A TECHNOLOGY SURVEY AND REGULATORY GAP ANALYSIS OF EMERGENCY RECOVERY AND FLIGHT TERMINATION FOR UAS

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For unmanned aircraft systems (UAS) to operate in the National Airspace System, regulations must exist to certify them as airworthy and pilot/crew procedures must be revised to ensure the safety of the general public. This paper presents a study of the current technologies, procedures, and regulations related to emergency recovery and flight termination systems for UAS. Emergency recovery includes health-based recovery in which the vehicle autonomously adapts to minor faults, and contingency-based recovery in which the vehicle must alter its mission profile to restore safe operation. If these systems fail, flight termination systems exist to bring the aircraft down immediately.

INTRODUCTION

The inclusion of unmanned aircraft systems (UAS) into the United States National Airspace System (NAS) has forced regulators to take pause to determine the best way to regulate and integrate these systems so that a reasonable level of safety is maintained. The process of changing the existing regulations for manned aircraft or adding new regulations specifically for UAS is both challenging and time consuming. Another approach is to re-interpret existing regulations toward UAS.

In order to maintain a sufficient level of safety, UAS must be equipped with systems to detect faults and failures of its onboard components including mechanical systems and avionic systems such as data links, onboard controllers, and sensors. Emergency recovery (ER) is the action of the aircraft to determine that a fault has occurred and to recover from that fault maintaining continuous safe flight. Flight termination (FT) represents a last ditch effort to handle a failure such that the aircraft is brought down while minimizing the risk to the public and property. This study looks at Emergency Recovery and Flight Termination (ERFT) systems onboard current and near-term future UAS to determine where these technologies onboard unmanned aircraft differ from...
those onboard manned aircraft and the impact of these differences on the current regulatory framework.

The first half of this study involved the gathering of information through a technology survey. In the technology survey, literature from conferences, journals, vendor data sheets, and technical white papers were gathered and analyzed to determine a common set of technologies and unique technologies currently used for emergency recovery and flight termination of unmanned aircraft. Health-based recovery focused upon ER technologies in which the aircraft maintains its current mission while necessary steps were taken to mitigate the impact of a fault or failure. Contingency-based recovery focused upon ER technologies that handled the recovery of the failure by modifying the aircraft’s flight path in order to restore some functionality or mitigate the risk to others during the emergency situation. Flight termination focused on technologies that provided immediate termination of flight such as an emergency landing or with more extreme prejudice such as using explosives to destroy the aircraft.

The second half of the study is a regulatory gap analysis, which identifies the gaps between the current technologies and their capabilities versus the requirements of existing regulations. Relevant regulatory materials were gathered including federal aviation regulations (FARs) identified in Title 14 of the Code of Federal Regulations. From each regulatory document, the sections specifically impacted by ERFT were identified. Using rubrics presented below, each section impacted by ERFT was analyzed to determine the level of applicability: applies as is, applies with revision, applies with interpretation, or does not apply. This was performed for each of the technology survey areas described above including health-based recovery, contingency-based recovery, and flight termination. In addition to these three technology areas, ERFT related pilot procedures were analyzed. From the analysis, fundamental gaps are identified in which the differences between manned and unmanned aircraft produce large and wide spread regulatory gaps.

The goal of this study is to produce a single report that can be used to provide knowledge to regulators. The report shall accompany a number of other reports produced by the authors for other UAS subsystems including: propulsion, command, control, and communications (C3); and detect, sense, and avoid (DSA). Second, the regulatory gap analysis is discussed. Finally, some conclusions are made regarding the results of the study.

BACKGROUND AND RELATED WORK

The need for ERFT is evident through existing literature. The topic is discussed in several published papers. Domestic and international civil and military air authorities have published guidance regarding ERFT for UAS. This section presents a summary of this work. A survey of existing manned pilot procedures for emergencies is then discussed. Lastly, a survey of previous regulatory gap analyses is provided.

Publications

In a 2004 publication from MITRE by Degarmo, “Issues Concerning Integration of Unmanned Aerial Vehicles in Civil Airspace”, the roles of lost link (LL) procedures and of ERFT were dis-

* http://ecfr.gpoaccess.gov/cgi/t/text/text-idx?c=ecfr&tpl=/ecfrbrowse/Title14/14tab_02.tpl
It is indicated that ER procedures are a predefined sequence of actions to recovery from a perceived failure and can be initiated by either the pilot or the aircraft itself. In the article, special classes of airspace were proposed for UAS emergency recovery activities, including designated and documented emergency landing sites throughout the world. Given these resources, emergency recovery flight paths could be preplanned and shared with air traffic control (ATC) to improve situation awareness and help controllers better react to a UA in distress.

The Hayhurst et al. paper, "Unmanned Aircraft Hazards and their Implications for Regulation," from Digital Avionics Systems Conference #25 considers the safety of individuals on the ground. Even if the kinetic energy of the aircraft does not pose a threat, there must be consideration for potentially hazardous payload or fuel. Similar do DeGarmo’s proposed emergency landing sites, a “crashport” is presented as an option providing designated areas for the UA to terminate its flight.

Existing Regulatory Requirements

The primary example of requirements for LL and ERFT procedures are found in the FAA Unmanned Systems Program Office (AIR-160) “Interim Operational Approval Guidance 08-01” regarding unmanned aircraft operations in the NAS. Included in that document is guidance for UAS operators seeking either a COA (public institution) or Special Airworthiness Certificate – Experimental (private endeavor). LL procedures must be defined for the aircraft, but no specific approach is mandated. The UAS must also have a FT system if sufficient redundancy does not exist to ensure continuous flight in the event of a system failure. The FT system must be independent and able to be actuated by the Pilot-in-Command (PIC).

More details on obtaining a Special Airworthiness Certificate–Experimental are found in FAA Order 8130.34, published 27 March 2008. This document provides guidance to FAA personnel responsible for issuing the Special Airworthiness certificates. It requires the applicant to describe FT system, LL contingency plans, and contingencies should the UAS run out of fuel.

Interim guidelines have also been defined by a number of international aviation authorities. The Australian government’s Civil Aviation Safety Authority’s AC 21-43(0) of June 2006 specifies the requirements for experimental certificates for research and development for daytime flight over unpopulated areas under visual flight rules (VFR). It mandates that under a FT scenario the aircraft must be guaranteed to have a probability of less than $10^{-5}$ that the aircraft will not depart the prescribed operating area. Lost link must be addressed by the aircraft either returning to base or triggering a FT. Other international examples include the final report by Transport Canada’s Civil Aviation UAS working group emergency recovery system guidance, the European Aviation Safety Agency (EASA) Notice of Proposed Rulemaking, and the UK’s CAP 722 document, “Unmanned Aircraft System Operations in UK Airspace – Guidance”.

Pilot Procedures

Issues of emergency recovery and flight termination are not limited to UAS. PICs in traditional pilot-on-board aircraft have to deal with emergency situations, some of which require unplanned landings or result in crashes. Knowledge of emergency procedures, including emergency landing due to engine failure, is required for basic certification as a pilot.
Generic FAA guidance for dealing with in-flight emergencies on traditionally piloted small fixed-wing aircraft is found in the FAA Airplane Flying Handbook (AFH). The AFH specifies that guidance material particular to the aircraft being operated supersedes its own generic instructions. The AFH defines types of emergency landings (forced landing, precautionary landing, and ditching into water), psychological aspects of emergency landings (reluctance to accept the situation, desire to save the aircraft, undue concern about getting hurt), basic safety concepts (sacrificing dispensable structures to avoid injury to pilot and passengers, utilizing vegetation to absorb energy, locating a flat and open field for an emergency landing) appropriate aircraft attitude and configuration to minimize risk, approach, terrain types, and ditching in water and snow. It addresses issues of safely returning to the runway in event of engine failure after takeoff and methods of emergency descent. It describes what to do in event of in-flight fire (engine fire, electrical fire, cabin fire).

The AFH describes dealing with flight control malfunction and failure (total flap failure, split flap, loss of elevator control, and landing gear malfunction). It discusses failure of other on-board systems, including the electrical system and the pitot-static system. It discusses the door-open-in-flight situation. It concludes with pilot procedures should the pilot encounter Instrument Meteorological Conditions (IMC) on VFR flights.

Material in the AFH maps to UAS differently as one distinguishes between UAS without passengers and remotely piloted aircraft with passengers (a situation that cannot be precluded from happening at some point). In both situations, however, regulatory gaps arise not because existing regulations fail to apply or apply only in part to novel technology, but because pilot procedures for manned aircraft require codification into rules for UAS.

A similar situation arises regarding pilot communications with ATC in both normal and emergency flight. That the PIC of a UAS is remotely located from the aircraft itself creates regulatory gaps as discussed in previous gap analysis studies on DSA and C3. Similar issues due to the remotely piloted nature of UAS arise regarding ERFT. FAA guidance material for such pilot procedures is found in the FAA Aeronautical Information Manual (AIM).

Methods for Performing a Regulatory Gap Analysis

The ERFT regulatory gap analysis is generated from a study of current regulations and the determined level of applicability for each in order to make statements regarding lack of coverage of ERFT technologies in the context of UAS by the current regulatory framework. This section is a review of ways in which regulatory gaps have been presented previously in the literature.

Previous regulatory gap analyses examined regarding UAS include Marshall et al., an examination of the FARS for applicability to UAS in general; and reported by other teams including the authors of this study regarding applicability of the FARS to the particular matters of propulsion, of Detect, Sense, and Avoid, and of Command, Control, and Communication for UAS. Frater et al. is a regulatory gap analysis regarding nanotechnology.

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1 http://www.faa.gov/library/manuals/aircraft/airplane_handbook/
2 http://www.faa.gov/air_traffic/publications/ATPubs/AIM/aim.pdf
In Griffis et al., the ensemble of rule applicability results was analyzed and the results summarized into two differing regulatory gaps. The first gap, the “Fundamental Gap” for propulsion technologies, was the lack of rules applying to electric propulsion systems. While some rules applying to other electrical systems might be leveraged to apply to aspects of propulsion systems, use of electric propulsion (in any aircraft system, not just UAS) was considered and presented as a fundamental gap. The second, the “Open-Set Gap,” was a more inclusive gap resulting not only from the introduction of electric motors for propulsion, but from a variety of energy-generation and storage mechanisms for electric-powered flight, from generators and batteries to photovoltaic cells and fuel cells. The open-set gap analysis suggested an evolution of the regulatory framework toward a more generic set of specifications in terms of a modular, almost plug-and-play, specification of energy generation, storage, transduction, etc.

In Reynolds et al., regulatory gaps were identified (1) as resulting from the transfer of the pilot from the aircraft cockpit to the ground-based control station, (2) current lack of specification regarding performance measures for detect, sense, and avoid technologies, and (3) currently lack of specification regarding human control of either manned aircraft or remotely-piloted aircraft. In Stansbury et al., fundamental regulatory gaps were identified regarding differences between command, control, and communication for manned aircraft and UA, and then specific regulatory gaps were identified in each of the areas of command, control, and communication.

All three of these previous studies relied on a process by which the collection of rule applicability results was looked at from both global (all rules together) and local (one rule at a time) to produce the gap analysis descriptions. An alternative method of presenting a gap analysis is the tabular form, where aspects of differing sets of legislation and regulations (e.g. in the case of nanotechnology, groundwater regulations, effluent release regulations, incineration regulations, landfill regulations) are summarized, the gap or potential gap due to the novel technology presented, and further comments and annotations to the presented gaps attached (see Annex 5 of Frater et al.). The various aspects of each set of laws or rules occupy the rows of the tables; the law/rule summary, regulatory gap, and discussion, the columns.

TECHNOLOGY SURVEY

The content of this section was previously presented at the American Institute of Aeronautics and Astronautics Unmanned Unlimited Conference and is being summarized to provide the necessary background for the regulatory gap analysis. This section provides a survey of current and future technologies for ERFT. The intent of the technology survey is to identify and articulate existing and near-future technologies and procedures used for ERFT.

The technology survey involves searching journal and conference proceedings; web sites for UA manufacturers, operators, and interest groups, and for regulatory agencies; and public records. The goal of the technology survey is not to generate an exhaustive listing of every approach for every class of UAS, but is an attempt to be representatively inclusive with an emphasis on an appropriate organization. It also considers at FT technologies applied to manned aircraft such as ballistic recovery techniques (i.e. parachutes) that can be applied toward UA.

To collect data from literature, an initial model was developed for ERFT technology. This model is discussed in the following section. Data sheets and other literature were collected on a number of UAS and UAS subsystems. Given the literature collected, the information gathered was organized based on the conceptual model.

Figure 1 presents the initial framework as it is used within this paper. From left-to-right, the criticality of a vehicle loss (as well as the ramifications of such a vehicle loss) increase.

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the criticality is low, health-based recovery systems attempt to diagnose and correct the problem so that the vehicle can continue onward. With greater criticality, it becomes necessary for mission-level contingency systems handle an emergency recovery. At this level, it is expected that the aircraft's mission must be terminated. The final and most extreme emergency response system is a flight termination system. With each category, there will always be shades of gray. This framework captures the majority of technologies surveyed.

![Diagram of ERFT categories](image)

**Figure 1:** A framework for guidance of ERFT technology survey.

In addition to the framework above, UAS pilot procedures are different in comparison to procedures of manned aircraft pilots. In some situations, these differences are tied into the technology being used. However, under some circumstances, the changes in procedures are universal as a result of the fundamental technology gap between the UAS architecture and the manned architecture.

Table 1 summarizes the ERFT capabilities of several surveyed autopilots for UA. Table 2 presents the ERFT capabilities of several of the surveyed aircraft.

**Table 1: Known capabilities of surveyed autopilots.**

<table>
<thead>
<tr>
<th>Autopilot</th>
<th>Contingency-based Recovery</th>
<th>Flight Termination</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cloudcap Piccolo</td>
<td>Return to waypoint</td>
<td>Mission selectable from close throttle, aerodynamic termination, and/or Deploy parachute</td>
</tr>
<tr>
<td>Procerus Kestrel</td>
<td>Shallow bank until restored</td>
<td>Aerodynamic termination</td>
</tr>
<tr>
<td>Micropilot MP-2028g</td>
<td>Mission selectable (see next column)</td>
<td>Mission selectable from fly-to, climb, descend, roll, eject chute, etc.</td>
</tr>
</tbody>
</table>

**Health-based Recovery**

Health-based recovery systems handle less extreme aircraft system faults and failures in which given an adjustment of the vehicle's control system it should be possible to continue with the aircraft's mission. Under this category, fault detection, identification, and recovery is a common example of control's technology for health-based recovery.
Redundancy is a quite common approach for addressing health related issues. Given sufficient redundancy, if a component becomes non-functional, it is possible for the control system to transition to a backup system and continue nominal operation. A European UAS research commission has recently funded the development of a medium altitude unmanned aircraft equipped with a redundant engine.  

Table 2: Known capabilities for surveyed aircraft.

<table>
<thead>
<tr>
<th>Aircraft</th>
<th>Manufacturer</th>
<th>Contingency-based Recovery</th>
<th>Flight Termination</th>
</tr>
</thead>
<tbody>
<tr>
<td>QH-50 Dash$^{18}$</td>
<td>Gyrodyne Helicopters</td>
<td>None</td>
<td>Autorotation</td>
</tr>
<tr>
<td>ScanEagle$^{*†}$</td>
<td>Insitu, Inc.</td>
<td>Loiter at point for lost link</td>
<td>Aerodynamic termination if departs mission area</td>
</tr>
<tr>
<td>Predator$^4$</td>
<td>General Atomics</td>
<td>Return home for lost link</td>
<td>Optional parachute for early models</td>
</tr>
<tr>
<td>Global Hawk$^{13,35}$</td>
<td>Northrup Grumman</td>
<td>Contingency flight paths for various emergency/contingency modes</td>
<td>Terminate with extreme prejudice</td>
</tr>
<tr>
<td>Polecat$^{14}$</td>
<td>Lockheed Martin</td>
<td>Unknown</td>
<td>Terminate with extreme prejudice</td>
</tr>
<tr>
<td>X-48B$^{15}$</td>
<td>Boeing and Cranfield Aerospace</td>
<td>Unknown</td>
<td>Parachute, airbags, and spin parachute (for stall testing)</td>
</tr>
<tr>
<td>Arrow$^5$</td>
<td>Jordon Military</td>
<td>Unknown</td>
<td>Parachute and flotation device</td>
</tr>
</tbody>
</table>

**Contingency-based Recovery**

Under mission contingency recovery, when a component or aircraft failure occurs, the aircraft shifts away from its current mission and into one of several possible emergency-recovery modes.

The Global Hawk UAS possesses a sophisticated contingency management system (CMS). Recovery modes are defined for lost link recovery, return-to-base command, abort landing command, and land now command. For each, the CMS redirects the aircraft to a predefined flight path appropriate for that mode. On these contingency routes, additional contingency routes could be branched off in order to handle additional failures should they occur. Figure 2 presents a pri-

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$^{*}$ Personal Communication, Paul McDuffee, Insitu, Inc.
$^{†}$ Personal Communication, Steve Heppe, Insitu, Inc.
mary flight path and a number of contingency branches. In this figure, only three contingency modes are considered and abstractly defined as $C1$, $C2$, and $C3$. Prior to a mission, an extensive effort must be made to identify all contingency routes, program them into the CMS, and notify local ATC at each site.

Lost link procedures are also considered a form of contingency-based recovery as it requires the aircraft to alter its mission to mitigate a risk due to failure of the communication system. From the survey, the most common LL procedure is for the aircraft to fly to a predefined location. Once at the predefined location, the UAS can either loiter until the link is restored, it can autonomously land, or it can be remotely piloted via secondary data link.\textsuperscript{21,23,28,34}

Many small commercial UAS have contingency management features for link loss. The Piccolo Autopilot\textsuperscript{33} is capable of defining a timeout for lost communication in seconds. If after so many seconds a message from the base station is not received, the aircraft will fly to a LL waypoint. The Procerus Kestrel lost link procedure returns the aircraft either to base or an alternate “rally point”.\textsuperscript{24} Micropilot's various autopilots\textsuperscript{22} allow users to define the response to the lost link procedure and the criteria for diagnosing the lost link. The lost link procedure could support the return to any waypoint, or alternatively to trigger a flight termination system.
Officials at Fort Carson have drafted a document for Unmanned Aerial Vehicle Flight Regulations. The military base includes two potential flight areas, one is restricted airspace, and the other is non-restricted airspace requiring either a COA or Temporary Flight Restriction (TFR) from the FAA. They defined two classes of UA as Tactical Unmanned Aerial Vehicle (TUAV) for flight over 1000ft and Small Unmanned Aerial Vehicle (SUAV) for flight below 1000 ft. For the restricted airspace, if a TUAV loses link, it returns to a predefined grid location and loiters at 8000 ft. If the SUAV loses link in the restricted airspace, it returns to the center of mass of the restricted airspace and lands. In both cases, necessary military authorities are contacted. When operating under a COA or temporary flight restriction (TFR), the procedures are modified in that FAA or other civilian authorities will be notified. If in either case the aircraft is likely to leave its restricted airspace, the flight will be terminated by some undisclosed means.

**Flight Termination**

A flight termination system is utilized as a last resort to bring down an aircraft expeditiously in order to maintain some level of safety to the public or property. Given sufficient redundancy, a flight termination system may not be necessary. However, two motivating factors for having a flight termination system include not having sufficient redundancy, which is very often the case for smaller UAS, or that the FTS is mandated as per the restricted airspace for which the aircraft is flying (i.e. range safety). In this section, a variety of flight termination systems will be discussed. For each, representative aircraft will be discussed.

Aerodynamic termination is one approach to flight termination. Under these cases, the aircraft’s control surfaces are set at a state that will result in the vehicle crashing into the ground or a body of water in a somewhat controlled manner. One form of aerodynamic termination is to set the control surfaces such that the vehicle performs a slow downward spiral. Under this termination technique, some aircraft damage can be mitigated depending upon the speed of the descent. Likewise, under a spiral descent, the aircraft’s final position could be well estimated and somewhat controlled. This mechanism is ideal under airspace violation events as it will prevent further violation of the restricted airspace. This technique is used by the Insitu ScanEagle and is also provided as a common feature for a number of autopilots including the Cloudcap Piccolo, Micropilot autopilots, and the Kestrel autopilot.

Glide-path descents are another alternative aerodynamic termination technique. For this termination technique, the aircraft glides from its current altitude to a landing site without engine power. Under a glide-path termination, if possible, a suitable landing site can be designated by the PIC or autonomously. Similar to glide path descents, for rotorcraft UAS, the vehicle’s autorotation capability may be used to provide some control during a FT situation. Several ballistic recovery systems are available to handle flight termination of an unmanned aircraft. Parachutes are one of the most common ballistic recovery systems for unmanned aircraft, and have a history of use in manned aircraft including existing technical standard orders. Autopilots such as the Piccolo and Kestrel allow for a parachute deployment to be part of the flight termination system if the target aircraft is appropriately equipped. A number of other UAS are parachute equipped. Parafoil parachutes provide additional lift permitting greater control for the aircraft such that it is possible to achieve a glide-path approach, which is used on the BAE SkyEye and the IAI I-View. The X-48b is equipped with airbags to reduce the forces at impact and a spin

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* Personal Communication, Paul McDuffee, Insitu, Inc.
parachute to assist in recovery from spins during stall testing. The Jordon Arrow is equipped with a foam body in order to remain buoyant if the aircraft is terminated in the water.

Flight test ranges including the White Sands Missile Range and Wallops Air Force Base explicitly require the inclusion of FTS that meets the commonality specifications of the Range Control Council, Document 319-07.

REGULATORY GAP ANALYSIS

The second half of this study involved analyzing existing regulations to determine where the current body of regulations and guidance materials fails to meet the technology and procedures of ERFT. For the study, from Title 14 of the Code of Federal Regulations, regulations were examined from Part 23 ("Airworthiness Standards: Normal, Utility, Acrobatic, and Commuter Category Airplanes"), 25 ("Airworthiness Standards: Transport Category Airplanes"), 27 ("Airworthiness Standards: Normal Category Rotorcraft"), 30 ("Airworthiness Standards: Transport Category Rotorcraft"), and 91 ("General Operating and Flight Rules"). The Aeronautical Information Manual (AIM) and Airplane Flying Handbook (AFH) were also examined. Even though not formally considered regulations, they define procedures and expectations of pilots of manned aircraft. In this section, the process of the gap analysis is presented. The regulatory gaps are presented for pilot/crew procedures, health-based recovery systems, contingency-based recovery systems, and flight termination.

Gap Analysis Process

An iterative process was taken for the regulatory gap analysis. The process begins by identifying the regulatory material to be analyzed. This is done based on past experience and an initial examination of Title 14 of the Code of Federal Regulations. As stated above, 14 CFR §§ 23, 25, 27, 29, and 91 were selected. Additional guidance materials related to ERFT were examined and the AIM and AFH were selected.

Once the material was gathered, an initial pass was made to identify which sections of each part of Title 14 CFR and AIM and what chapters of the AFH were relevant to ERFT. During this phase, the filtering of material was quite coarse so that any potentially plausible regulation remains under consideration. This dramatically reduces the number of regulations that must be closely analyzed to identify regulatory gaps.

With a set of relevant sections to be analyzed, rubrics were developed in order to determine their level of applicability. Unlike the previous regulatory studies discussed above, by using a well defined rubric, this study is attempting to provide greater transparency regarding how the gaps were identified. For each aspect of ERFT (crew/pilot procedures, health-based recovery,
contingency-based recovery, and flight termination) one rubric was created. For each rubric, criteria were defined to determine if the regulation fell into one of the following categories: does not apply, applies as is, applies with interpretation, and applies with revision. These rubrics are presented below. Using the rubrics, the sections were analyzed and annotations were provided to further justify each classification. Chapter 16 of AFH was analyzed through a less-formal procedure by deriving the implications of manned emergency procedures for UAS.

Using the annotations, the results of the analysis were gathered and discussed. The discussion focuses upon regulations that required revision or interpretation. Fundamental gaps and open-set gaps were also identified.

**Pilot and Crew Procedure Gaps**

For pilot and crew procedures, the focus of our study was upon 14 CFR § 91 and the AIM. The AFH is also discussed here as it indicates some expectations of the PIC of a manned aircraft during an emergency situation. To determine the level of applicability for procedures, the rubric shown in Table 3 was used.

<table>
<thead>
<tr>
<th>Does Not Apply</th>
<th>Regulation or guidance material does not discuss procedures relevant to the emergency recovery/contingency procedures to mitigate risk.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Applies As Is</td>
<td>Regulation or guidance material discusses procedures relevant to the emergency recovery/contingency procedures to mitigate risk. Given current language, applicable as is need for interpretation or revision for UAS paradigm.</td>
</tr>
<tr>
<td>Applies with Interpretation</td>
<td>Regulation or guidance material discusses procedures relevant to the emergency recovery/contingency procedures to mitigate risk. Parts of the language of the regulation require interpretation toward equivalent operations for unmanned aircraft.</td>
</tr>
<tr>
<td>Applies with Revision</td>
<td>Regulation or guidance material discusses procedures relevant to the emergency recovery/contingency procedures to mitigate risk. Regulation defines procedures of the pilot for safe operation within NAS that are unachievable for UAS given the language as it is written.</td>
</tr>
</tbody>
</table>

Several pilot and crew procedures defined both within the 14 CFR § 91 are written assuming that a pilot, crew, and possibly passengers are onboard the aircraft. While the pilot of a UAS may no longer be onboard the aircraft, it is still possible for an UAS to have passengers or crew onboard. As a result, these regulations cannot simply be dismissed for “unmanned” aircraft, but rather they must be interpreted or revised such that they are appropriate for cases in which humans either are or are not onboard. Examples of this regulatory gap include:

- 14 CFR §§ 91.509, 91.511, and 91.513, which define survival equipment for emergency evacuation for overwater flights.
• 14 CFR § 91.501 requires any crewmember onboard the aircraft to be familiar with the emergency equipment and emergency procedures onboard the aircraft before flight.

Other procedures for normal flight operations are impacted because of the pilot no longer being onboard the aircraft. For instance, many of the operations that a pilot would take to either diagnose or respond to an emergency situation could be better handled through a health-based recovery system, contingency-based recovery system, or flight termination system. Examples include:

• AIM §§ 5-4-11, 5-4-14, and 5-4-16 define the arrival procedures including instrument approaches and simultaneous landing approaches. Under these conditions, in which fast reaction times are required, if the need to abort a landing or deviate from an arrival path, it could be better handled through a contingency-based recovery system, which can both restore safety and send a notification to ATC. Similar issues of deviation and notification of ATC exist in AIM §§ 6-1-1, 6-1-2, and 6-2-1, which define emergency procedures; and AIM § 7-1-14, which defines weather avoidance assistance procedures.

• AIM § 6-2-5 defines the requirements of using the emergency locator onboard the aircraft during emergency situations such as ditching the aircraft, which under the UAS paradigm ought to be activated by the flight termination system.

• AIM § 6-3-3 defines the procedures for selecting a suitable glide-path to ditch the aircraft, which under the UAS paradigm could be performed by the PIC, FT system, or both.

• AIM § 6-4-2 defines procedures for a pilot handling the loss of a communication link with ATC. The health-based recovery system should be responsible for diagnosing the issue and switching to a redundant communication system if available. If communication is still not restored, the contingency management system is better capable of handling the procedures for transponder settings to alert ATC of the issue, and performing the appropriate lost-link procedure.

Aspects of Chapter 16 of the AFH suggest that new regulations likely will be required regarding emergency situations in UAS.

• In a traditionally piloted aircraft, the pilot uses visual means to best determine the location in event of an unplanned landing. UAS require either dedicated space in which to fly or technology to implement determination of the location for a flight-termination event. There is currently no performance specification for such a technological solution.

• The necessity and means of informing other aircraft in the event the UAS engages in ERFT procedures should be specified.

• In the event of a ground- or flight-based observer, procedures should be specified to handle loss of visual contact with the UA, whether due to IMC or some other situation.
Health-based Recovery System Gaps

For health-based recovery systems, the gap analysis focused upon regulations for equipment that identified potential risks and mitigated them through corrective measures that did not alter the aircraft’s current flight plan. Table 4 presents the rubric used.

Similar to the procedural gaps, the physical disconnect of the pilot from the aircraft lead to situations in which the regulation must be interpreted or revised toward the use of a health-based recovery system to address the situation. 14 CFR §§ 23/25/27/30.672 mandates that an indicator light notify the pilot if there is a loss in stability control. Under the UAS paradigm, due to latency, an indicator light may not be sufficient for notifying the pilot of this situation. However, a health-based recovery system could be capable of dynamically reacting to the fault and recovering stability control.

Engine fire suppression systems as mandated by 14 CFR §§ 23/25.1195 can be considered a health-based recovery system currently onboard some manned aircraft. This regulation requires revision for a number of reasons. The propulsion system may not be based upon the use of a combustion engine (e.g. fuel cell, electric motors, etc), which would likely not need a fire suppression system. Based upon the size of an aircraft, requiring such a system may produce a significant burden. For instance, a small hand launched UAS could likely be incapable of handling such a system onboard and remain airworthy.

### Table 4: Rubric for assessing regulations related to health-based recovery.

<table>
<thead>
<tr>
<th>Does Not Apply</th>
<th>Regulation or guidance material is not concerning aircraft components that autonomously mitigating risk toward the loss of an aircraft without alternation of the aircraft’s current flight plan.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Applies As Is</td>
<td>Regulation or guidance material concerning aircraft components that autonomously mitigating risk toward the loss of an aircraft without alternation of the aircraft’s current flight plan. Given current language, applicable as is need for interpretation or revision for UAS paradigm.</td>
</tr>
<tr>
<td>Applies with Interpretation</td>
<td>Regulation or guidance material concerning aircraft components that autonomously mitigating risk toward the loss of an aircraft without alternation of the aircraft’s current flight plan. Parts of the language of the regulation require interpretation toward equivalent operations for unmanned aircraft.</td>
</tr>
<tr>
<td>Applies with Revision</td>
<td>Regulation or guidance material concerning aircraft components that autonomously mitigating risk toward the loss of an aircraft without alternation of the aircraft’s current flight plan. Defines procedures of the pilot for safe operation within NAS that are unachievable for UAS given the language as it is written.</td>
</tr>
</tbody>
</table>

In AIM §§ 1-1-1, 1-1-12, and 1-1-20, it is assumed that minor failures of navigation aids may be detected by the pilot-in-command and the pilot can then act appropriately to maintain safe flight. Under the UAS ERFT framework, a health-based recovery system could both detect and recover from a minor fault without having a significant impact on flight.

Voice communication loss and recovery is discussed in AIM § 6-4-1. A health-based recovery system could be utilized in place of pilot procedures in order to autonomously change to a redun-
dant communication link. Similarly, power failures that impact the controls system such as those addressed in 14 CFR §§ 27/30.695 can now be recovered via a health-based recovery system.

**Contingency-based Recovery System Gaps**

Gaps related to contingency-based recovery exist as a result of existing procedures and regulations for the pilot to perform under emergency conditions in which the aircraft must deviate from its current flight plan. A rubric for analyzing regulations against contingency-based recovery systems is presented in Table 5.

The UAS performing lost link procedures fall under contingency-based recovery. Current regulations do not address the command data link, but do address the voice communication channel. Recovery procedures for voice communication loss are defined in AIM § 6-4-1 and AIM § 6-4-2. The later requires the pilot to notify ATC via a change in transponder setting. If the aircraft is used as a communication relay and the loss of communication with ATC occurs as a result in the link from GCS to UA failing, the pilot would be unable to command such setting change. Diagnosis and recovery of communication failures, however, could be handled entirely without the PIC actions as part of a predefined set of lost link procedures onboard the aircraft. Furthermore, it may be useful to define separate transponder alert settings for voice and data communication losses respectively.

**Table 5: Rubric for assessing regulations related to contingency-based recovery.**

<table>
<thead>
<tr>
<th>Does Not Apply</th>
<th>Regulation or guidance material does not relate to aircraft systems that alter the aircraft’s mission profile such as flight path, air speed, altitude, etc. autonomously in order to mitigate risk.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Applies As Is</td>
<td>Regulation or guidance relates to aircraft systems that alter the aircraft’s mission profile such as flight path, air speed, altitude, etc. autonomously in order to mitigate risk. Given current language, applicable as is need for interpretation or revision for UAS paradigm.</td>
</tr>
<tr>
<td>Applies with Interpretation</td>
<td>Regulation or guidance relates to aircraft systems that alter the aircraft’s mission profile such as flight path, air speed, altitude, etc. autonomously in order to mitigate risk. Parts of the language of the regulation require interpretation toward equivalent operations for unmanned aircraft.</td>
</tr>
<tr>
<td>Applies with Revision</td>
<td>Regulation or guidance relates to aircraft systems that alter the aircraft’s mission profile such as flight path, air speed, altitude, etc. autonomously in order to mitigate risk. Regulation defines procedures of the pilot for safe operation within NAS that are unachievable for UAS given the language as it is written.</td>
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</table>

Because contingency-based recovery results in the UAS deliberately changing course to recover from some emergency condition, the procedural guidelines as defined in the AIM may require some re-interpretation because of the physical separation from the UAS and its contingency-based recovery system and the pilot-in-command. For instance, AIM § 4-3-5 defines the necessity to quickly notify ATC in the event of a land-abort. Since such a deviation may be executed by the contingency-based recovery system, the system must either alert ATC directly, or
communicate the event to the PIC who then notifies ATC resulting in added delay. This gap exists for a number of sections of the AIM including AIM §§4-3-5, 4-4-1, and 5-5-2.

A number of other contingency situations may occur in which the contingency-based recovery system would override the actions specified in the AIM. For instance,

- **AIM §§ 1-1-1, 1-1-12, and 1-1-20** define the responsibility of changing flight path or taking corrective measures in the event of a navigation aide failure.
- **AIM § 7-1-14** discusses procedures for receiving in-flight weather avoidance assistance. A contingency-based planner could receive this information from a variety of data sources and perform the necessary rerouting.
- **Other impacted procedures include:** AIM §§ 5-4-11, 5-4-14, and 5-4-16.

**Flight Termination Gaps**

Evaluating the regulations and procedures based on flight termination focuses upon the systems and equipment mandated for manned aircraft to support a forced or ditch landing. 14 CFR § 91.609 establishes the requirement for flight data recorders and cockpit voice recorders in transport category aircraft. This regulation provides no exemption for aircraft without a pilot in the cockpit, such as an unmanned transport-category aircraft. While a voice recorder could be useful to record communication between ATC and the ground station operators, the wording of this requirement will likely require revision for it to fit correctly. 14 CFR §§ 25.1457, 27.1457, and 30.1457 also addresses cockpit voice recorders, though it provides the requirements for the device, rather than the requirement to have the device.

The AIM and Chapter 16 of the AFH define procedures for the pilot if the aircraft must be ditched or crash landed. AIM § 6-2-5 defines the requirements for triggering the emergency locator upon ditching the aircraft. AIM § 6-3-3 discusses the procedures for finding a suitable crash glide-path to ditch the aircraft in water. In all of these cases, it may be possible to automate these tasks as part of the onboard flight termination system.

Table 6 presents the rubric for evaluating flight termination.

One major gap that exists with respect to FT is the structural and restraint requirements for passengers and crew onboard aircraft. For UAS, it might be assumed that no pilot is onboard; however, in the future unpiloted aircraft may still be used for passenger or cargo transport. In these cases, structural requirements such as safety restraints and structural support must still be required. Emergency exits are currently mandated for pilot, crew, and passengers of manned aircraft. However, if the intent of the aircraft’s design is to be operated completely without any onboard humans, then these regulations could be seen as overly burdensome and impact the payload capacity of the aircraft. Impacted regulations include: 14 CFR §§ 23/25/27/30.561, 23/25/27/30.562, 23/25/30.803, 23/27/30.805, 23/25/27/30.807, 25/30.809, 25.810, 23/25/30.811, 23/25/30.812, and 23/25/30.813. Similarly, emergency/survival equipment and crew training on procedures to utilize this equipment are mandated in 14 CFR § 91.501, 91.509, 91.511, and 91.513.
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<th>Table 6: Rubric for assessing regulations related to flight termination.</th>
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<tr>
<td>Does Not Apply</td>
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<tr>
<td>Applies As Is</td>
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<tr>
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<td>Applies with Revision</td>
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**Fundamental and Open-Set Gaps**

The fundamental gap is that for unmanned aircraft there is no pilot onboard. While this is obvious, it produces a number of cross issues with the existing regulations regarding emergency
procedures, emergency recovery, and the necessity to terminate flight prematurely. As described above, dependent upon a pilot or crew being onboard the aircraft, it may or may not be necessary to equip the aircraft with safety equipment and emergency exits. Pilot procedures involving any immediate reaction or a high level of situational awareness to either react to a perceived threat or a warning from ATC may no longer be viable due to latency.

From this fundamental gap, a number of gaps known as “open-set gaps” exist in which no current regulation exists, but perhaps should be addressed for unmanned aircraft to operate safely in the NAS. Since the pilot is not onboard the aircraft, the pilot is less capable of perceiving the performance of the aircraft at the stick, which is debatably a major part of the pilot’s ability to detect and diagnose potential issues. Likewise, in the event of an emergency, the PIC must deal with the latency and the lack of sensory cueing to determine if a problem exists and if their countermeasures are successful. It may be necessary to require the GCS pilot interface to be approved via a TSO to meet a predefined set of performance and interface constraints.

When selecting a suitable crash site, the guidance defined by the AFH may no longer apply. First, some UAS may not be equipped with a camera allowing the PIC to identify the type of terrain and whether or not there are persons on the ground at risk from the intentional downing of the UA. Second, the level of kinetic energy of the aircraft may highly differ versus a manned aircraft and thus options that were previously discouraged may now be viable. Additional guidance and procedures must be developed specifically to aid UAS pilots for each aircraft regarding how to best and most safely terminate the aircraft’s flight.

CONCLUSION

This paper has presented two parts of a study of emergency recovery and flight termination of unmanned aircraft. First, a technology survey provides a baseline understanding of the existing and near-term future technologies of UAS to address health-based recovery of a system fault, contingency-based recovery, and flight termination. Procedures as defined by the AIM and AFH were also evaluated. Given this body of knowledge, existing regulations were evaluated to determine their shortfall with respect to UAS ERFT. From the regulatory gap analysis, a variety of gaps were identified. Several fundamental gaps exist as a result of the physical disconnect of the pilot from the aircraft, which results in reduced situational awareness and increased voice and data communication latency. For UAS designed to operate without a pilot, crew, and passengers, it was found that many safety precautions for manned aircraft are not necessary and burdensome for unmanned aircraft. Given the survey and gap analysis, this paper and later the final report shall provide insight both to the public, industry, and regulators about potential issues that must be addressed for UAS to enter the NAS.

ACKNOWLEDGMENTS

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REFERENCES


