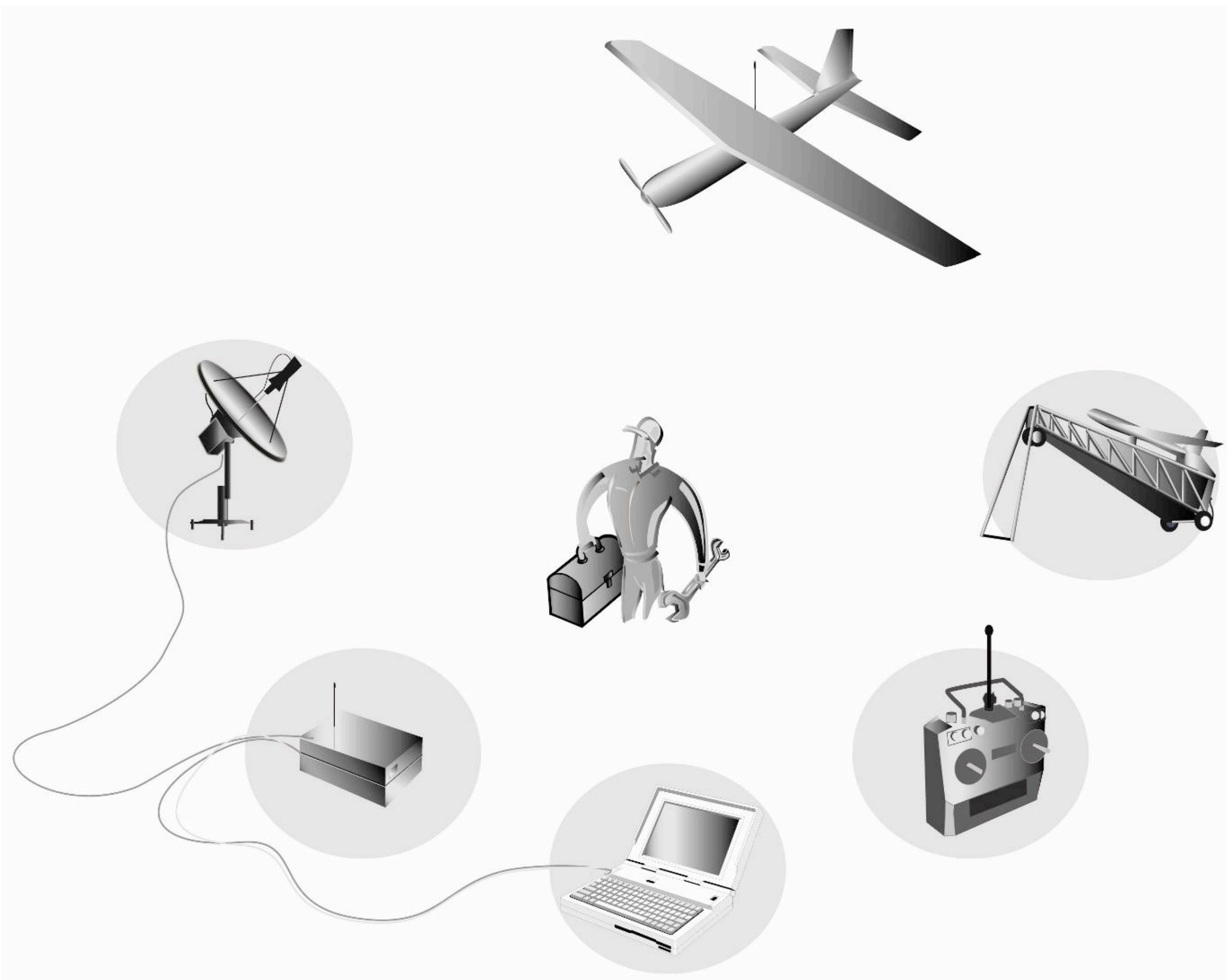
Federal Aviation Administration

Maintenance Challenges of Small Unmanned Aircraft Systems - A Human Factors Perspective

An Introductory Handbook



Maintenance Challenges of Small Unmanned Aircraft Systems - A Human Factors Perspective

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INTRODUCTION

Scope of this handbook

This document is about small fixed-wing and rotary-wing non-military Unmanned Aircraft Systems (UAS) in which the aircraft weighs between 1 and 100 pounds. The Academy of Model Aeronautics limits the maximum takeoff weight of a model aircraft to 55 lbs. Although much of the public discussion concerning unmanned aviation has been focused on unmanned aircraft (UA) significantly heavier than 100 lbs, it is likely that many small UA will be based on available model designs and will weigh less than 100 lbs.

Public discussion on the emerging UAS industry will be best served if realistic distinctions are made between UA weight classes. Issues that apply to small UA will not necessarily apply to large UA, and vice versa. Large UA tend to be maintained in a similar way to conventional aircraft by qualified aircraft maintenance personnel, working in accordance with comprehensive maintenance procedures. As this document shows, the maintenance of small UAS has little in common with conventional aircraft maintenance.

Purpose of this handbook

This handbook provides an overview of the emerging human factors relevant to the maintenance of small UAS. Its purpose is to raise issues that will be important in future FAA advisory material or rulemaking. The content is based on interviews with UAS maintenance personnel, and observations of UAS operations.

Definitions

For the purposes of this document, an Unmanned Aircraft (UA) is defined as “an aircraft controlled either autonomously or by a control station located on the ground or in a manned aircraft. An unmanned aircraft is not operated by an on-board pilot”. The term “UA” is used throughout this document to refer to unmanned aircraft weighing between 1 and 100 pounds. An Unmanned Aircraft System (UAS) is defined as “an unmanned aircraft and all of the associated support equipment necessary to operate the unmanned aircraft in the National Airspace System”[i].

For ease of expression, the terms “UA” and “UAS” are used to denote both the singular and the plural.

Note about photographs in this report

Photographs of UAS appear throughout this report to illustrate the range of systems currently operating, and typical UAS maintenance tasks. No connection between the maintenance issues identified in this handbook and the specific systems depicted in the photographs is intended.

THE EMERGING COMMERCIAL UAS INDUSTRY

Chapter 1

1. THE EMERGING COMMERCIAL UAS INDUSTRY

Potential for growth in the small UAS sector

The most rapid growth in the UAS industry may initially involve small UA. Technological developments, such as miniaturization of sensor equipment and autopilots, and developments in battery technology are allowing small UA to perform tasks that would have previously required larger aircraft. In many cases, UA are based on inexpensive hobby store model aircraft, sometimes with the addition of an autopilot.

Small UA have many potential uses, including the support of police or firefighters, traffic monitoring, aerial photography, agriculture, search and rescue, border surveillance, wildlife monitoring, power-line inspection, minerals exploration and homeland security applications. History shows that emerging technologies often find applications never anticipated by their developers. Examples can be found in the development of radio, the steam engine, and digital computers. Likewise, small, inexpensive UA may prove to be useful in ways currently not imagined.

A unique set of human factors are associated with the operation and maintenance of small UAS. As will be outlined in this document, UAS maintenance is significantly different to general aviation maintenance. Points of difference include the equipment to be maintained, practices and documentation, and the characteristics of the maintainers themselves. In many cases, small UAS are maintained by generalist operator/maintainers who do not necessarily have backgrounds in aviation maintenance.

Two fundamental hazardous outcomes of UAS operation

The most important objective of UAS maintenance is to manage hazards that threaten people or property. The two most important hazardous outcomes associated with unmanned flight are:

> **Hazard 1.** *The UA collides with people or property on the ground.*
> **Hazard 2.** *The UA becomes an airborne hazard to other airspace users.*

There are several scenarios where maintenance actions could increase the risk of one of these outcomes occurring.

Hazard 1 could arise if the UA became incapable of flight, such as through an engine stoppage or a failure of a control actuator. Hazard 1 could also occur if the UA, although capable of sustaining flight, could no longer be directed by the operator.

Hazard 2 could arise through a failure of a sense and avoid system; however at present few small UA possess such systems, and the risks to other airspace users are usually managed by ensuring the UA remains within authorized areas of class G airspace. In common with hazard 1, this requires maintenance personnel to ensure that the UA can be controlled and navigated by the operator at all times.

Some UAS maintenance is performed for purposes unrelated to airworthiness, such as ensuring the operation of sensors or other payload equipment. Such maintenance is not considered in this handbook, except where it could contribute to one of the hazardous outcomes described above.

OVERVIEW OF UAS MAINTENANCE

Chapter 2

OVERVIEW OF UAS MAINTENANCE

Definition of maintenance

For the purpose of this handbook, UAS maintenance is defined as any activity performed on the ground before or after flight to ensure the successful and safe operation of the system. This definition covers a wide range of ground support activities including assembly, fuelling, updates to software, and pre-flight testing.

This handbook does not deal with the maintenance of on-board payloads such as sensors, except where this maintenance has implications for the safe operation of the UA.

The simple message of this handbook is that small UAS maintenance bears little similarity to conventional aviation maintenance. It is currently unregulated, and is rarely performed by personnel with formal maintenance qualifications.

UAS maintenance personnel

Most operations of small UAS do not have dedicated maintenance personnel. Instead, a small team of multi-skilled individuals performs the full range of tasks required to prepare the UA for flight. Throughout this handbook, “UAS maintenance personnel” refers to a person who performs a maintenance task on a UAS, even though that person may not necessarily consider themselves to be a maintenance technician.

Although some manufacturers of small UAS offer maintenance training courses, most of the people who perform maintenance have no formal preparation for their tasks, but bring experience from diverse backgrounds such as engineering, electronics or radio control aircraft operations. In most cases, their area of specialty is a field other than maintenance, and few possess aviation maintenance or flight crew licenses. The issues of personnel knowledge and skills are dealt with in Chapter 3.

Scheduled vs unscheduled maintenance

Ground support activities can be divided into the two broad categories of scheduled and unscheduled maintenance, each with its own challenges.

Scheduled tasks include routine inspections, adjustments, and time replacements of components. Scheduled maintenance also included planned ground support tasks such as pre-flight system assembly, fuel mixing, battery charging and pre-flight functional tests. Scheduled tasks tend to be performed frequently and become familiar, routine activities for the technician. The routine nature of such tasks can increase the chances of absent-minded errors such as memory lapses.

Unscheduled maintenance includes the identification of damage and the replacement or repair of components. Fault identification and diagnosis can be a time-consuming part of UA maintenance, particularly when faults involve avionics or computer systems. Unscheduled maintenance, by definition, is less predictable than scheduled maintenance, and each task may be performed infrequently. As a result, unscheduled maintenance can impose greater mental demands on the technician due to the need for problem-solving and the need to deal with unfamiliar situations.

Although the distinction between scheduled and unscheduled maintenance is widely used in the aviation industry, UAS personnel do not tend to make a clear distinction between the two types of maintenance. This is partly because in the absence of maintenance procedures, virtually all maintenance tasks are unscheduled.

Three locations for maintenance

UAS ground support tasks occur at three main locations: in the field, workshop, or at a manufacturer or specialist facility. Various tasks occur at each location, involving differing demands on the personnel involved. Table 1 gives examples.

Table 1. Examples of UAS ground support activities at each of three locations

	SCHEDULED	UNSCHEDULED
Field maintenance	Assembly, fuel mixing, calibration and adjustment	Minor repairs, troubleshooting operational faults
Operator's workshop	Preventative maintenance, replacing spark plugs, updating autopilot software	Minor repairs and alterations
Manufacturer or specialist facility	Scheduled engine overhaul	Repair of laptop hardware

Preparations for flight typically begin in the UAS operator's workshop, with checks on critical components such as batteries, servo actuators and connectors. Minor repairs can also be made in this location.

Field preparations include transport and unpacking tasks, and the assembly and testing of components. Malfunctions and irregularities are also responded to in the field. The relative immaturity of some UAS can lead to time-consuming troubleshooting as unexpected faults are corrected.

Major repairs typically require the affected component to be returned to the manufacturer or a specialist facility. The small size and modularity of many components means that shipping components, or an entire UA back to the manufacturer is a viable maintenance action. Engine overhauls, repairs to autopilots, and repairs to computer hardware are examples of tasks that would typically be handled by the original equipment manufacturer or a specialist facility.

System elements supported by maintenance personnel

Before identifying the challenges of maintaining small UAS, it is necessary to first identify the systems with which maintenance personnel interact, and the tasks they perform.

In conventional aviation, the responsibilities of the maintenance technician are confined to the airworthiness of an aircraft as illustrated in figure 1 below.

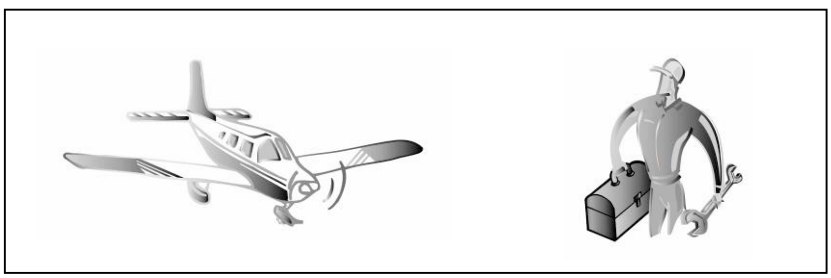


Figure 1. In conventional aviation maintenance, the technician's responsibilities are limited to the aircraft.

In contrast, the maintainer of a UAS is concerned with the reliable operation of an entire system, as shown in the figure 2 below. The system comprises not only the aircraft, but also ground-based support equipment, and the links between system elements. Ground-based system elements include launch systems, handheld controllers, ground control station, modem and radio transmitters, and antenna. Some UAS also possess landing systems such as nets or aircraft capture devices.

Where long duration flights are undertaken, satellite communication (usually via the Iridium system) may be important for control of the UA. In such cases, UAS technicians will also be responsible for the operation of satellite communication equipment on the ground and on-board the UA.

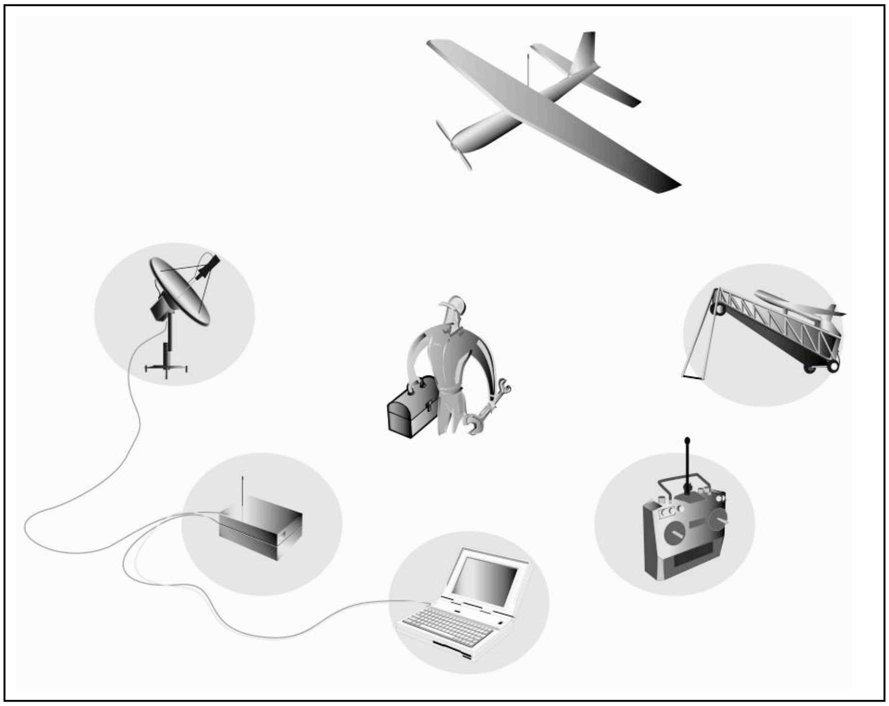


Figure 2. In unmanned aviation, the maintenance technician is responsible for the operation of an entire system, comprising airborne and ground-based components.

Maintenance activities can be divided into interactions with the aircraft, ground-based components, and whole-of-system interactions.

Case Study

An operator lost control of the UA on the first test flight after 40 minutes of flying because the battery pack, installed by the operator and fully charged, did not possess enough capacity to provide power during the duration of the flight. The operator originally requested a battery that was supplied for RC flying only. The operator was not aware that a different battery pack had to be installed for the longer flight test.

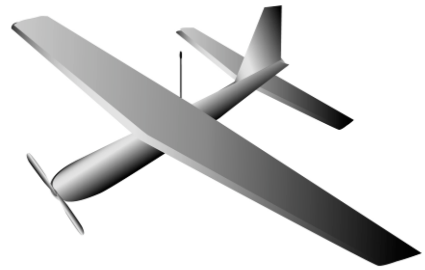
TYPICAL UAS MAINTENANCE TASKS

Chapter 3

TYPICAL UAS MAINTENANCE TASKS

Aircraft

The airborne components of the UAS include the airframe, propulsion and fuel system, autopilot, radio communication equipment, control surfaces, actuators, and electrical system. Some UA also include a feature unknown on manned aircraft, namely a flight termination system.



Scheduled maintenance

In addition to standard pre-flight visual inspections and engine runs, pre-flight tasks conducted in the field include some ground support activities particularly important for UA. Examples are shown below.

- Verify that connections have been securely made during assembly.
- Check the movement of control actuators.
- Measure the deflection of control surfaces, frequently with the use of a protractor.
- Test the activation of the flight termination system, such as an "engine kill" switch.
- Check the weight and balance of the aircraft, particularly after payload changes. Some operators adjust the balance of the aircraft by placing weights at points on the fuselage.
- Charge batteries.
- Fuel the aircraft. Most small UA do not have fuel gauges, so accurate measurement of fuel is critical.

Case Study

After the UA had climbed to its cruising altitude, the operator received a telemetry indication that the UA had less fuel on board than planned, even though the launch crew reported that the UA had been fueled with 2.8 kg of fuel immediately before launch. It was decided to continue the flight. Approximately 1 hour and 45 minutes into the flight, the launch crew noticed that the scales they had used to measure the fuel quantity were set to read in pounds. They realized that they had loaded 2.8 lbs (1.3 kg) of fuel instead of 2.8 kg of fuel. The incorrect setting of the scales was due to the relative inexperience of the launch crew and the plain and dull presentation of the scale instrument compounded with dust and dark conditions on the launch pad. The UA was returned and landed without incident. The actual fuel weight on recovery was 0.4 kg.

In recent years there have been significant developments in battery performance driven by the consumer electronics industry. UA rely heavily on batteries to power communication and navigation equipment, payloads, and increasingly, some propulsion systems. Electric motors are increasingly used to propel UA, and endurances of over an hour can now be achieved.

Batteries appear to be involved in a high proportion of UAS mishaps, both with airborne and ground-based components. Some types of batteries, particularly those containing lithium, can be dangerous if correct procedures are not followed, and careful attention must be given to battery charging/discharging cycles. These batteries may pose a fire hazard if abused, short circuited, overcharged, or damaged. A particular danger is that the fire may not start immediately, but may start after a period of time.

Case Study

"Rechargeable LI-Ion batteries must be charged in accordance with the manufacturer's 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".

Unscheduled maintenance

Compared to the ground-based components of the UAS, UA are more likely to experience impacts, mishaps, handling damage, vibration, and exposure to weather. Consequently, UA are more likely than ground-based components to require unscheduled maintenance. Hard landings are one of the most common reasons for unscheduled maintenance to UA.

In most cases, unscheduled maintenance is performed in the operator's workshop. Some tasks, such as specialized engine repairs, or testing of an autopilot, require the component to be shipped to the manufacturer.

Common unscheduled tasks include the following.

- Troubleshoot and correct faults with gasoline engines.
- Correct fuel system problems such as air in fuel lines.
- Repair airframe, wheels, or landing skids after hard landings.
- Repair electrical connectors.
- Tighten screws and fasteners that have backed out due to in-flight vibration.
- Respond to overheating avionics.
- Replace failed servos.
- Repair structural damage incurred during packing, transport, ground handling and flight operations.
- Respond to payload changes.

Case Study

"Every time we fly, we need to adjust our throttle setting. This is because we do not have any kind of engine feedback to the UAS ground control station or to the autopilot system. We must validate minimum throttle settings because the autopilot system is open-loop in terms of engine control. During one of our flights, the throttle settings were set too low or became lower during the flight possibly because of vibrations. This caused an engine stall, and we had to perform a quick emergency landing on the far end of the airfield. The location was beyond a safe visual distance. The result was an unexpected landing on the grass that caused some structural damage to the landing gear".

In conventional aviation, maintenance personnel have minimal interaction with aircraft cargo, and although weight and balance must be taken into account before flight, it is rare for the cargo of a conventional aircraft to interfere with the operation of the aircraft in-flight. In UAS however, carrying the payload aloft is the sole purpose of flight and payloads such as specialized sensors, may be more valuable than the aircraft. As well as potentially changing the weight and balance of the UA, payloads are also likely to require electrical power and cooling and have the potential to cause electro magnetic interference with other system components.

The modular construction of many UA enables major components such as engines and wings to be removed and replaced with relative ease. If the operator carries sufficient spares, the majority of unscheduled maintenance may involve "repair by replacement". Faulty units would then be shipped to specialized repair facilities, typically the manufacturer.

Ground equipment

A. User interface

In nearly all cases, a standard laptop or desktop computer serves as the user interface or "cockpit on the ground". Computers are subject not only to the usual threats of viruses, screen freezes, i.e. lockups, and flat batteries, but also hazards of outdoor environments, such as moisture, dust, and temperature extremes. As well as ensuring the reliable operation of the computer, ground personnel must also minimize the distractions caused by alerting and pop-up features. Several UA maintainers mentioned the problem of pop-up boxes appearing during a flight, such as indications that a wireless network was within range, or reminders to renew software licenses.

Case Study

After take-off, the UA began an uncommanded bank to the left. The operator attempted to command the UA to a waypoint but the system would not accept it. The operator then commanded wings level, without any response. The UA continued to turn left from its assigned heading until it had turned through 180 degrees at which point it overflew the ground control station. It then impacted the ground at full power in a nose down attitude approx 60 feet from the launch site. The aircraft was damaged beyond repair. No system errors or faults were identified during the launch or upon review of the telemetry. The UA appeared fully functional at the time of launch. Testing after the accident indicated that the ground station computer was running slow and the software was locking up. The computer was changed and the system returned to normal status. The manufacturer is investigating whether there is a software problem.

Some UA operators use their ground station laptops between flights for purposes such as checking email or word processing. This introduces potential threats such as viruses, or unintended effects of non-flight related software. Examples of common scheduled and unscheduled tasks are listed below.

Scheduled

- Update virus protection
- Verify that laptop batteries are charged sufficiently.
- Confirm that no extraneous utilities or programs are running in the background
- Check that latest flight software is loaded.
- Perform routine laptop maintenance such as periodic defragment of hard drive

Unscheduled

- Respond to software faults or laptop performance problems.
- Install software patches as necessary
- Respond to viruses

B. Radio transmitter and modem

In most cases, communication with the UA is via 900 MHz, using an unlicensed band of the radio spectrum, although other frequencies may be used as well. There are currently no radio frequencies reserved for non-military UAS use.

Although large UA may operate in controlled airspace, if it is assumed that small UA would operate in Class G airspace, no equipment would be needed for communication with air traffic control.

Managing the risk of radio interference from other users of the radio spectrum is a key concern of UAS operators. Flight preparation may involve checking that the frequency is not in use, or setting options for the transmitter and receiver to "hop" between frequencies.

When asked to describe maintenance activities, users referred to the need to check connections, but users rarely referred to unscheduled maintenance tasks being necessary with transmitters or modems.

Case Study
"I fly my UAV with an assistant with whom I communicate using a wireless duplex headset that runs at 900 MHz. This is the same frequency used to fly the UAV. While viewing the autopilot control screen, I sometimes see the telemetry system stop momentarily and then continue. It appears that the screen locks momentarily because there is conflict from the headsets that are operating in the same 900 MHz band. Despite this brief frequency interference, the UAV continues to fly properly. I now use a frequency hopping system to avoid this problem"

C. Antenna

Correct set-up of the ground antenna is critical to ensure a continuous link with the UA. Omni-directional antennas are frequently used, although some UAS use more complex tracking antennas. In 2003, loss of signal was identified as a causal factor in 11% of US military UAS failures[ii]. UA are typically 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. Examples of scheduled and unscheduled tasks are listed below.

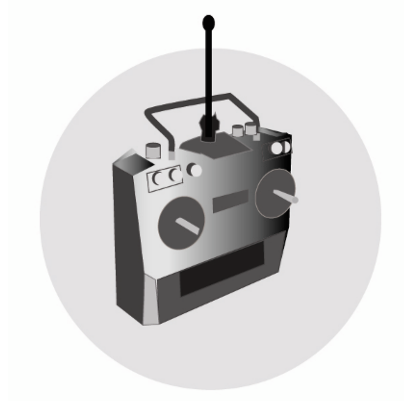
Scheduled

- Verify connections
- If tracking antenna, check for freedom of movement
- Perform range checks

Unscheduled

- If range checks indicate that the signal is interrupted, the problem must be diagnosed and corrected. In some cases, the presence of obstructions or personnel near the antenna can interrupt or attenuate the signal.

D. Handheld controller



Handheld controllers are used on many UAS for an external pilot to control takeoff and landing, with control transferred to the autopilot system for most of the flight. Controllers are generally maintenance free, although batteries must be charged or replaced. Unscheduled maintenance to a controller would generally involve return to the manufacturer.

E. Launch and recovery equipment

Launch systems, where used, require basic maintenance and may be a source of injury to personnel if not serviced correctly and treated with appropriate caution.

Relatively few UAS use ground-based recovery equipment. In most cases, the UA lands on a runway using landing gear or skids fitted to the aircraft.

Whole-of-system tasks

A unique feature of unmanned aviation is the whole-of-system check performed before flight. This check is sometimes referred to as a “connectedness” or “hardware-in-the loop” check. This check is particularly important given the number of distinct components that together comprise the UAS, the large variety of potential interactions that can occur between components, and the potential for interactions from external factors, especially from other users of the radio spectrum.

The check typically begins with tests of specific links, including the ability of the autopilot to move control actuators, the operation of the flight termination system, the functioning of the GPS, and satellite phone system, if used. Checks typically culminate in a final confirmation that all aspects of the UA can communicate with each other and perform their functions.

Whole-of-system checks are normally performed in the field, however some UAS operators perform full mission simulations in their workshops, with the UA “flying” an entire autonomous mission while secured to a test stand.

EMERGING MAINTENANCE CHALLENGES FOR UAS

Chapter 4

EMERGING MAINTENANCE CHALLENGES FOR UAS

A large amount of information has been published on human factors of airline maintenance, much of it based on FAA-sponsored research. Issues such as stress, poor communication, and distraction are now widely identified as hazards in conventional aircraft maintenance. While recognizing that these issues also apply to UAS maintenance, this handbook is focused on the emerging issues unique to UAS maintenance.

This chapter contains a summary of the emerging maintenance challenges of UAS. Issues have been placed into three broad categories, equipment and systems, personnel knowledge and attitudes, and information needs.

EQUIPMENT AND SYSTEMS

***1.** Maintainer responsible for whole system*

The most significant difference between the maintenance of conventional aircraft and UAS is that the UAS technician is responsible for a complete system, comprising the aircraft and a diverse set of ground-based equipment. As well as ensuring that each element of the system is functioning correctly, the technician must ensure the operation of the links between each system.

The servicing of ground-based components introduces a set of new demands unique to UAS maintenance.

***2.** Laptops and desktop computers now airworthiness items*

The guidance and control of most small UAS relies on standard laptop or desktop computers installed in a trailer. Ensuring the functioning of a commercial off-the-shelf computer has therefore become an airworthiness issue. The use of control station laptops for other purposes, such as surfing the web or checking email, may decrease laptop reliability. In some cases, computerized systems used in UAS produce faults that are poorly-understood by operators and maintainers. Some UAS operators acknowledged that they have resolved problems such as computer slowdowns, screen freezes, or radio frequency interference, without being completely sure why the problem occurred, and whether their actions addressed the underlying cause or merely removed the symptoms.

Case Study
The desktop computer, which was serving as the ground control system, locked up while the UA was in flight. This PC-based computer was housed in the ground control station trailer. The only alternative was to re-boot the computer, and this took about 2 to 3 minutes before command-and-control of the UA was reestablished. The UA flight path, however, was already uploaded so there was no effect on the flight sequence. The reaction from the flight team was minimal since the UA was in visual range and the RC pilot could have taken over at any time. The UA flight team reported that this sequence had never happened before.

It should be noted that the problem of ground control lockups is not limited to small UAS. The NTSB investigation into a crash of a General Atomics Predator B in 2006 identified that a series of unexplained Ground Control Station console lockups had occurred in the months preceding the accident[iii].

In addition to managing threats to computer reliability, there is also a need to manage normal but potentially distracting features of mass-market computers such as pop-up messages or software reminders.

***3.** Repetitive assembly and handling*

Conventional aircraft remain assembled throughout their service life. In contrast, the components of a UAS are regularly reassembled and disassembled before and after each flight. The frequent connection and disconnection of electrical and other systems can increase the chances of damage and maintenance errors. The chance of error may be increased by factors such as time constraints, poor lighting, or fatigue.

Operators report that transport and handling damage i.e. "ramp rash", are significant issues due to the need to move and assemble UA. Carrying UA into and out of vehicles and through doorways creates numerous opportunities for damage.

Case Study

After departure, the UA performed unusually slow rates of turn to right and tight turns to the left and struggled to track as designated by the operator. Approximately seven minutes into the flight, the UA commenced a slow left turn, which developed into an inverted roll. Once inverted, the outboard section of the right wing separated from the centre wing section. The UA immediately reversed its roll direction and entered a rapid clockwise spiral, before impacting the ground. The most likely explanation for the crash was that the outboard section of the right wing was incorrectly attached during pre-flight assembly of the UA and from launch it flew with difficulty until the wing section eventually separated.

***4.** The "Grandfather's ax" problem*

A consequence of the modular construction of many UA is that once major system components such as wings or engines have been swapped, 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 UA that has had several major component changes may be the same aircraft in name only.

***5.** Battery hazards*

UAS maintenance personnel must have an awareness of battery hazards, not only the hazards to the UAS, but also the potential hazards involved in handling and shipping batteries. The increasing use of re-chargeable lithium batteries in UAS operations raises the potential that maintenance personnel will be required to ship batteries, such as to return a faulty battery to the manufacturer. The transportation of lithium batteries is currently a matter of concern to several government agencies[iv].

***6.** Payloads and their implications for safety*

Conventional aircraft are typically used to transport passengers or cargo. UA are most commonly used as sensor platforms. In contrast to conventional aircraft, the payload on board a UA is more likely to be integrated with the structure, power supply and autopilot, and be capable of transmitting data during the flight.

Ground support personnel are generally responsible not only for the airworthiness of the UA, but also the functioning of payload equipment such as cameras or other sensing devices. UA maintenance personnel do not tend to make a clear distinction between the maintenance of the UA and the maintenance of its on-board payload.

Payloads have airworthiness implications, not only via weight and balance, but also by drawing power, generating heat, or producing electro magnetic interference with other equipment. In some UA, access to payloads may also require non-related systems to be disconnected or moved, thereby increasing risk.

There is a need for UA maintenance personnel to understand the distinction between payload issues that create safety hazards and payload issues that merely affect the functioning of the payload.

Maintainers should have the mindset that the question, “Will the installation, modification, or operation of this payload degrade the safety of flight?” should take precedence over the question, “Will this payload function?”

An important distinction can be made between UAS operations with fixed or standard modular payloads, and operations where the payload is changed or modified on a regular basis. Aircraft that carry payloads specifically designed and tested for use on the aircraft should be less likely to experience problems, such as out-of-limits weight and balance or electromagnetic interference, than aircraft with regularly changed or non-standard payloads. Standardized aircraft-payload configurations will significantly reduce the cognitive demands on the maintenance technician, particularly reducing the need for troubleshooting and knowledge-based problem solving, which is prone to error.

7. *Criticality of data link*

Although a manned aircraft can operate in the absence of a communication link, the loss of communication with a UA can result in the loss of the aircraft. Therefore, the maintenance of a data link between the ground control station and the UA takes on a level of criticality not present in conventional aviation.

PERSONNEL KNOWLEDGE AND ATTITUDES

8. *May not be a dedicated maintenance person*

The distinction between pilot and maintainer has existed since the beginning of aviation, but may not apply to small UAS, where there is unlikely to be a single person whose sole responsibility is maintenance. Small UAS tend to be maintained by teams of multi-skilled individuals who perform all necessary ground tasks from assembly, flight preparation and in-flight operation. For very small systems, a single owner/operator is likely to perform all tasks, including maintenance.

9. *Involvement of manufacturers or specialist repairers in maintenance*

Modular, compact construction enables most UAS components and even entire aircraft to be shipped to specialist repair centers with much greater ease than can occur with conventional aircraft.

A two-tier approach to UAS maintenance is emerging, where operators perform mostly routine and minor unscheduled maintenance tasks in the field or in small workshops, and return components to the manufacturer for more complex overhauls or repairs. Furthermore, many components such as laptop computers, autopilots, and GPS units, are not user-serviceable systems. One UA manufacturer reported that the dimensions of their aircraft had been chosen to fit within a UPS shipping box, to enable ease of shipping.

A two-tier system generally exists in military UAS, with a distinction 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.

10. *Wide but shallow skill set for operator/maintainers*

The skill set required to work on UAS in the field or at the operator's workshop is significantly different to that traditionally taught to aircraft maintenance technicians. In addition to a familiarity with the components of the aircraft itself, such as engines, batteries, fuel systems and servos, UAS maintainers require an understanding of the diverse technologies used to communicate with and control the UA, including computer software and hardware, micro autopilots, radio communication equipment, modems, the hazards of radio frequency interference, and in some cases, satellite navigation. An implication of the two-tier approach is that different skill sets will be required for minor UAS maintenance in the field or workshop, and major maintenance at a specialist facility

Members of the UAS operating team will need to have the skills and knowledge necessary to understand the operation of components, troubleshoot minor faults and integrate system elements, but will not generally be required to perform complex repairs or overhauls on specialized components. Shop maintenance personnel on the other hand will require a more in-depth set of skills and system knowledge.

Some larger manufacturers of UAS provide training courses for users of their systems, however in most cases, UAS maintenance personnel are self-taught. The development of maintenance skills must therefore come through experience, including trial and error learning.

Case Study

"The user of a recently purchased UA improperly assembled the aircraft after delivery. He simply did not tighten the propeller fully. The propeller came loose during the ground test of the system. Fortunately, no damage occurred to the UA. This incident could have been much more serious if it occurred in the air. It was caused by the user's lack of familiarity with basic maintenance procedures for tightening bolts".

11. *High accident frequency & salvage decisions*

Compared to conventional aircraft, small UA are more likely to experience damage caused by events such as hard landings, contact with water, or landing in trees. UA also tend to be less waterproof than conventional aircraft leading to a greater chance of water damage to internal components.

Referring to the five-pound Dragon Eye in operation with the US Military, a Marine official was quoted as saying "One of them has 50 crashes on it and it is still flying"[v].

To a greater extent than in conventional aviation, UAS maintenance personnel will be required to make judgments about the salvage, testing and re-use of components from damaged UA. In the case of modular aircraft designs, an apparently undamaged modular unit may have an unseen defect.

12. *Shift of risk from occupants of aircraft to uninvolved people*

The introduction of unmanned aviation shifts the balance of risk in ways that must be understood by maintenance personnel.

In conventional aviation, the safety risks associated with flight are in large part borne by the people who receive the benefit of flight, i.e. flight crew and passengers. Sometimes referred to as "shared fate", a threat to the safety of a conventional aircraft is also a threat to the occupants of the aircraft.

In unmanned aviation, the beneficiaries of the flight remain on the ground, and the safety risks are borne largely by non-involved individuals; occupants of conventional aircraft, people under the flight path of the UA, and property owners.

While there are no on-board lives at risk, the maintenance person is not necessarily conducting maintenance for the safety of specific identifiable individuals, but for the safety of the community as a whole. Even though the risk to the community from unmanned aviation may be small, it is well established that the community tends to demand higher safety standards of technologies that are new, are not well understood, and where the targets of the hazard have little control over their exposure to the hazard.

UA maintenance personnel must understand that precisely *because* there is no human life aboard the aircraft, the community may have a lower tolerance for incidents such as UA straying into the path of conventional aircraft or crashing into urban areas.

13. *Risk associated with maintenance of ground equipment while missions are underway*

Clearly, the cockpit of a conventional aircraft is out of reach of maintenance personnel once the aircraft has left the ground; however the ground station (or cockpit) of a UAS remains accessible to personnel on the ground, who may be required to perform unscheduled maintenance while a flight is underway. For example, an in-flight problem may require troubleshooting of ground equipment, or an unscheduled action, such as a re-start of the ground control laptop.

Although sometimes necessary, the maintenance of "live" systems introduces a unique set of potential problems and challenges. A maintenance technician interacting with a live system requires a clear understanding of the operational implications of their planned intervention, and must also consider the potential effects of errors.

There is also a need for clear communication with users before any maintenance with a live system occurs. Ideally, only unscheduled tasks that are operationally necessary should be carried out while the UA is in flight. There is little justification for scheduled preventative tasks on ground equipment while the UA is in flight.

Before performing any unscheduled maintenance of ground equipment while a UA is airborne, it is necessary to be especially mindful of potential risks. For example, technicians must consider what could potentially go wrong if a particular system were disconnected.

A clear difference between maintaining a "live" system and an "off-line" system is that maintenance errors can have an immediate impact on live systems. For example, an accidental interruption to a power supply can have an immediate impact and may take time to recover as systems slowly re-boot.

14. *Model aircraft culture*

Many UAS maintainers have a background with radio control aircraft and relatively few have experience in conventional aviation.

There is a view among some UAS operators that cultural differences exist between the radio control hobby world and mainstream aviation, in particular that some RC hobbyists may be accustomed to operating without formal procedures or checklists, and may be unfamiliar with the ethics and standard practices of aircraft maintenance, and the legislative framework within which maintenance occurs.

If a future UAS industry recruits maintenance and operational personnel from the RC hobby fraternity, there may be a need to provide advisory material to familiarize UAS technicians with aviation practices, legislation, and expectations.

In some cases, technicians may need to “unlearn” work habits that would be out of place in mainstream aviation. The use of ground control laptops as personal computers between flights is an example of an informal practice that could be targeted for cultural change.

INFORMATION NEEDS

15. *Lack of formalized procedures*

Maintenance documentation for many UAS is either non-existent or of a poor standard. Small UA generally have rudimentary operating documentation, however many are delivered without maintenance documentation. Users generally develop their own maintenance checklists and procedures to guide system assembly, perform scheduled pre-flight checks, and record defects. In most cases, UAS technicians lack guidance to assist with unscheduled maintenance such as troubleshooting and repair. In the absence of such documentation, technicians must rely on their own system knowledge and problem-solving skills. Procedures performed without documented guidance are more prone to error than documented procedures. Undocumented procedures are likely to provoke memory lapses (such as connections not mated properly, and caps and covers left undone) and knowledge-based mistakes (such as incorrect assembly of components or wrongly wired electrical connections). Undocumented procedures are also more susceptible to distractions and interruptions that can lead to omitted steps.

A reliance on personal expertise (sometimes referred to as “knowledge in the head”) may be acceptable in small craft-based industries, but becomes problematic during periods of rapid industry expansion, especially as a large number of inexperienced personnel enter a field. In the absence of documented procedures, a large proportion of new technicians can be expected to be on a steep learning curve as they develop expertise through experience.

16. *Replacement of on-board pilot reports with automated monitoring systems*

In conventional aviation, the on-board pilot has a direct experience of aircraft performance via the handling feel of the aircraft, as well as sounds, vibrations, and even smells. With no on-board pilot, UAS maintenance personnel lack a key source of information about aircraft performance. To some extent, automated in-flight monitoring provides an alternative source of detailed information. However automated monitoring systems can at times provide an overwhelming volume of precise data with relatively little consolidated information.

17. *Lack of on-board meters*

UA do not generally have on-board meters to 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 the scheduling of inspections. The modular construction of many UA also means that different flight hours may be accumulated by different components on a single aircraft. For example, the wings, engine and fuselage may each have their own history of hours flown.

18. *UAS accidents not investigated*

The internationally recognized definition of an aviation accident, contained in ICAO annex 13, specifies that the occurrence must occur while people are on board the aircraft with the intention of flight. Clearly, this definition excludes UAS and inhibits the reporting and investigation of UAS accidents.

Compared to a manned aircraft, a crashed UA is less likely to be located and recovered, making it more difficult to identify maintenance errors on the basis of physical evidence.

19. *No incident reporting system*

A safety incident is an occurrence that, although not resulting in damage or injury, had the potential to do so. In conventional aviation, human factors and other safety issues have been identified with the aid of confidential incident reporting systems, such as NASA's Aviation Safety Reporting System and industry-based Aviation Safety Action Programs. These systems enable personnel to report safety incidents without fear of retaliation or regulatory action.

Ironically, the nascent UAS industry, where safety issues are least understood, lacks an incident reporting system. In contrast to aviation reporting systems that collect mostly in-flight reports from pilots, any future UAS reporting system must gather information mostly from ground-support personnel, many of whom will be involved in maintenance.

In the course of discussions with UAS operators, it became apparent that concerns about confidentiality and FAA enforcement action are currently suppressing the open disclosure of incidents, which in turn may make it difficult for the UAS industry to learn from experience.

20. *Lack of information on component reliability*

The manufacturers of components used in small UA generally do not provide data on the frequency and mode of failure or the expected service life of these components. This information is particularly hard to find 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. The absence of such information makes it difficult to develop appropriate scheduled maintenance programs. Failures of off the shelf actuators have been identified as one of the leading causes of control failures in military UA[vi].

21. *Lack of part and serial numbers*

Smaller manufacturers of UAS do not generally use part numbers or serial numbers on components. This makes it difficult, if not impossible, to track the maintenance history of these components. In addition, a lack of serial numbers may increase the probability of errors resulting from misidentified parts, mistaking an unserviceable component for a serviceable one, or fitting non-compliant components to a UA

FUTURE DIRECTIONS

Chapter 5

FUTURE DIRECTIONS

UAS technology is evolving rapidly. As progressively smaller components are released to the market, it is likely that the first wave of commercially useful UA operations will involve light UA, used over relatively small distances at low level, possibly with electric propulsion. Key maintenance differences between conventional aviation and unmanned aviation are outlined in Table 2 below.

The absence of an on-board pilot does not mean that human factors will not apply to small UAS. Rather, it is possible that maintenance and other ground support activities will have an *increased* importance in UAS flight safety, perhaps mirroring the decreased role of humans as direct physical controllers of the vehicle in flight. Furthermore, without an on-board pilot to detect and respond to in-flight problems, maintenance-induced anomalies that would have been recoverable in conventional aviation may be non-recoverable in unmanned aviation. Examples of the issues that must be considered by the operator of a UAS before flight are listed in Attachment 1 of this handbook. This attachment is intended to illustrate how operators can systematically identify the hazards associated with their UAS and develop appropriate countermeasures.

The diversity and rapid pace of change in the small UAS sector make it difficult to specify in detail the skill and knowledge requirements for maintenance personnel. It is clear however, that UAS maintenance personnel require a significantly different skill set to their counterparts in general aviation. Components such as laptop computers, modems, and radio communication systems are critical to the safety of unmanned flight. Future requirements or guidance for UAS maintenance training or qualifications must go beyond the traditional curriculum for aircraft maintenance mechanic training, to include topics such as electronics, radio communications, computer maintenance, and software updating and troubleshooting.

The regulatory approach currently applied to the maintenance of conventional aircraft is not likely to be suitable for small UAS. Most notably, a specific profession of “UAS maintenance technician” is unlikely to emerge. Instead, maintenance and ground support activities are likely to performed in the field or operator’s workshop by multi-skilled personnel, with specialist personnel only becoming involved when components are sent away for major repairs or overhauls. In addition, many of the maintenance tasks performed on UAS fall well outside regulations that were designed for earlier generations of conventional aircraft. The maintenance of laptop computers and other ground-based systems are obvious examples of this.

It should also be noted that the maintenance of large UA, such as Predator and Global Hawk, may have very little in common with the maintenance of small UAS. The consequences of improper maintenance of large UA are likely to be significantly greater than those with very small UA. A single approach to UAS regulation is unlikely to fit the entire spectrum of UAS, and it would be beneficial if the public discussion about UA recognized the different magnitude of risk between large and small UA. Attachment 2 of this handbook lists potential responses from regulatory agencies, and the emerging UAS industry, to the issues outlined in Chapter 4. This attachment is intended to highlight areas where national or industry-wide coordination is required.

If it is considered that small UA will present a minimal risk to public safety, a self-regulatory model, such as applies to some forms of sports aviation, may be justified. Such an approach might involve an industry association representing the interests of operators of small UAS and handling the issuance of ratings for UAS operation and maintenance.

Table 2. Key maintenance differences between conventional aviation and small unmanned aircraft systems

CONVENTIONAL AVIATION	UNMANNED AVIATION
Specialized computer hardware and software used in flight system.	Commercial "off the shelf" desktop or laptop computers part of flight system.
Primary responsibility of maintainers is to ensure safety of people. Beneficiaries are occupants of the aircraft, other airspace users, and people on the ground.	Primary responsibility of maintainers is still to ensure safety of people, however beneficiaries are other airspace users and people on the ground.
Detailed maintenance documentation and checklists.	Limited or absent maintenance documentation or checklists.
Clear distinction between technician and pilot.	Single operator may perform piloting and maintenance tasks.
Ground facilities maintained by FAA personnel.	Ground facilities maintained by UAS technician.
Aircraft rarely sustain damage.	Frequent accident damage.
Aircraft remains assembled between flights.	Aircraft and ground station equipment frequently assembled and disassembled.
Cargo less likely to cause electromagnetic interference or physical interference with operation of aircraft.	Payload more likely to cause electromagnetic interference or physical interference with operation of aircraft.
Maintenance never occurs while aircraft is in flight.	Ground-based components may require troubleshooting or corrective maintenance while aircraft is in flight.
Difficult to return aircraft and/or major components to manufacturer.	Easier to ship aircraft and/or components to manufacturer.
Avionics systems are critical for navigation and communication.	Avionics systems are critical for flight. Modular construction makes it easier to swap out components.
Replacing components can be difficult and time consuming.	Manufacturer likely to perform major maintenance.
Manufacturer does not typically offer maintenance services.	Maintainer relies on remotely sensed data or visual observation of flight performance.
On-board pilot provides maintainer with direct experience of aircraft performance. Accident and incident reporting systems in place.	No accident or incident reporting systems.
Certificated aviation parts used.	Some parts sourced from hobby stores.
Extensive human factors guidance material available.	Limited human factors guidance material available.

Appendix 1. Critical scheduled maintenance activities for operators of small unmanned aircraft systems (Illustrations of tasks, not a complete list)

COMPONENT	ISSUE	ACTION
Laptop	Battery charge	Check battery charge before flight, even when an external power source is available
Laptop	Risk of computer viruses or interference from non-flight related software	Ensure anti virus software is current Disable pop-up messages or reminders not related to flight software Set the screen saver to "off" Ensure that laptop is not set to automatically connect with wireless networks Ensure that no software can initiate an un-commanded shut down or re-start
Laptop	New software updates may contain bugs	After updating software, run a ground test to ensure that aircraft and software function correctly.
Laptop	Failure of laptop	Ensure that aircraft is programmed to react safely to loss of link
Laptop	Bugs with new operating systems	Where possible, use familiar and well-proven operating systems in preference to newly- released operating systems
Laptop	Check battery for signs of physical damage	Defragment the hard drive at regular intervals
Laptop	Build-up of dirt or dust in keyboard, cooling vents, ports and on screen	Clean laptop following manufacturer's directions
Laptop	Risk of physical damage from handling and environment	Where possible, use a "ruggedized" laptop.
Laptop	Lockups or interference	Keep the laptop away from radio transmission equipment or equipment that produces strong magnetic fields
Transmitter and modem	Loose connections	Check connections
Antenna	Loose connections	Check connections
Antenna	Interrupted signal	Check signal
Antenna/Laptop	Interference	Check for interference
Handheld controller	Battery charge	Check battery charge
Handheld controller/ aircraft	No control or limited control	Check connection
Whole of system	Ground control station communication with aircraft	Perform "hardware in the loop" check to ensure all links are functioning
Aircraft	Handling and transport damage	Check aircraft for damage
Aircraft	Airframe assembly errors	Check physical connections
Aircraft	Avionics and engine assembly errors	Check electrical, data and fluid connections
Aircraft	Control actuators alignment and functioning	Measure the deflection of control surfaces under actuator control
Aircraft	Un-commanded activation of flight termination system, or failure of system	Check functioning of flight termination system
Aircraft	Disturbances to weight and balance, particularly after payload changes	Check weight and balance
Aircraft	Battery charge	Check battery charge
Aircraft	Battery damage and risk of fire in lithium ion batteries.	Check battery for physical damage

Appendix 2. Critical maintenance issues and potential responses from regulatory agencies and industry

ISSUE	POTENTIAL RESPONSE
1. Maintainer responsible for whole system	Regulatory or advisory material should be concerned with "unmanned aircraft systems" not just "unmanned aerial vehicles".
2. Laptops and desktop computers now airworthiness items	Ground station computers should be used only for flight-related purposes Encourage the use of ruggedized laptops Operators should be able to demonstrate that flight software performs reliably. This may include: *updated or new flight software is trialed on ground before flight *anti virus software installed and up to date
3. Assembly and handling	Systems should be designed for ease of repetitive assembly and disassembly.
4. The "Grandfather's ax" problem	Regulatory or advisory material should be prepared with the awareness that modular construction may make it meaningless to treat a small UA as a permanent aircraft, with a tail number.
5. Battery hazards	Batteries should not be returned to the manufacturer by air freight.
6. Payloads and their implications for safety	Other than in experimental aircraft, standardized payloads should be developed to interface seamlessly with the UA, minimizing the risk of interference with flight performance. Maintenance personnel should be aware that safety of flight takes precedence over operation of the payload
7. Criticality of data link	A dedicated range of the radio frequency spectrum may be required for UAS operations.
8. May not be a dedicated maintenance person	Regulatory or advisory material should be prepared with an awareness that the traditional pilot/maintainer distinction may not apply to small UAS
9. Involvement of manufacturers or specialist repairers in maintenance	Regulatory or advisory material should take into account the emerging 2-tier approach to UAS maintenance, where operators perform minor field and workshop maintenance, and specialist facilities perform more complex tasks. If in future, the FAA regulates the skills and knowledge requirements of UAS maintenance personnel, specialist repair personnel may require a narrow but deep skill set.
10. Wide but shallow skill set for operator/maintainers	If in future, the FAA regulates the skills and knowledge requirements of UAS maintenance personnel, operator/maintainers may require a broad but shallow skill set.
11. High accident frequency and salvage decisions	Maintainers should have knowledge and skills to make decisions about repair and salvage of components after an accident or contact with water Manufacturers should provide guidance on how to check a UA after an accident or contact with water
12. Shift of risk from occupants of aircraft to uninvolved people	Regulatory action for small UAS should recognize that the risk of UA operations, although potentially small, is borne primarily by other airspace users and by people and property on the ground.
13. Risk associated with maintenance of ground equipment while missions are underway	Maintainers must be aware of the risks of interacting with ground-based equipment while a flight is underway.
14. Model aircraft culture	Advisory material could be developed to familiarize UAS maintenance personnel with standard practices in conventional aviation maintenance, and their legal responsibilities.
15. Lack of formalized procedures	Manufacturers should provide detailed documentation for those preventative and corrective maintenance tasks performed by users.
16. Replacement of on-board pilot reports with automated monitoring systems	On-board sensors should provide useful and appropriate data to maintainer, without an excessive amount of low-value information.
17. Lack of on-board meters	Manufacturers should make full use of on-board vehicle health monitoring, but without overloading ground personnel with trivial data.
18. UAS accidents not investigated	The definition of "accident" should be updated to include UAS occurrences.
19. No incident reporting system	A confidential incident reporting system for UAS operations should be established.
20. Lack of information on component reliability	Encourage sharing of operational experience on component failure modes and rates.
21. Lack of part and serial numbers	Manufacturers should use appropriate labelling or numbering to identify components.

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