UAV operations and must be understood by maintenance personnel.

Salvage of UAV and associated hardware

UAVs often experience operational-related damage caused by events such as hard landings, contact with water, or landing in trees (in the case of small UAVs). UAVs also tend to be less waterproof than conventional aircraft (Office of Secretary of Defense, 2003) leading to a greater chance of water damage to internal components. An advantage of UAV systems over conventional aircraft is that without an on-board pilot, UAVs can be exposed to greater risk. UAVs may also be more rugged and are cheaper to repair when damaged. Referring to the five-pound Dragon Eye UAV in operation with the US Marines, a Marine official was quoted as saying " One of them has 50 crashes on it and it is still flying" (Lunsford, 2003).

To a greater extent than in conventional aviation, UAV maintenance personnel will be required to make judgments about the reuse and salvage of components involved in such occurrences. The testing of components removed from damaged aircraft will be a critical task for maintenance personnel.

Repair work by UAV manufacturer

The small size of many components and the modular approach of many UAV designs permits operators to ship damaged components back to the manufacturer for repair. A trend was detected indicating that minor maintenance was performed by operators, but major repairs generally involved sending the UAV back to the manufacturer. It is likely that some manufacturers will actively discourage UAV owners from performing major maintenance. Much like consumer electronics products, in the future some UAV components may display the warning “No user-serviceable parts inside”.

The frequency with which a maintenance task is performed by an individual is a key factor determining the speed and accuracy with which the task can be completed. Infrequent tasks can place maintenance personnel on a learning curve, and such tasks are more error-prone than frequently performed tasks (Hobbs & Williamson, 2002). The distribution of UAV maintenance tasks between field maintenance personnel and specialized factory personnel is likely to have a positive impact on the quality of maintenance.

Absence of information on component failure modes and rates

The manufacturers of components used in small UAVs generally do not provide data on the failure modes of their components and the expected service life or failure rate of these components. There are generally also no methods for maintenance personnel to provide manufacturers with reports of component failures. This absence of information is particularly notable for components purchased from Radio Control (RC) hobby shops. For example, there is little information on the service life of servos designed for radio controlled aircraft, and now being used in UAVs (Randolph, 2003). Failures of actuators have been identified as the primary cause of control failures in UAVs, and in many cases the actuators have been off-the-shelf subsystems (Defense Science Board, 2004). Logan, Vranas, Motter & Shams (2005) note that commercial off the shelf (COTS) components used in UAVs can have high failure rates. They provide failure rates for common UAV components such as analog servos (20% failure rate) and electronic speed controllers (30% failure rate). In the absence of service life and failure rate information, reliability-centered maintenance programs cannot be developed (Kinnison, 2004). The first risk of this situation is that critical components will not receive preventative maintenance in a timely manner. The opposite risk is that systems will be “over-maintained” with each unnecessary maintenance event introducing the risk of a maintenance-induced failure.

Modular design and the “grandfather’s ax” problem

The modular construction of many UAVs enables major components such as engines and wings to be removed and replaced relatively easily. If the operator carries sufficient spares, much corrective maintenance may involve “repair by replacement”. Faulty units would then be shipped to specialized repair facilities, typically the manufacturer. One implication of the ability to swap major system components, is that it may become meaningless to track the long-term history of a specific aircraft. Like grandfather’s ax that has had the handle and the blade replaced many times, a UAV that has had several major component changes may be the same aircraft in name only.

Recording of flight hours

UAVs do not generally have on-board meters that record airframe or engine flight hours. If this flight history information is not recorded by the ground station, the timing of hours flown must be recorded manually for maintenance purposes and inspection scheduling. The modular construction of many UAVs also introduces the possibility that different flight hours may be accumulated by different components on a single aircraft. For example, the wings, engine and fuselage on a UAV may each have their own history of hours flown. As mentioned above, the ability to swap major system components also may make it meaningless to track the long-term history of a specific aircraft.

Lack of part numbers

Smaller manufacturers of UAVs do not generally use part numbers on rotable components, non-consumable parts that can be removed and repaired. A lack of part numbers makes it difficult if not impossible to track the maintenance history of these components. In addition, a lack of part numbers may increase the probability of errors such as misidentifying parts, mistaking an unserviceable component for a serviceable one, or fitting non-compliant components to a UAV.

Unconventional propulsion systems

An increasing number of UAV designs make use of technologies that are not conventionally used in manned aviation. For example, fuel cells, solar power systems, and electric propulsion systems are relatively new to aviation. Limited experience is available on the maintenance requirements of such systems.

Fuel mixing and storage

Unlike conventional manned aircraft, some UAVs require fuel to be mixed on-site. Two stroke gasoline engines require a mix of gasoline and oil. Fuel preparation tasks are typically performed by the UAV operator/maintainer rather than by dedicated refuelers. The hazards of fuel storage and transport are well recognized, however vigilance is essential and errors during the handling of fuels may result in health and safety, and airworthiness hazards.

Personnel issues

Complacency

Several interviewees considered that complacency could be a threat to the quality of UAV maintenance. This issue has also been identified in manned aviation, with the awareness that there is no human on board the aircraft, there is a potential for maintenance personnel to become relaxed about maintenance tasks, particularly with regard to deviations from procedures.

Model aircraft culture

The most commonly cited skill sought for UAV maintenance was experience with RC planes. Some interviewees, however, considered that personnel with a RC background needed to be introduced to the practices and discipline of mainstream aviation. There was a view among some UAV operators that cultural differences existed between the Radio Control hobby world and mainstream aviation, in particular that some RC hobbyists take an informal approach to maintenance and may be accustomed to operating without formal procedures or checklists. If a future UAV industry recruits maintenance and operational personnel from the RC hobby fraternity, it may be necessary to provide bridging training to inculcate aviation practices and expectations, and perhaps to "unlearn" work habits that may be out of place in mainstream aviation.

Lack of direct pilot reports

In manned aviation, the onboard pilot gathers significant maintenance-related information from the in-flight performance of the aircraft. Unusual flight characteristics, noises, vibrations or odors may be indicators of airworthiness problems. The pilot's log book entries are an important source of such information for maintenance personnel (Munro, 2003). Although flight history may be recorded in the UAV ground control station and reports may be made by the ground-based UAV operator, these reports will not capture the on-board sensory experience of the aircraft's flight performance. This lack of on-board sensory data removes a source of information that would otherwise be available to maintenance personnel. This issue was recognized in a draft Advisory Circular prepared (but not released) by the FAA in 1996.

Operator and maintainer may be same person

The distinction between maintenance personnel and pilots has existed in aviation since the Wright Brothers employed Charlie Taylor as their mechanic. This distinction is still being observed for large UAVs, where maintenance personnel are expected to possess standard Aviation Maintenance Technician (AMT) qualifications or equivalent. At the smaller end of the UAV spectrum, however, a primary attraction of UAV technology is the ability to operate the vehicle with a small number of multi-skilled individuals, and both maintenance and in-flight operation tend to be performed by the same people. The traditional maintainer/pilot distinction may not fit this sector of the industry.

Need for wide skill set

Small UAV operators expect maintenance personnel to possess skills in a wide range of fields, including electrical and mechanical repairs, software, and computer use. Given the potential risk of electromagnetic interference (EMI), another fundamental requirement is an understanding of radio transmission, wireless communication, and antenna electronics. Some branches of the military distinguish between UAV avionics technicians and mechanics. It is unlikely, however, that commercial UAV operators will want field maintenance personnel to possess narrow specialization. Regarding the training of maintenance staff, 42% of the interviewees were involved with or managed their own UAV maintenance training program. The general consensus among interviewees focused on small UAVs was that the staffing needed for UAV maintenance featured individuals who were “jacks of all trades.” The issue of skills is covered in more detail in a later section.

Environment

One advantage of UAVs compared to conventional aircraft is that they are not generally stored outdoors where they would be exposed to threats from the elements. Additionally, although some flight support tasks may be performed in the open, in many cases, the vehicle can be brought inside a shelter for maintenance.

In flight however, UAVs may be exposed to harsh environments to a greater extent than conventional aircraft. The problem of water ingress was emphasized by one of the interviewees. One operator reported that at high altitude, the grease used in servos would freeze, as the servos had been designed for low-level radio controlled flights. In addition, without a pressurized cabin, operation at high altitude can expose on-board avionic systems to extremely low temperatures. Low temperatures and high altitude also may affect the performance of batteries (Reid, Manzo & Logan, 2004). These challenges will require maintenance personnel to be attuned to the airworthiness consequences of extreme environments.

Technician Qualification and Training Requirements

At this stage, it is not possible to make definitive conclusions about UAV maintenance technician qualification and training requirements. Nevertheless, some observations can be made, as outlined in the following sections.

Existing standards for maintenance of conventional aircraft

The FAA does not directly certificate personnel who maintain avionics or related equipment, although such personnel would typically work under the authority of a certificated organization, or may possess qualifications such as an FCC radiotelephone license and/or FAA repairman certificate. In contrast, other regulatory authorities specify extensive knowledge and skill requirements for electrical, instrument and radio maintenance technicians (e.g. EASA Part 66, Civil Aviation Safety Authority, 2004).

The FAA does specify standards for licensing of aviation maintenance mechanics with airframe and/or powerplant ratings. FAR 65 specifies basic requirements to obtain a mechanic certificate with airframe and/or powerplant ratings. FAR part 147 specifies curriculum subjects in three groupings: general subjects; airframe subjects; and powerplant subjects.

In recent years, there has been discussion of updating the contents of FAR 147 to reflect the demands of the modern aviation industry. It has been claimed that some curriculum topics, such as wood structures and fabric, are no longer relevant to modern aviation. Adam et al. (1997) conducted a job analysis of the work of aviation maintenance technicians designed to identify the range of tasks actually performed in the industry.

Military practices

The military has had extensive experience with the maintenance of UAVs. The Army trains UAV maintenance personnel in two streams: avionics technicians; and mechanics. Avionics technicians are selected from among electronics warfare specialists, and bring expertise in fields such as computer theory and electronics. Mechanics performing engine and airframe repair are selected from among the small engine repair military occupational specialty. The Marines have two job categories related to UAV maintenance, and, as with the Army, distinguish between mechanical and electrical/avionics technicians. Marine UAV mechanics are trained to standards in Military Occupation Specialty (MOS) 6014, Marine avionics technicians are trained to standards in MOS 6314. The Navy has a single job category, AE 8361 Unmanned Aerial Vehicle (UAV) Systems Organizational Maintenance Technician.

Maintenance skills and knowledge required for UAV maintenance

No analysis comparable to that of Adam et al. (1997) has been conducted for UAV maintenance tasks; however, on the basis of a preliminary assessment, three sets of skill/knowledge areas can be identified. These areas are illustrated in Figure 5.

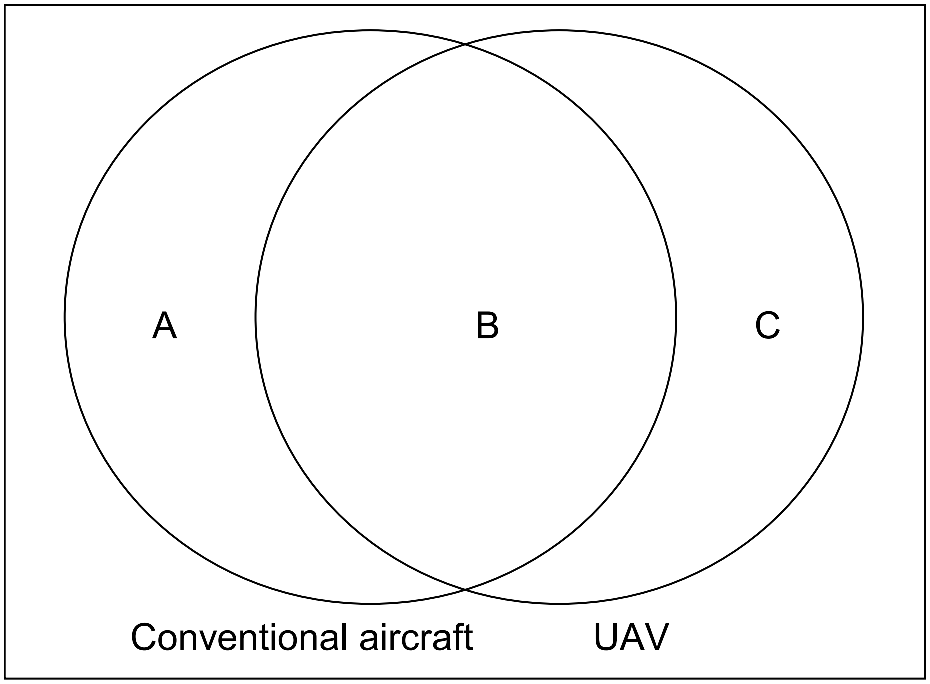

Figure 5. Overlap of maintenance skill and knowledge requirements between conventional aviation and UAV operations

The first set comprises topics included in the current FAR 147 that are unlikely to be relevant to the maintenance of UAVs with a MTOW less than 500lbs. In Figure 5, these areas are labeled A.

Examples of such topic areas include:

1. Hydraulic and pneumatic power systems (Appendix C, 30-32)
2. Cabin atmosphere control systems (Appendix C, 33-35)
3. Passenger address interphones (Appendix C, 39)
4. Fire protection systems (Appendix C, 54-55)
5. Radial engine repair (Appendix D, 1)
6. Thrust reverser systems (Appendix D, 32b)
7. Auxiliary power units (Appendix D, 41)

The second set are requirements currently listed in FAR 147 that will also be relevant to the maintenance of UAVs. In Figure 5, these are represented by the area labeled B. Core areas include aircraft structures, fuel systems and basic electricity. A view widely expressed in interviews was that, in most cases, the skill and knowledge required for UAV maintenance is broadly similar to that required to maintain conventional aircraft. Given the range of materials used in the construction of UAVs, certain apparently "outdated" topics included in the current FAR 147 may become important once more. Examples are wood structures and fabric repairs.

The third set are topics that are likely to be relevant to UAV maintenance that are not currently listed in FAR 147. In Figure 5, these areas are labeled C. Although in Figure 1 the skill and knowledge requirements for UAV maintenance are represented by a single circle, the diversity of UAV types mean that specialized skill sets are likely to be required for specific UAV types, such as rotary wing, lighter than air, fixed wing, electric propulsion etc. A feature common to all UAV systems is that they rely on computer technology, autopilots, radio transmission and allied fields to a greater extent than a conventional general aviation airplane. For this reason, many of the skill and knowledge requirements critical to UAV maintenance will lie in the avionics field, a field currently unregulated by the FAA.

The following is a general list of topic areas that are not currently included in FAR 147. This is not intended to be an exclusive list and the requirements will vary across UAV types and will develop as new technologies are introduced.

1. Salvage decisions, including assessment of water damage
2. Computer management
3. Understanding of computer operating systems
4. Fuel storage and mixing
5. Fuel cell systems
6. Theory and maintenance of electric motors
7. Composite materials
8. Software, networks, Ethernet hubs
9. Electronics
10. Radio transmission and theory of radio control
11. Radio frequency interference and shielding
12. Ground transmission equipment and ground based antennas
13. Autopilot maintenance, including software uploads
14. Understanding of different types of electric batteries, care and maintenance of batteries
15. Maintenance of flight termination systems (may include parachute systems)
16. Launchers, pneumatic, bungee systems
17. Recovery systems
18. Unconventional fuel systems (e.g. liquid hydrogen)
19. Weight and balance (particularly after payload changes)
20. Understanding of RC control systems
21. Measuring of control surface movements after assembly and interaction with autopilot software

Distinctions between major and minor servicing

During the interviews with subject matter experts, it became apparent that an emerging practice in the UAV industry is for minor servicing and preventative maintenance to be conducted in the field by operational personnel, while major maintenance tasks are carried out by the manufacturer. Typically, entire units are shipped to the manufacturer's site for major maintenance tasks.

A similar system exists in the military. Military UAV operators generally distinguish between basic operational maintenance and major repairs. Basic operational maintenance includes servicing, fuelling, daily inspections, simple preventative maintenance and replacement of line replaceable units (LRUs). Major repair include complex structural repairs, complex overhauls and, diagnosis/resolution of complex faults. This distinction is broadly similar to the airline distinction between line and heavy maintenance. The modular construction of UAVs and the generally small size of components enables operators in the field to ship entire systems to specialist facilities for major maintenance. Such a trend is already emerging, typically where manufacturers provide ongoing support for their products. An implication of the distinction between minor and major maintenance is that different skill sets will be required for minor maintenance of UAVs in the field versus major shop maintenance.

It is conceivable that field maintenance will require a general overview of system operation, an ability to carry out preventative maintenance tasks, an ability to diagnose faults and replace LRUs. However, maintainers in the field may not be expected to carry out major repairs or overhauls. Such tasks would typically be performed by repair shops, comparable to repair stations that service conventional aircraft and aircraft components.

Level of regulation vs. risk

Decisions concerning the regulation of skill and experience requirements for UAV maintenance personnel need to be informed by risk judgments. If the risk to other airspace users or the public on the ground is considered low, it may not be necessary to impose extensive regulations on UAV maintenance in all cases. For example, the Australian Civil Aviation Safety Authority does not place restrictions on the operation or maintenance of small UAVs that are operated at low level and away from populated areas (Civil Aviation Safety Authority, 1998). Under the Australian system, small UAVs are maintained under procedures applicable to model aircraft (Civil Aviation Safety Authority, 2002).

In addition, the emerging distinction between field maintenance and major shop maintenance may have implications for the skill and knowledge requirements for UAV maintainers. Personnel who perform field maintenance may require less specialized knowledge and skills than shop personnel who perform major repairs or major preventative servicing tasks.

Discussion

Technological developments such as the Global Positioning System (GPS), micro autopilots, improved battery technology, and miniaturized sensors are rapidly expanding the capabilities of UAVs. Once regulatory issues are resolved, a major expansion in civilian UAV activity can be expected.

The absence of an on-board pilot does not mean that human factors will no longer apply to this sector of aviation. It is possible to fly an aircraft on autopilot; however, it is not possible to “auto-maintain” the vehicle and its associated ground-based equipment. Maintenance will still require direct human intervention and contact with systems. It is possible that maintenance and other ground support activities will take on an increased importance in UAV flight safety, perhaps mirroring the decreased role of humans as direct physical controllers of the vehicle in flight.

The aim of the current research was to identify how the maintenance of a UAV system differs from the maintenance of a conventional aircraft and how this will impact the qualification and skill requirements for UAV maintenance personnel.

Human factors in the maintenance of UAVs is a new field with little prior research. It was considered appropriate to take a broad qualitative approach to identify broad issues, rather than focusing in detail on specific technical questions. The interview method used involved asking general probe questions and then recording the information that interviewees chose to reveal.

The evidence collected at this stage has identified significant differences between the maintenance of UAVs and conventional aircraft, and a set of unique maintenance tasks applying to UAVs.

In conventional aviation, the mechanic’s responsibility is confined to the aircraft itself, and the responsibility for the maintenance of ground based communication equipment and navigation aids rests with the FAA. In contrast, the maintenance of a UAV system involves more than attending to an aircraft. The UAV system includes additional ground based elements such as control units and transmission equipment.

The UAV system includes unique components and corresponding unique maintenance tasks. Examples are transmission equipment, computer systems (typically laptops), flight termination systems, parachute or recovery systems and electric propulsion systems.

Other unique issues reflect the relative infancy of the industry. The infant civilian UAV industry can be compared to the automobile industry of 100 years ago. There are many manufacturers, a diversity of models, little mass production, and little standardization. The diversity of systems, the lack of maintenance documentation, and the lack of information on component failure modes and rates are problems which are likely to diminish as the industry matures. However, the industry will need to develop appropriate information management systems. A key element may be an incident reporting system through which personnel could report operating incidents without fear of negative consequences. In the course of interviews, it became apparent that some UAV operators are concerned that the FAA could ground their flights. This atmosphere of uncertainty is likely to suppress open disclosure of incidents, which in turn will make it more difficult for the UAV industry to learn from experience.

Reporting systems such as the Aviation Safety Reporting System (ASRS) and the Aviation Safety Action Program (ASAP) have enabled personnel in conventional aviation to report errors and safety incidents without fear of prosecution. These systems began with a focus on pilots (and air traffic controllers in the case of ASRS) however both have recently been extended to include maintenance personnel. With the UAV industry currently in its infancy, it is crucial to have in place a reporting system enabling UAV maintainers to report error and incidents.

Several unique personnel issues were identified. Interviewees referred to the “model aircraft culture” in either positive or negative terms. Some considered that maintenance personnel with a hobbyist background would not possess a level of professionalism equivalent to that of AMTs. Others felt that only radio control hobbyists would have the knowledge and experience needed to maintain UAVs. If hobbyists are to be involved in the UAV industry, the FAA may need to take steps to bridge the gap between model aircraft culture and mainstream aviation.

The FAA has identified a need to define qualification and training requirements for UAV maintenance technicians. At present, however, there are several reasons why it is difficult to make definitive statements on qualification and training issues. First, no specialized profession of UAV maintenance technician may exist in the same way that specialized AMTs exist in mainstream aviation. The trend emerging within the UAV industry is for maintenance and operation to be performed by the same multi-skilled personnel. One factor that makes this possible is that field maintenance personnel will not necessarily need to maintain all UAV components. The modular design of most UAVs, and the ability to easily ship components to the manufacturer for major maintenance may remove any need for field personnel to perform complex maintenance tasks. Shop maintenance personnel on the other hand will require a more in-depth set of skills and system knowledge. Some manufacturers are currently providing extensive training and maintenance systems for their UAVs and they may be in the best position to determine the skill requirements for maintenance personnel.

The diversity of UAV systems and the current fluid state of the industry also make it difficult to define qualification and training requirements. Lighter than air, fixed wing and rotary wing vehicles will each have specific maintenance requirements, as will fuel cell systems, electric propulsion systems and internal combustion engines.

Setting an appropriate level of qualification requires judgments to be made balancing safety with the risk of over-regulation. Without an on-board pilot, a small UAV that operates at low speed may be judged to present a minimal maintenance-related risk, particularly if operated away from populated areas.

The focus of this stage of research has been on UAVs less than 500 lb weight. Manufacturers and operators of larger UAVs generally intend their systems to be maintained to the same standards as conventional aircraft by personnel possessing standard AMT qualifications. One difficulty in applying existing AMT standards is that they do not currently focus on airframe and powerplant maintenance, to the exclusion of avionics and radio issues. Current FAA standards may not be suitable any longer for mainstream aviation, let alone a new sector of aviation.

This research is continuing. Future stages of this work will consider human factors training needs of UAV maintenance personnel and the manner in which the organization of UAV maintenance may differ from that of general aviation maintenance.

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Appendix A: Interview structure.

1. Provide a general description of vehicle and operations.

2. Who performs maintenance?

3. What are the key maintenance tasks? What are the key ground support tasks?

4. Are there maintenance tasks unique to unmanned aircraft? Are these tasks different to those in maintenance of RC aircraft?

5. Are there particular maintenance problems associated with your operation?

6. Are there any special maintenance facilities needed?

7. What qualifications, skills and training are needed to perform maintenance? If you were advertising for a UAV maintenance person, what skills and experience would you look for?