Range Commanders Council
RANGE SAFETY GROUP

DOCUMENT 326-16

# UNMANNED AERIAL VEHICLE MISHAP TAXONOMY FOR RANGE SAFETY REVIEWS

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96TH TEST WING
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ARNOLD ENGINEERING DEVELOPMENT COMPLEX

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# UNMANNED AERIAL VEHICLE MISHAP TAXONOMY FOR RANGE SAFETY REVIEWS

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# Preface

Unmanned aerial vehicles under test may pose unexpected risks to personnel and property on or near the flight test range. The local safety decision authority must ensure that risk is managed to an acceptable level. Mishap taxonomy is useful in dividing the large question: "Is this vehicle safe to test on this range?" into a series of smaller, more manageable questions. This taxonomy is based on the collected mishaps experienced in the Department of Defense, National Aeronautics and Space Administration, and with some foreign vehicles.

The Range Safety Group developed this document in response to Range Commanders Council task RS-60, which requested a taxonomy structure to better understand types of unmanned aerial vehicle mishaps. The Atlantic Test Range Range Safety Office developed this document in collaboration with the NAVAIR Unmanned Aerial System Test Directorate.

Address questions about this document to either the Atlantic Test Range Range Safety Office or to the Range Commanders Council Secretariat.

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# Acronym List

| | |
|---|---|
| AGL | above ground level |
| ATC | Air Traffic Control |
| CFIT | controlled flight into terrain |
| CRC | control and reporting center |
| EP | external pilot |
| FTS | flight termination system |
| GCS | ground control station |
| GPS | Global Positioning System |
| ICAO | International Civil Aviation Organization |
| IMU | inertial measurement unit |
| INS | inertial navigation system |
| mIRC | internet relay chat |
| MSL | mean sea level |
| NM | nautical mile |
| NATO | North Atlantic Treaty Organization |
| NMAC | near midair collision |
| PIO | pilot-induced oscillation |
| RATO | rocket-assisted takeoff |
| RF | radio frequency |
| RPM | revolutions per minute |
| RTB | return to base |
| TALS | tactical automatic landing system |
| TCAS | traffic collision avoidance system |
| UAV | unmanned aerial vehicle |

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# CHAPTER 1

## Executive Introduction

> There are known knowns. These are things we know that we know. There are known unknowns. That is to say, there are things that we know we don't know. But there are also unknown unknowns. There are things we don't know we don't know.[1]

Mishap lessons learned are valuable tools for use in identifying otherwise unrecognized hazards that can then be addressed and reduced to an acceptable level of risk. Lessons learned reduce the risk of exposure to "unknown unknowns" that have previously been encountered by others.

Unproven unmanned aerial vehicles (UAVs) are flown on Department of Defense test and training ranges to establish test evidence of airworthiness and to demonstrate potential for acquisition. A range safety risk management process provides the test team with an assessment of risk to local personnel, property, and range operations associated with the proposed test of the unproven vehicle. This assessment is intended to allow the risk decision authority to make an informed decision and answer the question: "Is this unproven vehicle safe to fly on this range?"

We used cluster analysis of mishaps to develop groups that can be defined as a common hazard scenario describing the transition from normal flight to loss of the ability to maintain normal controlled flight.

We developed a taxonomy of hazard scenarios based on review of mishap data from 612 UAV mishaps. The major categories of the taxonomy, each used as a chapter in this document, were based on vehicle material failures (Chapter 2), operator/vehicle interaction (Chapter 3), launchers and recovery systems (Chapter 4), environment (Chapter 5), multiple sources of control (Chapter 6), and the airspace system (Chapter 7). Each scenario was further categorized by phase of flight and the cause or event leading to loss of flight-critical capability.

Appendix A describes the degraded flight situation using modified International Civil Aviation Organization (ICAO) airline mishap terminology. The frequency of hazard scenarios transitioning to specific degraded states was determined.

This document provides three distinct benefits to range safety.

### 1. A foundation for in-depth risk management

The mishap taxonomy is a means for defining and bounding the body of knowledge to manage UAV flight test risk to personnel and property. The sum of unique terms, concepts, and experiences from individual mishap scenarios combine as the foundation for effective safety efforts. Systematic validation and amplification of the taxonomy by subject matter experts will further increase the value of updates.

### 2. A framework for consistent Range Safety support

The mishap taxonomy provides a list of potential hazard scenarios a UAV test might encounter during test and operations. A mishap history can provide a basis for estimating

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[1] Secretary of Defense Donald Rumsfeld. Department of Defense News Briefing. 12 February 2002.

probability and severity of a list of hazard scenarios associated with a specific UAV. Grouping hazard scenarios into categories helps to form strategies for each category. These broad strategies may then address similar but unanticipated hazards.

3. **A basis for identifying and prioritizing strategic improvement opportunities**

Mishap taxonomy and corresponding mishap experience allows systematic investigation and search for unrecognized risks and improvement opportunities. Identifying and prioritizing strategic improvement opportunities allows for changes in policy, procedures, training, equipment, and facilities to be implemented.

The study is categorized by breaking the mishap data into broad, general groups of common mishap causes. Each of these general groups is then further divided into subgroups that contain mishaps of a similar nature, i.e., those that experience the same general loss of function resulting from a particular cause are grouped together (see Figure 1-1). Figure 1-2 shows the number and percentage of each general common-cause mishap group in the data.

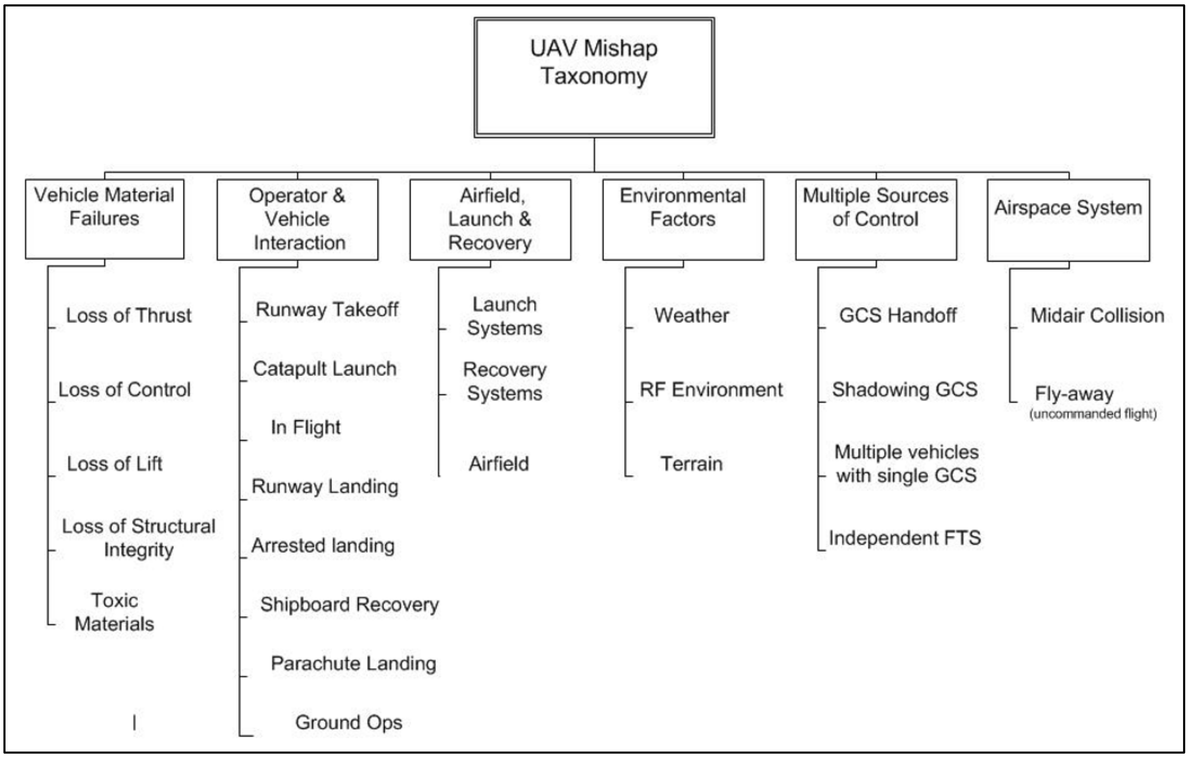

Figure 1-1. Taxonomy Arrangement by Category

**NOTE** Some mishap events listed below have multiple or overlapping causal factors and may be listed in multiple areas. Some mishap events are not detailed in the text due to lack of investigation details or redundancy.

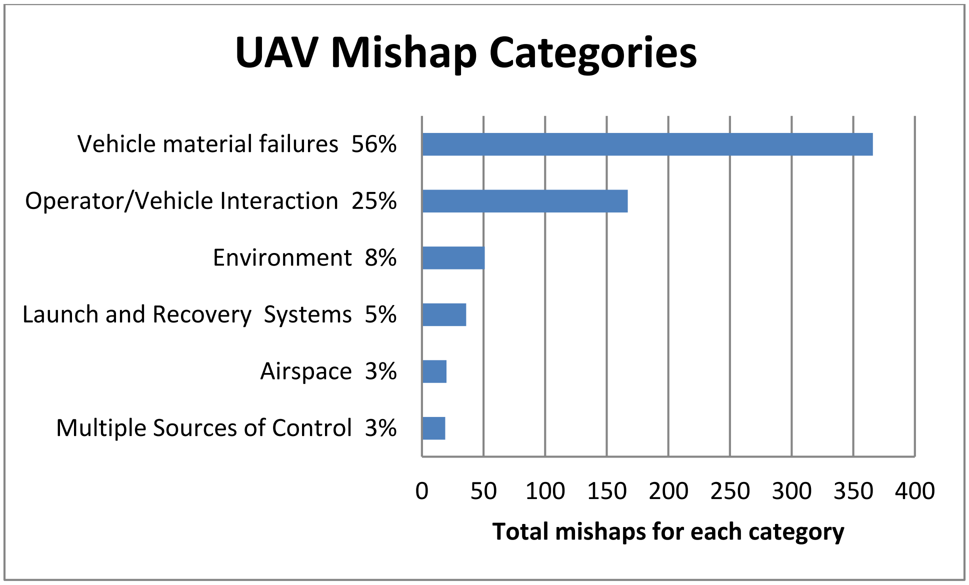

Figure 1-2. Distribution of Reviewed Mishaps by Category

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# CHAPTER 2

## Vehicle Material Failures

> Sustained flight is only possible when the structure of the aircraft is intact and the forces of lift, thrust, and control are sufficient to maintain the desired altitude, speed, and attitude. Consequently, the essential functions of flight are structural integrity, and lift, thrust, and control.[2]

One model used by the Aircraft Combat Survivability community is based on lessons learned from combat losses. The model categorizes these losses in terms of which flight-essential function was lost. Addressing the survivability problem (i.e., aircraft vulnerability) as a series of smaller problems based on specific flight-essential deficiencies allows incremental improvements resulting in improved survivability. This same approach can be used to address mishap lessons learned where material failures were a significant causal factor. Figure 2-1 shows the breakdown of vehicle material failures based on a loss of a flight-critical function and Figure 2-2 shows the distribution of mishaps based on these failures.

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[2] Robert E. Ball. *The Fundamentals of Aircraft Combat Survivability Analysis and Design, Second Edition*. Reston: American Institute of Aeronautics and Astronautics, 2003.

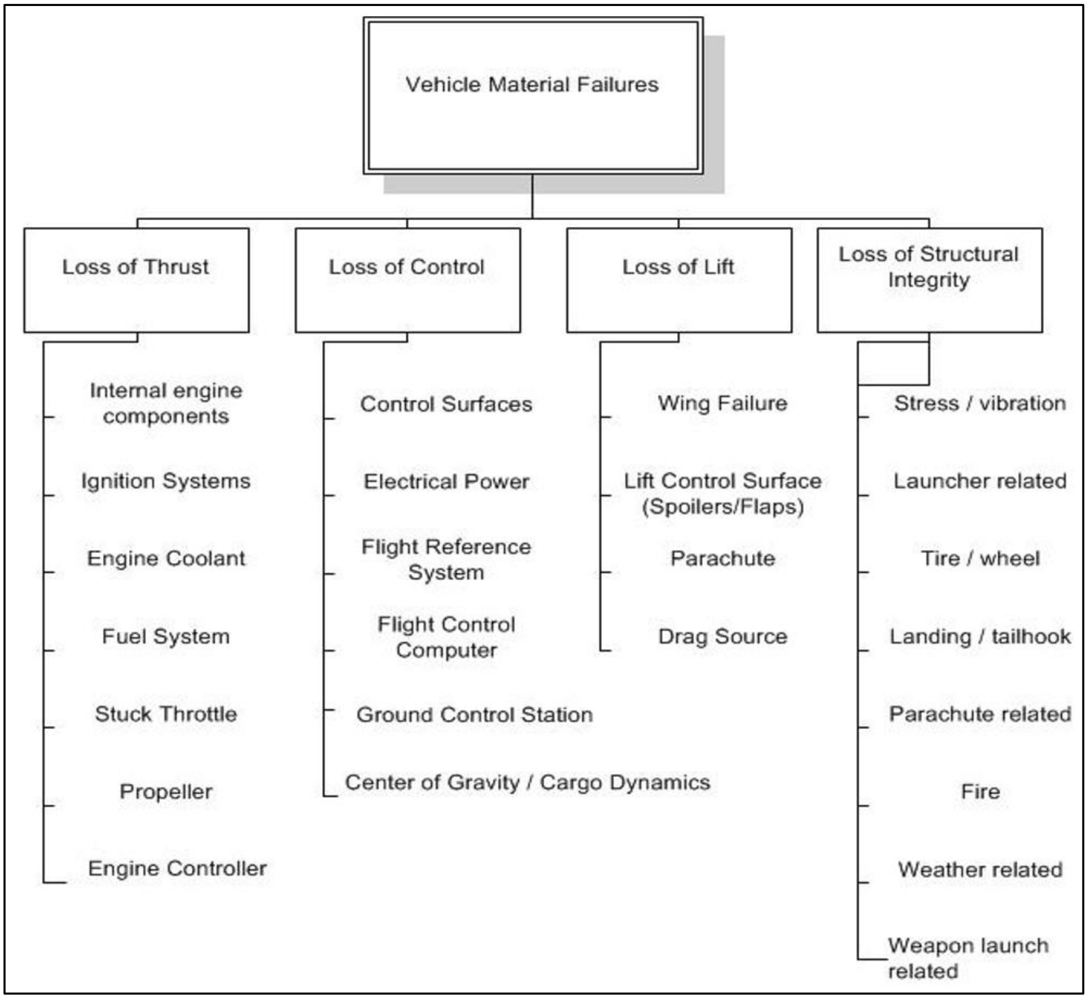

Figure 2-1. Taxonomy of Vehicle Material Failures

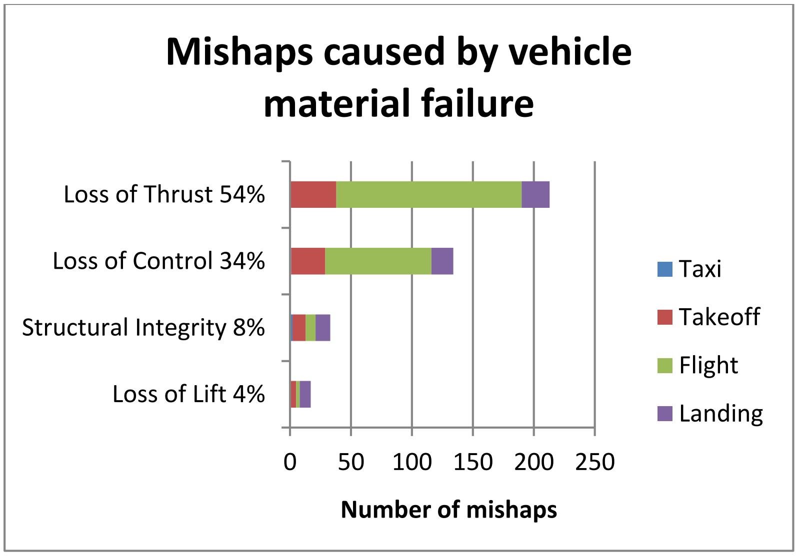

Figure 2-2. Distribution of Material Failure Mishaps by Loss of Flight Critical Function

## 2.1 Loss of Thrust

A variety of subsystem failures can result in loss of thrust, which relates to a vehicle's ability to maintain desired altitude and climb rate and to remain in aerodynamic control. Figure 2-3 shows the number and percentage of mishaps by subsystem failure resulting in a loss of thrust in each phase of flight. (The percentages in this figure are rounded to the nearest whole number, so they may not total 100%).

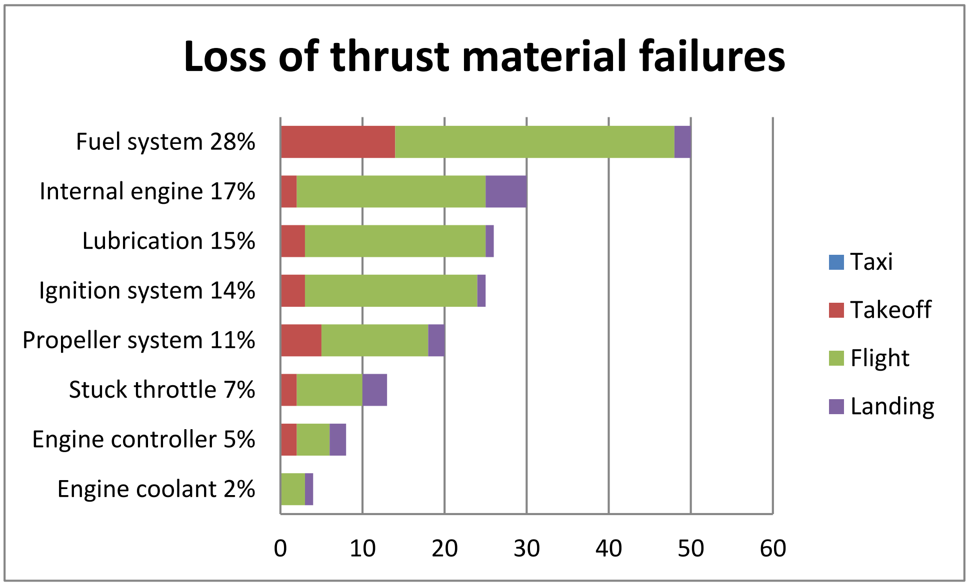

Figure 2-3. Distribution of Loss of Thrust Mishaps by Subsystem

With minor exceptions, outcomes of loss of thrust mishap scenarios were the following.

- Controlled ditch in an unpopulated area or at sea
  - Used to minimize damage with hopes of vehicle recovery
- Intentional crash in unpopulated area
  - If difficult to recover by friendly forces, used to make debris/weapons less valuable to adversary
- Uncontrolled ditch
- Successful parachute recovery with minor damage
- Unsuccessful parachute recovery
- Attempted landing on runway at primary airfield
  - Impact short of runway
  - Runway excursions
  - Hard landing
- Forced landing at a contingency or alternate airfield

**NOTE** Successful landings and landings with only minor damage are not categorized as mishaps and are not included in the data used for this report.

### 2.1.1 Internal Engine Components

**Scenario:** Failure of internal engine components results in engine failure and loss of thrust.

There were 30 mishaps in our sample that can be characterized as loss of thrust due to failure of internal engine components, affecting three different types of vehicles.

The largest group of internal engine component failures was due to an engine bearing failure that caused the engine to seize. The next largest group of failures was internal engine foreign object damage due to loose bolts or washers and related to unexpected corrosion, vibration, and/or maintenance procedures.

- Engine bearing failure
- Omissions in maintenance publications
- Component corrosion from dissimilar metals
- Bolts loosening from vibration
- Manufacturing quality assurance deficiencies

### 2.1.2 Ignition System

**Scenario:** Failure of the engine ignition results in reduced engine performance or engine failure and loss of thrust.

There were 25 mishaps in our sample that can be characterized as loss of thrust due to ignition system failures, affecting two different types of vehicles.

The ignition system is used to provide and time the spark needed for engine combustion. The majority of ignition system failures was traced to the magneto and were primarily attributed to exposure to high engine temperature or loose wiring connectors, although several cases attributed to magneto failures were reported as “unknown causes.”

- Dirt and sand on the spark plug gap caused pre-ignition, damaging the engine.
- Sand in the spark plug thread exposed a spark plug to combustion temperatures, causing the spark plug to melt.
- Fuel, oil, or carbon covering the spark plug firing tip results in a fouled spark plug.

### 2.1.3 Lubrication

**Scenario:** Loss of engine lubrication results in reduced engine performance or engine failure and loss of thrust.

There were 26 mishaps in our sample that can be characterized as loss of thrust due to loss of engine lubrication, affecting six different types of vehicles.

Typical lubrication-related mishaps involved oil starvation (engine no longer supplied with lubricating oil). Oil starvation caused engine temperatures to rise and reduced engine revolutions per minute (RPM), which corresponded to either reduced thrust or, if the engine seized, no thrust.

- Failure to service the oil system before flight
- Failure to check the oil level before flight

- Oil leak (loose bolts, oil filter or oil seal failure)
- Oil flow blockage (oil filter clogged, thermo control valve installed incorrectly, oil return line blocked)
- Scavenge pump failure
- Oil pump drive belt failure
- Oil tube to engine came loose during pneumatic launch
- Turbocharger failure due to oil sump line capacity inadequate for some operating conditions (e.g., high gross weight)

Lubrication-related damage to engines was experienced on some vehicles by unfiltered air mixing with oil in a dust-filled environment. The particles in the oil acted like liquid sandpaper, damaging the moving internal engine parts.

### 2.1.4 Engine Cooling System

**Scenario:** Failure of the engine cooling system results in reduced engine performance or engine failure and loss of thrust.

Four mishaps in our sample can be characterized as loss of thrust due to engine failure from overheating. This scenario was only experienced by one type of vehicle using a unique independent engine cooling system.

### 2.1.5 Fuel System

**Scenario:** Failure of fuel system components results in loss of thrust.

The fuel system is used to store and deliver fuel to the propulsion system. Failures of the fuel system have resulted in reduced thrust, total loss of thrust, damage to the engine, and engine fire.

There were 50 mishaps in our sample that can be characterized as loss of thrust due to fuel system failure. Most of the fuel system failure-related mishaps (36 of 44) were specific to one type of vehicle.

The majority of fuel system failure mishaps can be characterized as **fuel starvation**, in which sufficient fuel is present on board the vehicle but does not reach the engine.

- Fuel line disconnected or separated
- Fuel line blocked by debris or air bubble
- Fuel pump failure
- Fuel filter clogged by contaminated fuel
- Difficult to assemble connections
- Inadequate guidance in maintenance manuals
- Fuel handling procedures
- Bolts that had worked loose over time

**Fuel exhaustion**, in which all of the on-board fuel is used up, was also a key scenario. Fuel measuring inaccuracies were a significant causal factor.

- Fueling method introduces errors

- Inaccuracies in the starting quantity of fuel
- Fuel remaining is calculated, not measured
- Erroneous fuel measurement algorithm (calculates fuel based on engine RPM and throttle position, not taking into account variations of individual engines, or the operating environment)

**Carburetors** ensure the correct mixture of fuel and air is supplied to the engine. Failure of the carburetor can result in reduced engine RPM and loss of thrust.

- Flight in icing conditions
- Failure of carburetor deice
- Maintenance assembly errors

**Contaminated fuel** degraded engine performance in several instances. Improved fuel inspection procedures, filtering from the fuel supply source, aircraft fuel filters, and spark plug cleaning intervals were mentioned in reports as corrective actions for these scenarios.

One instance of **fuel nozzle failure** in a turbine-powered UAV resulted in an internal engine fire.

### 2.1.6 Throttle

**Scenario:** Failure of the engine throttle control results in uncontrollable thrust or insufficient thrust to maintain altitude.

There were 13 mishaps in our sample that can be characterized as loss of thrust control due to throttle failure, affecting three different types of vehicles.

- Failed throttle servo (loose connector, mechanical failure)
- Carburetor butterfly valve stuck, uncontrolled RPM, uncontrolled climb, then idle
- Throttle body failed, blocking airflow, resulting in low manifold pressure (idle RPM)

### 2.1.7 Propeller

**Scenario:** Failure of the propeller structure, drive train, or propeller feathering function results in loss of thrust.

There were 20 mishaps in our sample that can be characterized as loss of thrust due to failure of the propeller, drive train, or propeller feather function, affecting four different types of vehicles.

There were eight failures in which variable-pitch propellers went into a negative pitch mode, resulting in loss of thrust and high drag.

- Failed blade shaft
- Failed blade pitch servo
- Failed blade pitch bearing
- Software control error caused negative blade pitch

Other propeller failures:

- Propeller struck pneumatic/rocket-assisted takeoff (RATO) launcher components.
- Failure of propeller hub retention screws.
- Sheared bolts due to high cycle fatigue or excessive wear.
- Propeller disintegrated on takeoff or launch.
- Drive shaft sheared on an experimental vehicle.
- Propeller broke apart after hitting improvised chemlight runway lights at remote site.
- Propeller thrust bearing failed, contaminating the engine oil lubrication system, causing engine overheat and failure.
- The propeller went into BETA (reverse) mode on approach, causing excessive sink rate and drag that the pilot did not recognize until it was too low to recover. The UAV hit power lines.

### 2.1.8 Engine Controller

**Scenario:** Failure of the engine controller results in reduced engine performance or engine failure, uncontrolled thrust, or lost thrust.

There were six mishaps in our sample that can be characterized as loss of thrust due to failure of the flight control computer, affecting four different types of vehicles.

- Loose circuit cards or connections.
- Electrical short in control cable.
- Failed sensor provided erroneous information.
- An automatic engine cut feature based on wheels touch-down G-force sensor was activated by turbulence on final, shutting off engine prematurely.

## 2.2 Loss of Control

A variety of subsystem failures can result in loss of aerodynamic control, to include heading or attitude (pitch, yaw, roll) control and navigation position information.

Typical outcomes of “loss of control” mishap scenarios were:

- Undirected flight until fuel exhaustion or collision;
- Orbit at preprogrammed rally point until fuel exhaustion;
- Entering “safe” mode, such as automatic shutoff of propulsion and deployment of parachute;
- In-flight breakup.

Figure 2-4 shows the number and percentage of mishaps by system failure resulting in a loss of control in each phase of flight.

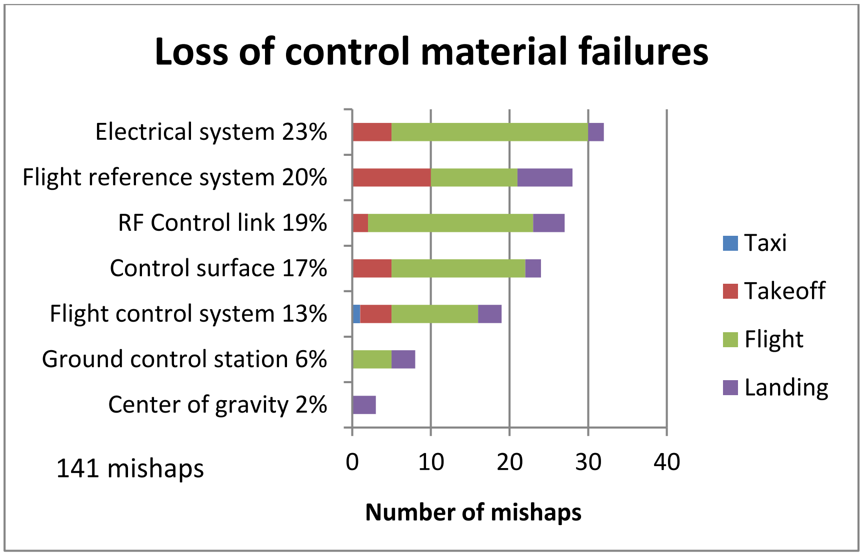

Figure 2-4. Distribution of Loss of Control Mishaps by Failed System

### 2.2.1 Radio Frequency Control Link

**Scenario:** Loss of radio frequency (RF) control link results in loss of operator ability to continuously monitor and direct vehicle flight.

There were 27 mishaps in our sample that can be characterized as loss of control due to failure of the RF link, affecting seven different types of vehicles.

- Inability to regain link after turning link off
- Flying over the horizon or behind high terrain or obstruction
- Avionics failure due to rain/moisture intrusion
- RF interference from another ground station or UAV
- RF connectors vibrated loose
- High gain satellite antenna unable to point to or regain satellite
- Software prioritized unusable C-band direct link over satellite link

There was also one hazard report in which the satellite lost-link emergency mission caused an unexpected climb that triggered a traffic collision avoidance system (TCAS) alert in another aircraft.

### 2.2.2 Control Surface

**Scenario:** Failure of a vehicle's aerodynamic control surface to function results in reduced or complete loss of the ability to maintain controlled flight.

There were 24 mishaps in our sample that can be characterized as loss of control due to failure of control surface components, affecting five different types of vehicles.

- Control surface servo or actuator failure (14 of 19 mishaps)
- Three control surface linkage failures resulting in loss of or insufficient control authority
- Control surface feedback sensor failure
- Stuck control surface

- Encounter with lightning, lost aileron control

**Scenario:** Failure of a vehicle's ground control surface results in its inability to stop or maneuver on the runway.

The NASA Wallops facility noted they have had experiences with locked brakes, failed brakes, or asymmetric brakes.

### 2.2.3 Electrical System

**Scenario:** Failure of the vehicle's electrical system results in loss of function of vehicle subsystems and loss of ability to continue controlled flight.

There were 32 mishaps in our sample that can be characterized as loss of control due to electrical system failure, affecting four different types of vehicles.

- Voltage regulator failure resulting in short circuit.
- Power cable chafing resulting in short to ground.
- Voltage spikes from generator rebooted computer and caused lost link.
- Single generator failure induced fault in remaining generator.
- Electrical system control module failure.
- Inadequate backup battery power.
    - The flight controls froze on approach as battery power ran out.
    - The generator had insufficient battery power to operate automatic landing system or parachute.
    - After the generator had tripped offline due to a voltage spike, insufficient battery voltage to reset the generator.
    - The controlling ground control station (GCS) turned off non-essential systems to reduce battery load after generator failure. On control turnover for recovery, initial settings of the recovery GCS turned vehicle systems back on, loading the battery, and possibly contributing to loss of control.
    - Both alternators failed and the operator attempted to return to base (RTB) on battery. The UAV operator incorrectly calculated remaining battery life and did not reduce battery load sufficiently. The batteries expired, the UAV went lost-link, lost control, and crashed one half mile from the runway threshold.

### 2.2.4 Flight Reference System

**Scenario:** Failure of the flight reference system results in loss of attitude, air speed, heading, position, and/or altitude references. This causes reduced or lost ability of the operator or autopilot to maintain controlled flight.

There were 28 mishaps in our sample that can be characterized as loss of flight reference data, affecting nine different types of vehicles.

#### Loss of airspeed reference

Two mishaps were related to airspeed system failure. After launch, one vehicle showed oscillating indicated airspeed and porpoising pitch attitude. The vehicle quickly stalled and crashed. The cause was determined to be bird strike damage that caused a pitot tube blockage.

In a second case, again after launch, the vehicle pitched down and impacted the ground. A blocked pitot tube was again suspected.

### Loss of altitude reference

In one mishap, failure of the altimeter pressure transducer or related hardware caused erroneous altitude input prior to catapult launch. The erroneous altitude resulted in the vehicle to be auto-launched in "constant airspeed" mode rather than "constant pitch climb" mode. The vehicle did not climb, and impacted the ground.

In another mishap, inaccuracies in the inertial navigation system (INS)/Global Positioning System (GPS) navigation system resulted in a glide path 400 feet below the intended glideslope. Clouds obscured the view of the surface and the vehicle impacted the ground on approach to the runway.

### Loss of attitude reference

Failure of the attitude reference source was a factor in 10 mishaps in four different types of UAVs. Typical outcome was pitch oscillations followed by departure from controlled flight characterized by stall, rapid descent, and/or in-flight breakup. In one case, in a newly operational type vehicle, an external pilot (EP) was able take over manual control, but emergency landing procedures for this failure had not yet been provided, and the vehicle was damaged on landing. In another case, the vehicle descended behind a ridge so the control link was lost and the pilot was no longer able to update emergency procedures.

### Loss of heading reference

There were three mishaps on two different types of vehicles related to loss of heading reference. Two involved a failed magnetometer and one pointed to a wiring failure from the magnetometer. In one case the failure induced an un-commanded turn. During the emergency recovery attempt, control was lost on final approach and the vehicle crashed. Two mishaps resulted in a sudden uncontrolled rapid descent and crash. In one of these two events, replay showed that a "magnetometer fail" indicator had been on for 16 minutes prior to loss of control.

### Loss of navigation information

Six mishaps (one fatal) on four different type vehicles were related to loss of navigation position information.

Two failures were due to crew preflight errors. In both cases, the crew failed to initialize the GPS properly by allowing sufficient time to acquire satellites. For both vehicles, flight was erratic and the vehicle crashed shortly after takeoff.

In one mishap, the GPS antenna cable detached in flight, so an accurate position was not provided to the automatic landing system and the vehicle crashed on landing.

In another incident, the GPS component or cable vibrated loose in flight resulting in loss of position information. The vehicle was successfully recovered with minor payload damage using emergency procedures.

One vehicle had a dual navigation system failure, and encountered a previously undetected software flaw that prevented it from using inertial measurement unit (IMU) attitude and heading. The vehicle departed controlled flight and crashed.

According to news reports,[3] jamming of GPS signals by North Korea may have contributed to the fatal crash of a Schiebel S-100 Camcopter UAV near Incheon, South Korea, on May 10, 2012. The small helicopter crashed into its ground control van, killing a Schiebel engineer and injuring the two remote pilots, both Koreans. The jamming started on April 28 and disrupted passenger flights into Seoul's two airports, Gimpo and Incheon. South Korean government officials told local media that the jamming originated from the border town of Kaesong. Schiebel said that an incorrect response by the operators after the Camcopter lost its GPS signal is what led to the crash some minutes later. The UAV is equipped with multiple IMUs for backup, the company noted. The recorders on board the UAV and in the ground station were burned during the crash, and could not provide any explanatory data.

Loss of visual reference

Pilots sometimes use the targeting video camera rather than a fixed camera in the nose for takeoff or landing. If the targeting camera moves unexpectedly or if the video becomes unusable, the pilot can become disoriented and fail to maneuver correctly.

In one instance, the targeting camera moved during takeoff roll, which resulted in the pilot inducing a left yaw and hitting an obstacle near the runway.

Failure of ground sensing reference

One UAV failed to sense the ground and attempted to go to next airborne waypoint.

### 2.2.5 Flight Control Computer

**Scenario:** Failure of the flight control computer results in reduced or lost ability of the operator or autopilot to control flight.

There were 19 mishaps in our sample that can be characterized as loss of control due to failure of the flight control computer, affecting four different types of vehicles.

- Flight control computer software caused uncommanded control deflections.
- Flight control computer hardware failure caused uncommanded control deflections.
- Flight control computer failure resulted in no authority of control surfaces.
- Incorrect flight control logic resulted in divergent vehicle stability and loss of control
- Automatic G-force landing detection engine shutoff was triggered while in flight when the vehicle encountered turbulence.

### 2.2.6 Ground Control Station

**Scenario:** Failures within the GCS result in lost or degraded operator ability to continuously monitor and direct vehicle flight.

There were eight mishaps in our sample that can be characterized as loss of control due to failure of GCS, affecting five different types of vehicles.

- Loss of link occurred due to corrosion-induced reduction of the GCS antenna.

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[3] Pocock, Chris. "UAV Crash in Korea Linked to GPS Jamming." AINOnline, June 1, 2012. Retrieved 13 October 2015. Available at http://www.ainonline.com/aviation-news/defense/2012-06-01/uav-crash-korea-linked-gps-jamming.

- A GCS restart while the vehicle was in flight reset the vehicle's parameters to an unsafe state.
- A second GCS signal caused interference with GCS control (see Chapter 6).
- A stuck keyboard in GCS caused a delay in critical commands to the vehicle.
- Frozen software in the GCS control rack on landing caused the vehicle to go to high-speed lost link and run off runway.

### 2.2.7 Center of Gravity

**Scenario:** The motion of shifting interior cargo or swinging cargo slung below a vehicle causes the vehicle to become unstable and depart controlled flight. Cargo dynamics shifts the center of gravity beyond limits.

- There was one mishap in our sample in which the cargo that was slung below a vertical-flight UAV began to swing in the wind. The swinging cargo caused increasing vehicle pitch instability and the vehicle crashed.
- A similar hazardous situation developed when the vehicle operator switched back and forth between manual and automatic control as the vehicle was hovering in preparation to land with a sling load. The operator noticed the cargo swinging and switched from manual to auto mode to stop the swinging, which made the swinging worse until the vehicle lost GPS, went into lost navigation mode, and climbed several thousand feet. The climb stabilized the swinging and the UAV returned to base.

**Scenario:** Asymmetric loading of left and right fuel tanks leads to loss of control.

There is a single mishap in our sample in which a small UAV with a fuel tank on each wing experienced loss of control when only one fuel tank was being used and the vehicle became unbalanced. The operator could no longer control the roll axis, and the vehicle departed controlled flight and crashed. Unauthorized maintenance procedures caused the fuel feed and vent lines to become kinked.

## 2.3 Loss of Lift

Several types of material failures can result in loss of aerodynamic lift, which relates to a vehicle's ability to maintain altitude or control its climb or descent rate. Typical outcomes of loss of lift mishap scenarios were:

- Hard landing;
- In-flight breakup;
- Crash.

Figure 2-5 shows the number and percentage of mishaps by component failure resulting in a loss of lift in each phase of flight.

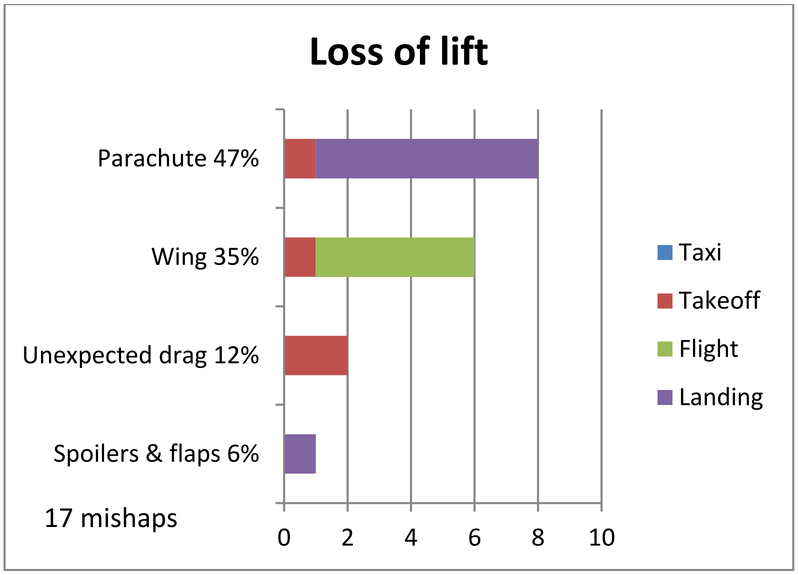

Figure 2-5. Distribution of Loss of Lift Mishaps by Failed Component

### 2.3.1 Wing

**Scenario:** Failure of or structural damage to one or both wings results in loss of lift.

There were six mishaps in our sample that can be characterized as loss of lift due to failure or structural damage of a wing or wing component, affecting five different types of vehicles.

- Wing or wings separate from vehicle
  - Screws loosened due to vehicle vibration during flight. Insufficient pre-inspection procedures
  - Excessive bank angle, coupled with manufacturing defect (wing spar failure to adhere to skin at high altitude)[4]
- Catastrophic wing failure in testing of new, high-altitude, long-endurance design
- In-flight break up
  - Exposure to turbulence in an experimental vehicle
  - Attitude gyro failure resulted in overstress of the vehicle

### 2.3.2 Lift Control Surface (spoilers, flaps, etc.)

**Scenario:** Failure of a lift control surface causes loss of the ability to maintain control of desired altitude and descent rate. Asymmetric failure of lift control surfaces causes the vehicle to depart controlled flight.

There was a single mishap of this type in our sample that can be characterized as loss of lift due to lift control surface. Spoiler flap actuators on a test vehicle failed at high altitude after a sudden encounter with turbulence. The vehicle was successfully recovered with minor damage in an engine-out landing.

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[4] Merlin, Peter W. "Crash Course: Lessons Learned from Accidents with Autonomous and Remotely Piloted Aircraft." NASA, 2013.

### 2.3.3 Parachute

**Scenario:** Parachute failure during a parachute recovery results in unretarded ground impact, causing damage to or loss of vehicle.

There were eight mishaps in our sample that can be characterized as loss of lift due to material failure of the recovery parachute, affecting four different types of vehicles.

- Parachute failed to deploy during landing sequence.
- Parachute partially deploys (suspected misrigging).
- Uncommanded parachute deployment becomes tangled in the propeller.
- Parachute fails to deploy when commanded after generator failure.
- During high altitude test, parachute deployed after engine failure, but tore in cold temperatures at altitude.
- Installation of cable over parachute pack prevents flight termination system (FTS)-commanded parachute deployment.
- Momentary lost link causes emergency parachute deployment during takeoff roll (not a mishap, but illustrates a potential mishap causal factor if it had occurred in another phase of flight).

| | |
|---|---|
| **NOTE** | Parachute-induced structural damage to vehicle (as opposed to loss of lift) is discussed in Subsection 2.4.5. Parachute failures due to operator procedure error are discussed in Section 3.7. |

### 2.3.4 Unexpected Drag (airbag, speed brakes, etc.)

**Scenario:** Unexpected deployment of vehicle drag sources results in loss of ability to maintain desired altitude or climb rate.

Scenario lessons learned are based on two mishaps of a foreign UAV. The vehicle's airbags, intended to minimize ground impact damage during parachute recovery, deployed during catapult launch. The vehicles failed to gain altitude and impacted the ground soon after launch. One failure was thought to be due to a failed airbag control box, and the other was related to sand intrusion into the airbag control.

## 2.4 Loss of Structural Integrity

Several types of material failures can result in loss of structural integrity. Typical outcomes of loss of structural integrity mishap scenarios were:

- Loss of thrust outcomes when power plant structure was involved;
- Loss of control outcomes when control surfaces were involved;
- Loss of lift outcomes when lifting surfaces or parachute were involved;
- Runway excursions (i.e., rolls off the paved runway surface).

Figure 2-6 shows the number and percentage of mishaps by causal factor resulting in a loss of structural integrity in each phase of flight. (The percentages in this figure are rounded to the nearest whole number, so they may not total 100%).

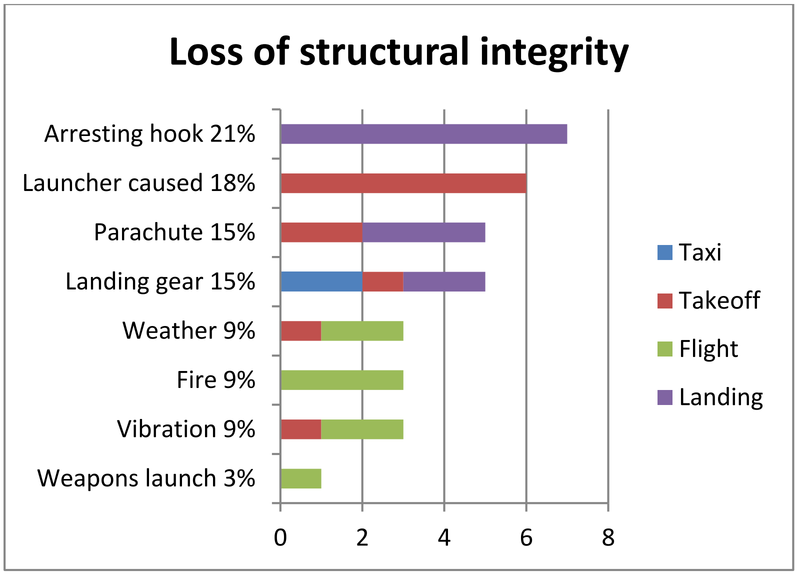

Figure 2-6. Distribution of Loss of Structural Integrity by Cause

### 2.4.1 Vibration

**Scenario:** Vehicle vibration causes mechanical components to gradually loosen until critical components come loose.

- Attachment bolts come loose:
  - causing transmission failure;
  - causing fuel tank separation.
- Structural screws come loose over the course of several flights, causing the wing to separate from the vehicle after catapult launch (combination of vibration and launcher-induced failure resulting in loss of lift).

### 2.4.2 Launcher-related Structural Failure

**Scenario:** Material failure of the vehicle results in failed launch from UAV launcher.

There were no vehicle failures of this type in the mishaps we examined, although nine were attributed to the launchers. Upon further investigation, launcher-related failures were found to be either material failure of the launchers themselves *(see Section 4.1)* or operator errors in configuring the launcher *(see Section 3.2)*.

### 2.4.3 Landing Gear

**Scenario:** Failure of the landing gear or related components, such as tires or wheels, results in loss of directional control during ground operations.

There were five mishaps in our sample that can be characterized as loss of structural integrity due to failure of landing gear or landing gear components, affecting four different types of vehicles. An additional event was related to a sudden stop on the taxiway.

- Underinflated tires
- Nose servo shaft failure

- Wheel failure
- Landing gear failure to deploy
- Tail damage due to the vehicle’s sudden stop and backwards tilt on an inclined taxiway

In one instance, runway operations at an airfield were halted for several hours due to trunnion bolt damage discovered during taxi. This incident is not categorized as a mishap; however, hindrance to normal runway operations is an undesirable outcome.

### 2.4.4 Arresting hook

**Scenario:** Failure of the arresting hook, or “tailhook,” to function correctly or deploy during recovery operations results in failure of the vehicle to remain on runway after landing.

Seven events were attributed to an arresting hook failure; however, there was only one event in which the tailhook structure failed on engagement with the arresting gear cable. The vehicle rolled off the end of the runway and was damaged.

| | |
|---|---|
| **NOTE** | Other mishaps related to material failures of the arresting gear rather than the arresting hook are covered in Section 4.2. Operator skill in engaging the arresting gear with the arresting hook, rather than material failures of the vehicle itself, are discussed in Section 3.5. |

### 2.4.5 Parachute

**Scenario:** Recovery parachute deploys and tangles with the vehicle or propeller, causing structural damage to the propeller or vehicle.

There were four mishaps in our sample that can be characterized as loss of structural integrity due to parachute failure, affecting one type of vehicle. In all four mishaps, the parachute deployed and caused damage to the vehicle or propeller.

| | |
|---|---|
| **NOTE** | Parachute failures resulting in loss of lift (as opposed to structural damage) are discussed in Subsection 2.3.3. Parachute failures due to operator procedure error are discussed in Section 3.7. |

### 2.4.6 Fire

**Scenario:** Onboard fire causes structural failure.

There were three mishaps in our sample that can be characterized as loss of structural integrity due to fire, affecting one type of vehicle. Both instances were related to oil leaks that ignited. In both cases, the fire consumed the engine compartment and eventually caused attached control surfaces to separate, resulting in departure from controlled flight.

### 2.4.7 Weather

**Scenario:** Weather phenomena cause structural damage or structural failure.

There were three mishaps in our sample that can be characterized as loss of structural integrity due to weather, affecting two different types of vehicles.

- Crosswind gusts exceeded the limits of the inertial measuring unit, causing an abrupt yaw followed by a structural failure of the tail boom.
- Hail conditions resulted in leading edge structural damage and engine damage.

Weather as a more general cause of mishaps (not specifically related to structural damage) is discussed in Section 5.1.

### 2.4.8 Weapons Launch

**Scenario:** Weapons launch causes vehicle structural damage.

There was one mishap in our sample that can be characterized as structural damage caused by weapons launch. On launch, a missile did not immediately release from the UAV's missile rack, causing the aircraft to yaw and roll, then depart controlled flight and crash.

## 2.5 Toxic Materials

**Scenario:** Toxic materials used in the construction of the vehicle or as fuel causes harm to personnel or property after a crash.

Hazardous aerospace materials are materials and systems integrated into aerospace vehicles that can present a potential safety and health hazard to personnel responding to mishaps. These materials can include: composite materials, radioactive materials, metals, and protective coatings.

At a crash scene, hazardous materials may require special handling or disposal procedures.

Although there were no mishaps in our sample in which toxic materials were a causal factor, the presence of toxic materials in the event of a mishap can significantly increase the severity of the mishap by causing additional injuries. Prevention measures may reduce this severity.

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# CHAPTER 3

## Operator and Vehicle Interaction

Operator-vehicle interaction failures can result in a variety of mishaps. Recognizing and categorizing which safety-critical tasks have caused problems in the past can provide a basis for risk management of operator-task mismatch issues.

Phase of flight and type of launch or recovery are major categories because they represent significantly different tasks and problems for the operator to resolve, different configurations of the vehicle, and different operating environments.

Aviation tasks have frequently been categorized using the terms “aviate,” “navigate,” and “communicate” - especially in relation to prioritizing responses to emergency situations. We will use these same categories and adapt their definitions[5] as follows.

**Aviate**. Control the vehicle’s path.
- Maintain altitude, heading, air speed, pitch, roll, vertical velocity, etc., within safe limits.
- Avoid obstacles in vicinity of flight path.
- Detect and avoid other aircraft.
- Perform emergency maneuvers, waveoffs, or runway aborts as necessary.

**Navigate**. Direct the vehicle from its origin to its destination; awareness of aircraft position in relation to its desired trajectory.
- Plan/update flight plan considering mission, environment, resources, and vehicle health.
- Global awareness of the environment from origin to destination, as well as contingency destinations (routes, special-use airspace, boundaries, weather, geographic obstacles, etc.).
- Local guidance (e.g., to the next waypoint).
  - Current position
  - Runway site survey, runway selection for current wind conditions
- Make performance calculations as necessary.
  - Takeoff distance
- Plan/update contingency routes for emergencies or lost link.

**Communicate**. Provide data and requests; receive instructions and flight-related information.
- Communicate with airspace authority (e.g., Air Traffic Control [ATC]).
- Monitor weather information for route and destination.

**Manage Systems.** Manage the resources available.
- Update vehicle configuration for phase of flight.
- Monitor vehicle health status.
- Monitor fuel quantity.

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[5] Ververs, Patricia. “Understanding a Pilot’s Tasks.” University of Illinois Aviation Research Laboratory, 1997.

Figure 3-1 shows the breakdown of mishaps related to vehicle-operator interaction, grouped into safety-critical aviation tasks.

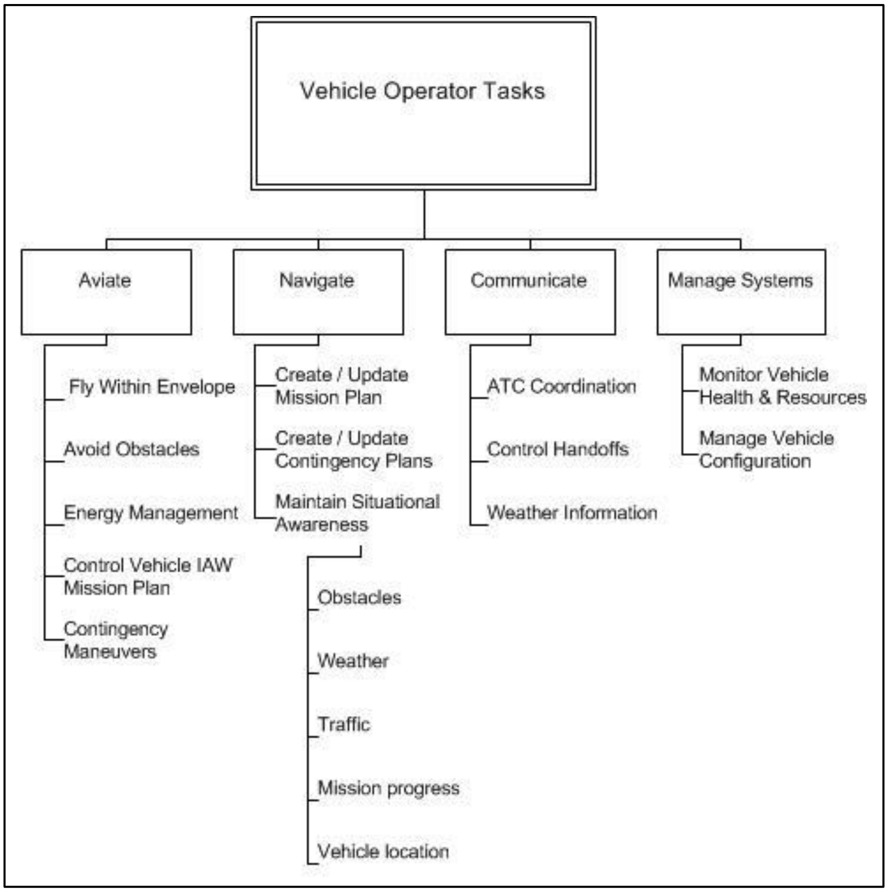

Figure 3-1. Taxonomy of Operator and Vehicle Interaction Mishaps by Operator Task

Once an operator or automation-controlled task is identified as a causal factor in a mishap, it can be further analyzed in order to discover opportunities to avoid such mishaps in the future.

Recognizing that a mishap related to this task has happened before can prompt a closer examination of a new and similar situation. Then more in-depth analysis can be used to look for preconditions, supervisory issues, or organizational influences.

Review of UAV mishap operating tasks can also be used to examine differences in manned and unmanned decision capability, such as diminished “air sense” capability, situational awareness, and feedback latency.

This document identifies operator or automation tasks related to mishaps and leaves in-depth analysis to future efforts.

Figure 3-2 shows by task category and pilot safety-critical aviation task the number and percentage of mishaps related to operator-vehicle interaction.

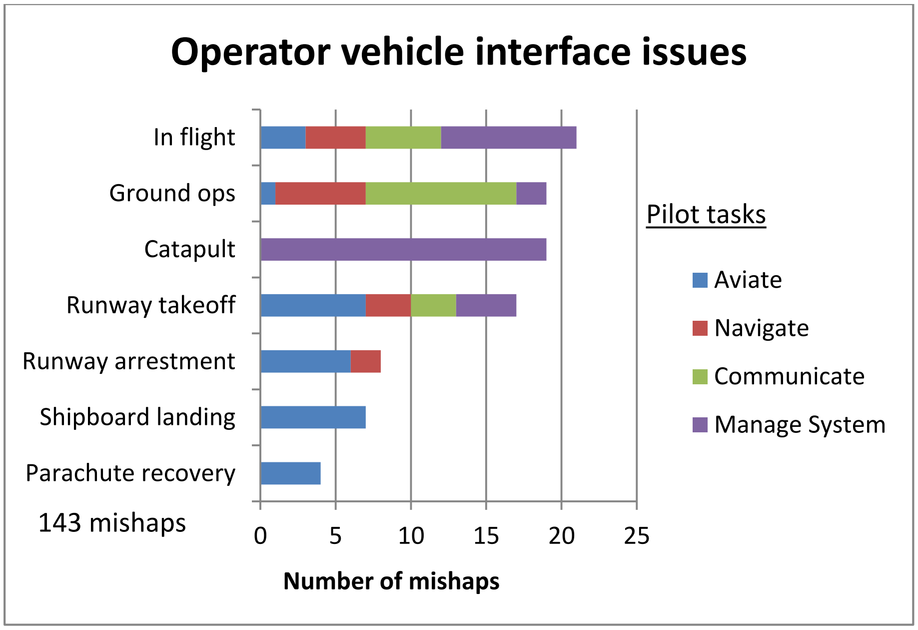

Figure 3-2. Distribution of Operator and Vehicle Interaction Mishaps by Task Category

## 3.1 Runway Takeoff

Aviate Tasks - Runway Takeoff

**Scenario:** Operator-commanded early rotation and/or stall causes loss of lift.

- During initial flights at a high-altitude airfield, the EP rotated early based on visual distance estimate rather than velocity readout. Performance charts were inaccurate for the runway altitude. The presence of far-end rigged arresting gear was a factor.
- The EP did not notice a wind shift and attempted takeoff with an unexpected tailwind, over-rotated, and stalled.
- An unqualified EP stalled the vehicle during touch and go. No qualified EP was with him at the time.
- The EP over-controlled the vehicle rotation and stalled. The roll distance had been calculated inaccurately, and the EP accepted a runway with tailwinds.

**Scenario:** An operator fails to avoid obstacles, maintain centerline, or achieve the appropriate rate of climb on runway takeoff, causing a mishap.

- During a night operation, there were no runway centerline lights and the nose navigation light was not working. As a result, the EP did not recognize the vehicle drifting off centerline until it was too late to avoid colliding with an obstacle near the runway.
- A trainee EP delayed announcing the vehicle's failure to climb, resulting in a late takeoff abort attempt. The vehicle hit upslope off the end of the runway.
- A trainee EP drifted off centerline during a touch and go and overcorrected the heading, so the vehicle propeller hit a runway light by the side of the runway.

Navigate Tasks - Runway Takeoff

**Scenario:** Navigate task deficiencies cause incorrect operator actions during runway taxi/takeoff, resulting in damage to or loss of vehicle.

- Takeoff distance calculated incorrectly.
- Wrong runway selected for current winds.
- Wrong speed set in autonomous taxi mission plan not discovered during review process; vehicle taxied off runway at high speed.

Communicate Tasks – Runway Takeoff

**Scenario:** Non-standard tower terminology causes a potentially hazardous departure.

Three mishap or hazard events relating to tower unclear use of terminology or tower situational awareness during takeoff were found in our data set. These events are described in Chapter 7.

Manage System Tasks - Runway Takeoff

**Scenario:** System management task deficiencies cause incorrect operator actions during runway taxi/takeoff, resulting in damage to or loss of vehicle.

- An operator inadvertently selected autopilot pre-programmed mode rather than cooling fan. The vehicle attempted to go to an airborne waypoint, ran off the taxiway surface, and hit a runway light (also relates to Section 7.1).
- An operator failed to turn on the stability augmentation system in accordance with the checklist. After takeoff, the vehicle experienced pitch, roll, and yaw excursions, then stalled and crashed.
- An incorrect mission plan was loaded, causing the vehicle to taxi in the wrong direction. The chase driver aborted taxi with no damage to the vehicle. Multiple cross checks had failed.
- In two similar incidents, incorrect configuration of the targeting system camera on takeoff resulted in pilot loss of situational awareness. The vehicle entered into lost-link mode and struck an obstacle near the edge of the runway.

## 3.2 Catapult Launch

This section refers to mishaps related to failure of mechanical or pneumatic launchers. There were no mishaps in our sample caused by aviate, navigate, or communicate tasks, but there was a number of system management causal factors.

Manage Systems Tasks - Catapult Launch

**Scenario:** A crew fails to ensure the vehicle and/or GCS are in the correct configuration prior to catapult launch.

- The pre-launch inspection missed a loose alternator plug. The plug detached after launch and the vehicle lost electrical power and crashed.
- During preflight, GPS was in “dead reckoning” mode rather than satellite navigation mode. The operator under instruction launched the vehicle without an instructor present. The vehicle crashed just after launch.

- The communications link modem failed on preflight; however, the operator launched the vehicle anyway. The vehicle lost contact after launch and is presumed to have run out of fuel and crashed.
- The GCS transmitter and a separate transmitter for the EP were unexpectedly both transmitting at the same time as a result of improper preflight. After launch and under EP control, the GCS transmitter prevented the EP from controlling the vehicle and it crashed.
- The vehicle was launched in manual control rather than automatic launch mode due to a skipped step in the checklist. The vehicle rolled and crashed after launch as the operator expected auto control, so was not providing manual inputs. There was a total of three similar mishap events.

**Scenario:** A crew fails to ensure the launcher (with vehicle loaded) is in the correct configuration prior to catapult launch.

- A loose tool left on top of the vehicle struck the propeller on launch, shattering the propeller. The vehicle performed a forced landing after launch.
- The crew started to switch launchers during preflight, but changed their minds and launched from the original launcher. They did not restart the checklist, and tried to launch with a launch pin still in place. The vehicle snagged on the launch pin and broke apart as it was launched.
- The crew skipped a checklist step and failed to disconnect an external power cable from the aircraft. The cable struck the propeller on launch, destroying the propeller. There were two similar mishaps of this type.
- A tool left on the launcher hit and destroyed the propeller on launch. The vehicle crashed just after launch.
- The vehicle was launched with solar panels still attached and crashed just after launch.

**Scenario:** A crew fails to ensure preflight and run-up checks are completed before launch.

- High engine temperature was noted on preflight; however, the vehicle was launched from the catapult anyway. The vehicle was unable to sustain climb out and crashed.
- The crew failed to verify sufficient RPM for launch. The vehicle was pneumatically launched with insufficient engine thrust and crashed. This was found to be a checklist error. There were two mishaps like this in our sample.
- There were three instances of a vehicle being pneumatically launched with engine at idle in which the vehicles quickly hit the ground. Checklist steps were missed in all three instances. Distraction was a factor in two of the mishaps. A challenge and response checklist technique was suggested.

## 3.3 In Flight

Aviate Tasks - In Flight

**Scenario:** A vehicle operator fails to maintain flight within a safe operating envelope.

There were three mishaps of this type involving three different types of UAV.

- Camera position off centerline caused the internal pilot to misperceive vehicle heading and attitude. The pilot over-corrected and stalled the vehicle, which entered into a spin.

Negative transfer (i.e., previous manned aircraft experience) may have been a contributing factor.

- The pilot improperly controlled the speed, causing a stall.
- A foreign UAV "exceeded operating limits" and crashed. No additional information is available.

Navigate Tasks - In Flight

**Scenario:** Inadequate route planning leads to loss of aircraft.

- The emergency mission plan was improperly programmed; the vehicle hit terrain when it lost link.
- A vehicle operator attempted to find a route between thunderstorms. The vehicle was lost after a lightning strike and apparent encounter with icing conditions *(this mishap is also used to illustrate thunderstorm hazards in Subsection 5.1.1).*
- After on-station mission completion and RTB, a UAV flew through snow, ice, and turbulence. While in these conditions, the UAV encountered five severe downdrafts and went lost link. The review board determined that the pilot failed to assess the weather, and that lost link was due to lightning strike.

**Scenario:** Inadequate calculation of the remaining battery vs. distance to base results in loss of the aircraft.

Both alternators in the UAV failed and the operator attempted to RTB on battery power; however, the operator incorrectly calculated the remaining battery life and did not reduce battery load sufficiently. The batteries expired and the UAV went lost link, lost control, and crashed one half mile from the runway threshold *(see also Subsection 2.2.3).*

Communicate Tasks – In Flight

**Scenario:** Non-compliance with ATC communications causes a potentially hazardous airspace situation.

There were five mishap or hazard events in our data sample relating to in-flight communications deficiencies. These events included two non-compliance events, two events in which instructions were not understood, and one instance of failure to maintain communications. These events are described in more detail in Section 7.1 and Section 7.2.

Manage System Tasks - In Flight

**Scenario:** An incorrect or unauthorized configuration decision by operator results in the loss of a flight-critical function and loss or damage to the vehicle.

- A UAV had experienced an uncommanded engine cut during preflight but was launched anyway. The engine failed during the mission and the vehicle entered an uncontrolled glide and crashed.
- An operator used an unauthorized local procedure to adjust pitot heat, but inadvertently erased vehicle memory. The vehicle went into lost-link mode, stalled due to the erroneous data in memory present files, and crashed.
- A vehicle operator became confused by pitch trim settings being engaged or disengaged depending on autopilot mode selection. This confusion increased when pitch attitude

caused loss of link and the vehicle began to cycle between lost-link and link engaged modes. The vehicle went through several more pitch excursions and crashed.

- The GCS experienced a rack lockup, requiring a reset. The crew used an incorrect restart procedure that reset aircraft parameters and resulted in permanent loss of link. The crew did not have the most recent validated GCS rack lockup reset checklist. The vehicle followed its emergency route for several cycles and eventually crashed (also in Section 7.1).
- The operator mistakenly deactivated the stability augmentation system while the UAV was in flight and then did not notice the vehicle roll, causing lost link and departure from controlled flight. The UAV crashed in a remote area.
- The operator inadvertently turned off the ignition when intending to raise landing gear at low altitude. The UAV glided to a landing short of the runway and damaged the vehicle when it hit a hole in the runway clear zone.
- The operator attempted to troubleshoot a known faulty secondary autopilot. When the operator switched to the bad autopilot, the vehicle pitched down. The operator commanded lost link but the faulty autopilot maintained the pitch down attitude and the vehicle crashed.
- The operator inadvertently activated the fuel shutoff valve while the UAV was in flight, causing the engine to quit. The operator attempted a forced landing; however the vehicle was destroyed when it went off the end of the runway.
- The operator improperly set the throttle quadrant settings prior to launch. The pre-launch checklist, which should have caught the error, was not used correctly. The vehicle stalled in flight as a result of the unrecognized reverse thrust condition that exists when the throttle is in any position other than full forward.

## 3.4 Runway Landing

Aviate Tasks - Runway Landing

Some contributing factors unique to UAVs were mentioned in multiple mishap reports.

- Latency of commands to the UAV contributes to induced oscillation.
- Limited visual, audio, and relative motion cues affect situational awareness.
- There is no immediate touchdown feedback indication to the pilot.

**Scenario:** An operator fails to maintain a stable approach, flares high or has a high sink rate, and impacts on the nose gear or in a crab, with one or more bounces, resulting in aircraft structural damage, runway excursion, or runway overrun.

There were 20 mishaps affecting two different type vehicles that encountered this situation. Four mishaps involved operators under instruction, and three of these incidents also involved crosswinds as a contributing factor.

**Scenario:** Fast approach by the EP results in runway over-run.

There were two mishaps on the same type of vehicle. In a third, similar mishap in a different vehicle, the internal operator failed to recognize the throttle stuck high (which resulted in a high, fast approach) and was unable to brake before running off the end of the runway.

**Scenario:** A low approach attempt at night by an EP touches down short of the runway, causing vehicle damage.

There was one incident of this scenario in our data.

**Scenario:** A high sink rate during training results in a hard landing, tail strike, or impact short of the runway.

There were three mishaps with two different types of vehicle involved with this scenario.

**Scenario:** An operator use of a stabilized camera display causes confusion on approach, resulting in loss of control.

There were three events in which the operator used a stabilized camera that caused misperception during runway approach and resulted in disorientation and abnormal runway contact or pilot-induced oscillation (PIO).

**Scenario:** An operator fails to maintain clearance above obstacles on approach or during landing rollout.

In the one mishap in our sample, an EP misjudged vehicle altitude and collided with trees on final approach.

**Scenario:** An operator fails to fly the emergency profile correctly.

- A UAV experienced a slow loss of coolant resulting in high engine temperature and engine failure during approach to base. The crew failed to perform a flameout approach and the UAV overflew the runway and impacted the ground 1/2 mile from the runway threshold.
- A UAV in flight developed a coolant leak (coolant pump seal) and elected to RTB. Due to heavy gross weight, the operator elected to perform a normal approach rather than flameout approach. During the normal approach, the engine lost thrust and the pilot attempted a forced landing 1.4 nautical miles (NM) short of the landing threshold. According to the review board, the operator failed to diagnose the severity of the mishap engine's problem, did not perform required critical actions associated with the high descent rate, and did not maintain limits for a forced landing.
- The propeller went into BETA (reverse) mode on approach, causing an excessive sink rate and drag that the operator did not recognize until the UAV was too low to recover. The UAV hit power lines.

### Navigate Tasks - Runway Landing

Failure to adequately perform navigation tasks contributed to runway landing mishaps in nine events that can be broken down into three scenarios.

**Scenario:** Vehicle operators fail to identify obstacles on or near the anticipated approach path and runway.

- Trees along approach path
- Trees along route of unauthorized low pass demo
- An unused arresting net pole near the approach end of the runway
- Another aircraft parked near the approach end of the runway
- A light pole at an improvised landing demonstration site

**Scenario:** A vehicle operator does not enter the landing site altitude correctly for automated landing. The vehicle impacts with the ground *(multiple similar occurrences for one type of vehicle).*

**Scenario:** Vehicle operators use incorrect wind data in approach runway selection, which contributes to landing mishap.

- The crew did not correctly record the crosswind component for landing either due to incorrect crosswind component chart use or mishearing the tower winds. The aircraft performed a landing approach with out-of-limits winds, significantly increasing pilot workload.
- Two different sets of wind measuring equipment showed differing winds. The tower used winds from one system showing winds within crosswind limits. The other system, used by the local weather service, showed winds out of limits. The aircrew proceeded on approach using tower winds; however, actual winds were out of limits. Excess crosswind contributed to the landing mishap.
- The remote site tower did not have a wind speed and direction indicator, so the pilot relied on hour-old wind data. Current wind conditions gave a 13-knot tailwind, which resulted in a runway overrun and collision with a barrier at the end of the runway.

### Manage System Tasks - Runway Landing

Failure to manage vehicle system configurations adequately during landing resulted in five mishap incidents.

- A pilot inadvertently introduced left aileron trim and misperceived a crosswind. The pilot focused on the crosswind rather than the more critical decreasing airspeed and increasing sink rate on final approach.
- The pilot under instruction pushed the “autopilot disconnect” switch rather than the “master caution acknowledge” switch next to it. The UAV on approach departed controlled flight and crashed into the trees.
- The pilot attempted an approach while in cruise mode, which causes the vehicle to try to maintain constant airspeed. The vehicle did not respond to manual control inputs on approach as the pilot expected. The pilot was confused and the vehicle crashed short of the runway.
- The pilot flew a slightly fast approach on final, just above the threshold where cruise mode automatically turns on and retracts flaps. The pilot reduced throttle, decreasing airspeed, and the vehicle left cruise mode, which caused the flaps to return to normal, reducing airspeed even more (not noticed by the pilot, who was focused on lining up on the runway). The airspeed continued to decrease until the vehicle stalled and impacted the side of the runway.
- Engine cut logic causes the engine to shut off if it detects a landing impact (i.e., sudden G force change at low altitude). A sudden wind shift on final approach caused the engine cut logic to trigger, resulting in a hard landing.

## 3.5 Arrested Runway Landing

Aviate Tasks - Arrested Runway Landing

**Scenario:** A pilot (or automatic landing system) does not fly the vehicle to intercept the center of the arresting cable.

There were six mishaps that affected two different type vehicles.

- The vehicle did not maintain centerline and struck an object on the side of the runway before the arresting gear.
- The EP performed a fast approach due to perceived engine problems. The vehicle bounced, then rolled over the arresting gear at the edge of the runway where the cable had been previously repaired with a section of nylon cable that lay flat, not allowing the hook to catch. The vehicle continued past the runway end into the over-run area.
- The EP flew a slightly fast approach. In the rollout after touchdown and engine cut, the vehicle became airborne and overflew the arresting cable and overran the runway.
- A vehicle flew over the arresting gear and impacted a fence at the end of the runway.
- A vehicle flew over the arresting gear and past the runway safety net and landed in a ditch past the runway.
- A vehicle under control of an EP at night struck a pole along the side of the runway.

Navigate Tasks - Arrested Runway Landing

**Scenario:** The aircrew and/or test team fails to perform an adequate site survey for arrested landings.

There were two mishaps related to this hazard that affected two different vehicles.

- A prototype vehicle was being tested at a rocky, remote airfield. The vehicle tailhook bounced on the irregular stone surface and bounced over the arresting cable. The vehicle was damaged after the operator made a sudden turn to prevent it from leaving the side of the runway. Latency was determined to be an issue.
- A taxiway was used for arrested UAV landings. On landing, the vehicle tailhook bounced over the taxiway centerline reflectors and missed the cable, so the vehicle rolled past the end of the runway.

## 3.6 Shipboard Landing

Aviate Tasks - Shipboard Landing

**Scenario:** An EP does not direct the vehicle to the center of the recovery net within limits.

Seven mishaps of this type occurred with the same type of vehicle.

- The pilot over-adjusted the vehicle’s approach heading and the vehicle bounced off the edge of the recovery net and into the sea.
- A pilot under instruction flew an approach with wind near the maximum allowable limit. The ship entered a Dutch roll as the vehicle approached the net. The vehicle hit the side of the net and a support pole, and then fell into the sea. Wind limits were reduced after this mishap. There were two other similar mishaps.

- A pilot under instruction flew a series of approaches at night. The final approach attempt was well left of centerline. The pilot under instruction used a hard turn to return to centerline, but the vehicle lost attitude and slid under the net, damaging the aircraft. The pilot did not attempt to wave off. The mishap was attributed to inexperience and inadequate training in night visual illusions or waveoff guidance. There were two other similar mishaps involving inexperience and night operations. In one case, pilot eyesight limitations were a contributing factor.

## 3.7 Parachute Recovery

Aviate Tasks - Parachute Recovery

**Scenario:** A UAV operator delays activation of the emergency/recovery parachute, resulting in damage to or loss of vehicle.

Delays in deploying a parachute may result in:

- Vehicle altitude too low for parachute to fully deploy before impact;
- Vehicle descending behind terrain and option to deploy parachute is lost;
- Operator losing option to deploy parachute when emergency battery voltage drops below threshold to maintain RF link or activate parachute.

Parachute material failures are discussed in Subsection 2.3.3 and Subsection 2.4.5.

- The UAV’s autopilot failed and the vehicle went into a dive. The aircrew delayed deploying the emergency parachute and the vehicle impacted the ground. An intermittent link due to line-of-sight issues may have been a factor in the delay.
- The vehicle reported unusual attitudes prior to loss of control. The crew did not deploy the parachute.
- During a generator failure emergency, the vehicle was operating on battery power and the crew was attempting to make an emergency landing. After a second attempted landing, the battery voltage dropped below the threshold necessary to deploy the parachute. The vehicle lost link and crashed.
- A UAV operator activated the parachute at the correct time; however, the battery voltage dropped below the level necessary to deploy the parachute. The parachute did eventually open, but at too low an altitude to prevent damage to the vehicle.

## 3.8 Ground Operations/Taxi

Fourteen hazardous ground events and mishaps relating to operator errors, route planning, communication errors, switch selection, situational awareness deficiencies, and ground vehicle incursions were found in this data set. These events are described further in sections 7.4, 7.5, and 7.6.

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# CHAPTER 4

## Launch Systems, Recovery Systems, and Airfield

Some UAV mishaps were due to failures of launch or recovery equipment or the airfield environment itself (e.g., obstacles in the flight path, the quality of the runway surface, etc.), as shown in Figure 4-1. Figure 4-2 shows the number and percentage of mishaps by airfield scenario.

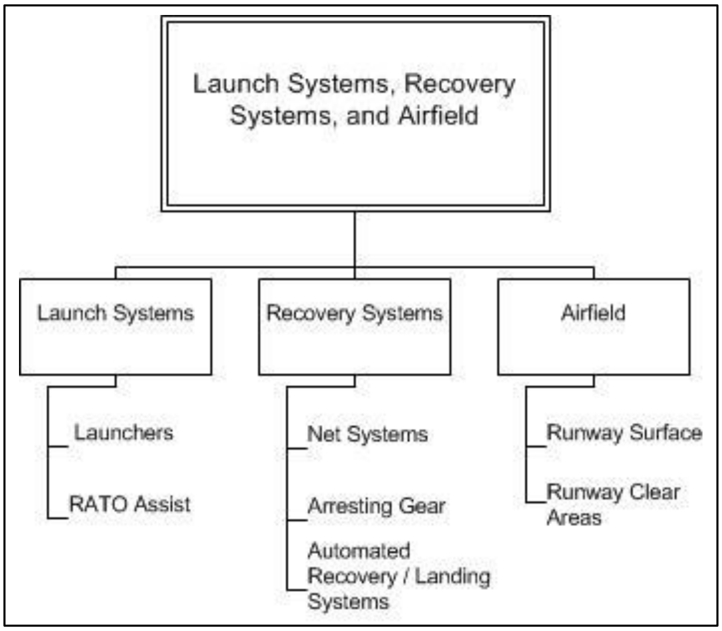

Figure 4-1. Taxonomy of Launch Systems, Recovery System, and Airfield-Related Mishaps

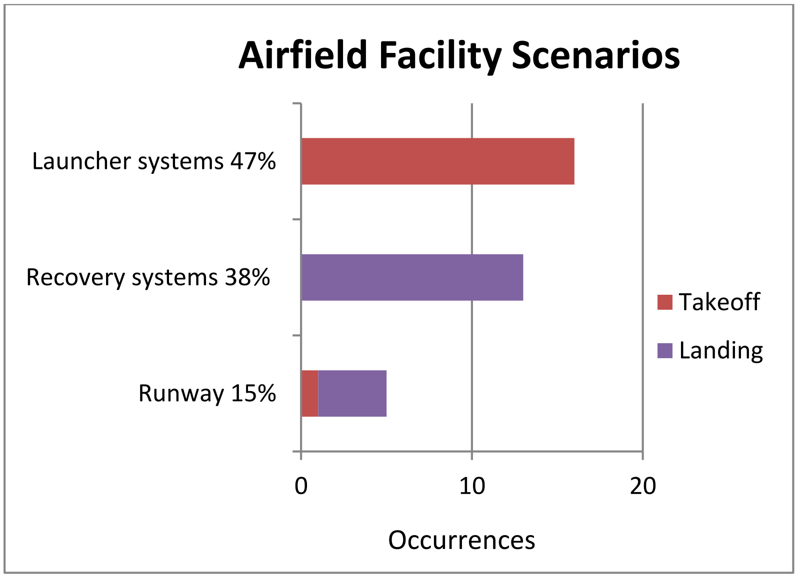

Figure 4-2. Distribution of Launch System, Recovery System, and Airfield Mishaps

## 4.1 Launch Systems

*"The flight was uneventful until launch." – A comment from a mishap report narrative*

**Scenario:** A launcher fails to provide sufficient thrust assistance for the vehicle to become airborne.

Four mishaps of this type occurred due to mechanical failure, failure of the control box wiring, or timing failure.

**Scenario:** A launcher mount fails to hold the vehicle on rails and release during launch.

- Locking mechanism mechanical failure
- Guide assembly failed and was torn from launcher, hitting propeller
- Launch strap failed on two vehicles
- Holdback hook released early before launcher was ready
- Launcher shuttle did not release vehicle at end of launch stroke
- Aircraft fell off launcher when attachment failed
- Launcher rails became misaligned over time

**Scenario:** The RATO components fail to detach from the vehicle after launch, hindering tailhook deployment and arrested landing.

There was one mishap in which this scenario occurred.

## 4.2 Recovery Systems

**Scenario:** Inadequate design of a ship recovery net allows a UAV to hit the ship.

- Excess net runout did not provide sufficient room for the vehicle to decelerate upon landing before hitting the ship superstructure.
- The recovery net design specific to one type of ship was used on a different ship with different landing area geometry. These differences resulted in a gap in the net that the UAV was able to pass through on recovery. The UAV then hit the ship.

**Scenario:** Maintenance and wear on the arresting gear results in inadequate performance.

- The stakes that were driven into the ground to hold the arresting gear attachment points in place at a remote site came loose over time and broke free during an arrestment.
- The incorrect adjustment of the arresting gear brake drum torque resulted in excessive braking, which snapped the landing vehicle's tailhook rather than gradually decelerating the vehicle. The tailhook popped off the cable and the vehicle rolled past the end of the runway.
- The arresting gear restraining straps failed due to deterioration caused by exposure to weather and repeated use.
- An unauthorized field repair resulted in a shorter section of cable available to catch the vehicle's hook. The repaired section was made of a nylon strap rather than cable material. A vehicle landing near the edge of the runway ran over the repaired nylon strap section and not the cable, and did not engage the cable.

**Scenario:** Failures of the automatic landing system result in loss or damage to the UAV. There were four mishaps with two different vehicle types in the data.

- Incorrect landing parameters were entered into the automatic landing system control, which resulted in an approach well off centerline. The vehicle hit an obstacle on the side of the runway.
- The automatic landing system transponder failed on approach; however, the failure was not recognized on preflight or during approach. The review board recommended diagnostics for tactical automatic landing system (TALS).
- An automatic landing system transponder lost link during the approach just prior to touchdown. The vehicle rolled off the side of the runway. The previous vehicle event had experienced a TALS warning on preflight. The mishap summary did not specify wind limits for the vehicle; however, there was a large headwind shift between 350 ft and the surface from 40 knots headwind to 10 knots at the surface, which may have been out of limits *(see Subsection 5.1.2)*.
- Careless aircraft maintenance actions resulted in water getting into the automatic landing system transponder antenna connection. The automatic landing system became unusable for landing and the vehicle was lost at sea.

**Scenario:** The net design stops the vehicle, but causes minor damage.

A hazard report describes multiple occurrences of minor damage to the pitot system and antennas as a result of engaging the runway recovery net.

## 4.3 Airfield

**Scenario:** Unimproved runway surface conditions cause the tailhook to skip over the arresting gear cable.

- Embedded stones in a runway caused the tailhook to bounce over the arresting cable.
- A dry lakebed used for landing had ruts from vehicle traffic when the lakebed was still wet. The tailhook hit the rut prior to the arresting cable and did not catch the cable.
- The disks that hold the arresting cable above the ground sank in soft sand so the cable was lying on the ground. The vehicle tailhook passed over the cable without catching it.

**Scenario:** A vehicle is damaged when it hits an obstacle near or on the runway.

At a remote site, a paved road was being used as a landing surface. The UAV hit a pothole at the end of the landing surface on rollout and was damaged.

**Scenario:** Lack of operational ATC radar and reduced tower situational awareness contributed to a collision.

A small UAV requested recovery clearance from Tower control and received clearance to land at their discretion. The UAV intended to overfly the south end of the runway, but was advised of a helicopter conducting a hover check in that area. The UAV operator adjusted his heading to cross over mid-field but did not update Tower. A second helicopter was cleared for takeoff and cleared to cross the runway at mid-field. The UAV struck the second helicopter’s rotors and was destroyed. The helicopter was able to make a controlled landing with damage to its rotor tips.  The airfield was designated as Class G (uncontrolled) rather than Class D because the ATC radar had not yet been checked and certified *(see also Section 7.1)*.

# CHAPTER 5

## Environment

The environment, both natural and man-made, can cause or contribute to mishaps in combination with other failures discussed elsewhere in this document or independently. Figure 5-1 shows mishaps grouped as natural (weather and terrain) or man-made (RF) environmental conditions. Figure 5-2 shows the number and percentage of environment-related mishaps by phase of flight.

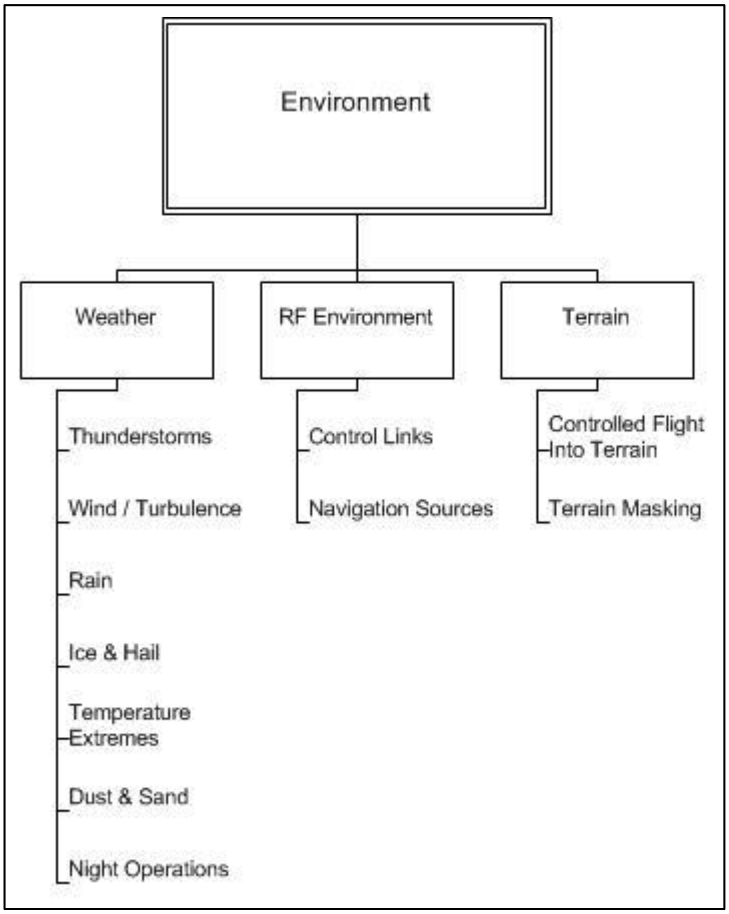

Figure 5-1. Taxonomy of Environment-Related Mishaps

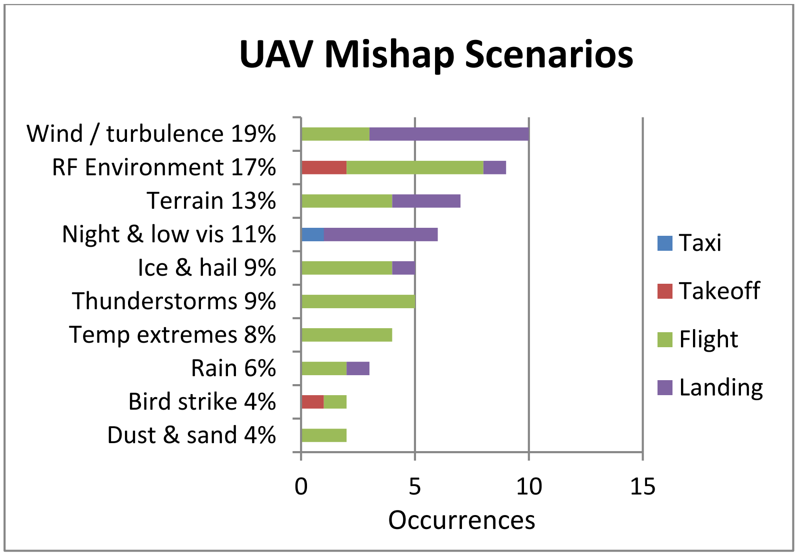

Figure 5-2. Distribution of Environment-Related Mishaps

## 5.1 Weather Causes

There were 53 different mishaps in our sample in which weather was a primary or significant causal factor, affecting many different types of vehicles.

### 5.1.1 Thunderstorms

**Scenario:** A vehicle is damaged or destroyed due to proximity to thunderstorm(s).

- A pilot misjudged the distance from a thunderstorm boundary and inadvertently flew into it. A lightning strike or static discharge caused a temporary loss of DC power and subsequent ability to control the control surfaces. The vehicle crashed.
- A UAV was assigned to support troops on the ground in contact with the enemy. Thunderstorms were forecast to be present in the area. The crew turned the vehicle away from observed cloud build-ups. The vehicle then lost satellite link. Post-flight analysis determined a lightning strike as causing the loss of communications and subsequent crash.
- A vehicle was struck by lightning and damaged in flight, but was able to RTB.
- After departing a mission area, a UAV entered a storm system and was damaged by turbulence, icing, and a lightning strike. Aileron control was lost, but the operator was able to regain limited control with ruddervators. The vehicle transited back towards base and it was determined that there was insufficient control for a safe runway landing. The decision was made to intentionally crash in the sea.
- A UAV on station at 18,000 feet mean sea level (MSL) experienced deteriorating weather. The mission commander requested a new location and tasking. As the UAV was transiting to the new location, it was hit by lightning or experienced electrostatic discharge, went lost link, and departed controlled flight.
- After the on-station mission was complete and during RTB, a UAV flew through snow, ice, and turbulence, which resulted in the UAV encountering five severe downdrafts and going lost link. The review board determined that the operator failed to assess the weather and that lost link was due to lightning strike.

### 5.1.2 Wind/Turbulence

**Scenario:** Wind gust or wind shear causes vehicle structural failure.

- A vehicle encountered a sudden crosswind gust that exceeded the limits of the IMU, which failed, causing an abrupt yaw followed by a structural failure of the tail boom, which caused the vehicle to enter a flat spin.
- A wing failure on a high-altitude long-endurance experimental vehicle was caused by exposure to turbulence, which resulted in an in-flight break up.

**Scenario:** Wind shifts, gusts, or downdrafts at the landing site cause a landing mishap.

- Wind shear or microburst phenomena on final approach resulted in sudden high sink rate and impact with the ground 1500 feet short of the runway threshold.
- Unreported wind shear on short final caused a vehicle to impact the runway nose gear first, breaking the nose strut.
- During an automated landing, the vehicle encountered a wind shift from acceptable crosswind to tailwind. The shift occurred after the decision point for waveoff. The system cut the engine too high and too long for a normal approach and the vehicle landed past the arresting wire. The vehicle bounced over a capture net, ran off the runway, and impacted a sign.
- Engine cut logic causes the engine to shut off if it detects landing impact (i.e., sudden G-force change at low altitude). A sudden wind shift on final approach caused the engine cut logic to trigger, resulting in a hard landing.
- A UAV was launched in marginal winds and the winds increased, as was forecast. The UAV experienced wind shear on approach. Due to the known forecast, decision making was a main factor in this incident.
- A vehicle experienced a TALS transponder failure and overshot the runway with a 40-knot headwind at 350 ft. The wind dropped to 10 knots at the surface, which was out of wind limits for TALS *(see Section 4.2)*.

### 5.1.3 Rain

**Scenario:** Flight through visible moisture (rain, fog, clouds) and/or water intrusion into the vehicle causes an avionics failure.

Flight in moderate rain resulted in lost link and loss of vehicle for three separate mishaps involving the same type vehicle. In this design, the avionics bay was not protected from rain intrusion.

### 5.1.4 Ice and Hail

**Scenario:** Flight in hail or freezing conditions results in structural or engine damage.

- The vehicle unexpectedly encountered hail. The operator was able to land the vehicle safely, but with significant engine and leading edge damage.

- The vehicle ice detector indicated that the UAV had encountered icing conditions in flight. The crew flew the vehicle away from the icing conditions. A transmission chip light illuminated during RTB, and something was observed falling off the vehicle. The vehicle then crashed into the sea.

**Scenario:** Pitot icing results in loss of airspeed reference.

- The vehicle encountered icing conditions; however, the operator did not turn on pitot heat. The pitot system became blocked by ice, and the vehicle made excessive pitch changes when the autopilot tried to capture the airspeed. The abrupt pitch changes resulted in structural breakup.
- On return from a mission, the operator was unable to avoid flying the vehicle through rain showers and icing conditions. The autopilot was engaged in airspeed hold mode. The pitot tube became clogged with ice and gave indications of low airspeed, so the vehicle went into a dive to increase airspeed. When the pilot turned pitot heat on, the ice abruptly melted, and the vehicle suddenly pitched up to slow the airspeed. With the sudden pitch up, the vehicle exceeded a structural limit and departed controlled flight.

**Scenario:** Icing conditions cause carburetor failure, resulting in loss of thrust.

A vehicle encountered icing conditions and the carburetor iced up, possibly due to failure of the heated throttle plate. The engine shut down due to fuel starvation and the vehicle was recovered under parachute.

### 5.1.5 Temperature Extremes

**Scenario:** Exposure to cold temperature (without icing conditions) at high altitude causes engine failure and loss of thrust.

- There were two mishaps in which lubricating oil is suspected to have congealed at cold temperatures at high altitude in flight. This is thought to have caused oil starvation to the engine and loss of thrust.
- During a high-altitude test flight, an O-ring in the fuel line became brittle, allowing air seepage into the fuel line, which caused fuel starvation to the engine. The emergency battery voltage was also low due to the cold temperature, so the emergency parachute did not deploy.

**Scenario:** Exposure to cold temperatures causes avionics failure, resulting in loss of control.

A vehicle’s circuit board cracked during exposure to cold temperatures at high altitude, which resulted in loss of uplink control.

### 5.1.6 Dust and Sand

**Scenario:** Sand or dust gets into engine components, causing engine damage or reduced thrust.

- Sand in spark plug threads created a path for compression gases to escape the engine cylinder chamber. This caused the spark plug to melt and resulted in vehicle loss of thrust.

- A hazard report described multiple occurrences of minor damage to engines as a result of sand being ingested into the air intake and exhaust port, mixing with engine oil, and having the effect of sandpaper on internal engine components.

### 5.1.7 Night and Low-Visibility Operations

**Scenario:** Low visibility results in loss of situational awareness by EPs during landing, contributing to landing mishaps.

This was a contributing cause for six mishaps previously discussed in sections 3.4, 3.5, and 3.6, affecting three different types of UAV and a helicopter air-taxi near collision discussed in Section 4.3.

### 5.1.8 Bird strike

**Scenario:** A collision between a bird and an aircraft that is in flight or on a take-off or landing roll can be a significant threat to aircraft safety and lead to significant damage or total loss of the aircraft.

There were two mishaps in our sample in which a bird strike caused damage to a vehicle, one leading to the loss of a vehicle.

- A bird strike blocked a pitot tube just after catapult launch, causing the vehicle to crash.
- One UAV experienced a bird strike that resulted in minor structural damage. The UAV was able to continue flying, and landed safely.

## 5.2 Radio Frequency Environment

The RF environment can adversely affect a properly functioning UAV and pose a hazard.

### 5.2.1 RF Interference with Control Links

**Scenario:** Interference with vehicle or system control links results in an unexpected loss of control.

- The link to an airborne UAV was lost when maintenance personnel turned on the transmitter of another UAV undergoing maintenance on the ground.
- An unknown source of RF interference triggered the self-destruct mechanism of an experimental commercial vehicle during a test flight.

### 5.2.2 RF Interference with Navigation Sources

**Scenario:** Interference with navigation signals results in a mishap.

Jamming of GPS signals by North Korea may have contributed to the fatal crash of a Schiebel S-100 Camcopter UAV near Incheon, South Korea, on May 10, 2012. The small helicopter crashed into its ground control van, killing a Schiebel engineer and injuring the two remote pilots, both Koreans.

### 5.2.3 RF Interference with Communication Links (e.g., ATC, other GCS, etc.)

**Scenario:** Interference with communications links between the operator and ATC or handoff GCS results in reduced airspace situational awareness or loss of mission effectiveness.

No mishaps of this type were recorded.

## 5.3 Terrain

The presence of terrain on or near the flight path can pose a hazard to UAV operation.

### 5.3.1 Controlled Flight into Terrain

**Scenario:** Incorrect operator configuration or programming results in controlled flight into terrain (CFIT).

- A UAV required the landing altitude be specified prior to an automated landing. The operator skipped this step in the checklist, the vehicle used a default landing altitude, and the vehicle flew into the ground during a recovery attempt.
- A UAV impacted terrain during a practice approach for autopilot recovery training; the cause was not specified.
- An improperly programmed emergency mission caused the vehicle to impact terrain after link was lost.
- Inaccuracies in the INS/GPS navigation system resulted in a glideslope 400 ft below the correct glide path. Clouds obscured the camera view of the surface, and the vehicle impacted the ground on approach to the runway.

### 5.3.2 Terrain Masking

**Scenario:** Flight over the horizon or behind high terrain results in an unexpected loss of the RF control link.

- Due to engine performance, a UAV was flying at a lower-than-expected altitude in mountainous terrain, contributing to intermittent link performance. The vehicle emergency mission had inadvertently been erased by the backup GCS. The vehicle lost link as it descended behind a mountain range and was not recovered.
- On a training mission, the crew inadvertently descended behind a ridgeline and lost link. Prior to losing link, the crew had attempted a heading change. The vehicle properly flew its emergency mission and emerged from behind the ridgeline, which allowed the GCS to regain control of the vehicle and subsequently command the previously entered heading change. The heading change directed the vehicle toward the mountains. The crew attempted to change the heading again, but did not turn off heading hold and the vehicle impacted the mountain.

# CHAPTER 6

# Multiple Sources of Control

Enabling multiple sources of control in a UAV system introduces more complexity to the system, as well as the potential for increased failures. As shown in Figure 6-1, multiple sources of control can be categorized as multiple control stations monitoring or controlling a single vehicle, a single control station controlling multiple vehicles, or an independent FTS that operates separately from the control station. Figure 6-2 shows the number and percentage of mishaps related to multiple sources of control by phase of flight.

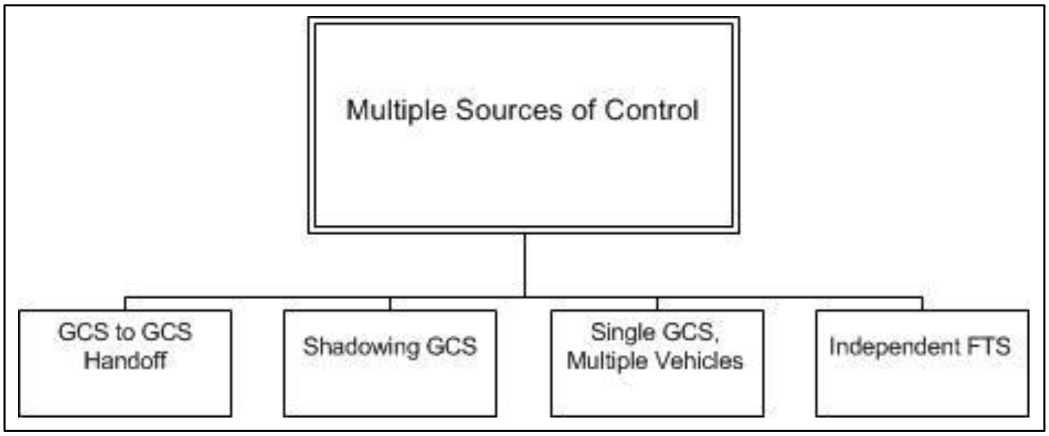

Figure 6-1. Taxonomy of Multiple Source of Control Mishaps

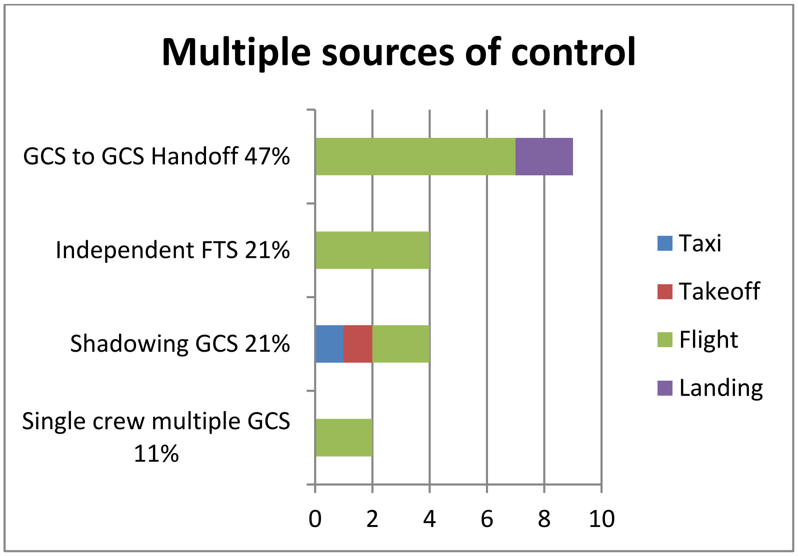

Figure 6-2. Distribution of Multiple Source of Control Mishaps

## 6.1 GCS-to-GCS Handoff

**Scenario:** The process of handing off control from one GCS to another contributes to loss of or damage to the vehicle.

- In preparation for a GCS-to-GCS handoff, the crew advised the receiving crew via chat that one attitude source was not working correctly and should not be used. The receiving crew erroneously thought the vehicle would automatically deselect a failed attitude source. The non-working attitude source was selected and the vehicle departed controlled flight. The review board noted that the mishap pilot had disregarded the brief in selecting a degraded attitude source, but also noted that the technical manual was not consistent with programming (automatic switching only occurs when the source is inoperative, not when it is merely degraded).
- During GCS-to-GCS turnover, the receiving GCS did not follow the turnover checklist and inadvertently set the vehicle into emergency mode. The vehicle unexpectedly deployed the parachute and was damaged on landing. There was no direct communication between the two GCSs.
- Due to checklist errors, the stability augmentation system and engine ignition were inadvertently switched to “off” during GCS-to-GCS handover. Vehicle control was lost and it departed controlled flight.
- A vehicle experienced an uncommanded descent upon handoff to the launch/recovery controller. The recovery chute was deployed, and the vehicle was recovered from the crash location. The exact cause was not determined.
- A vehicle went into a rapid descent on handoff to the launch/recovery controller. The turnover occurred at low altitude, so no recovery was possible. No minimum turnover altitude had been established.
- A vehicle was returning to base on battery power after alternators had failed in flight. The aircrew had turned off unnecessary electrical loads (i.e., load shedding) in an effort to preserve battery life. When the launch/recovery GCS gained control, the electrical loads were all turned back on. The vehicle ran out of battery power on approach to landing and crashed.
- A UAV had marginal link connectivity and reduced engine performance, so the crew started a second GCS in an attempt to get a better link. The second GCS took control, but inadvertently erased the emergency mission and changed the emergency response to “emergency glide mode.” The vehicle lost link as it descended behind a mountain range and was not recovered.
- The UAV launch and recovery element inadvertently turned on electrical loads during lost engine recovery, draining battery and causing loss of control.

## 6.2 Shadowing GCS

**Scenario:** A shadowing GCS not intended to be in control inadvertently takes control, resulting in loss or damage to the vehicle.

During taxi to takeoff, the GCS noted uncommanded control inputs and vehicle acceleration without corresponding throttle inputs. A shadowing GCS, which had been established for safety/backup purposes, had inadvertently left its transmitter on and unknowingly took control when the RF transmitter from the primary GCS was shadowed by buildings. The vehicle crashed into a fence.

## 6.3 Single GCS or Single Crew Controlling Multiple UAVs

**Scenario:** The GCS is unable to monitor and control multiple UAVs assigned to it in unexpected situations, resulting in loss of control of at least one vehicle.

A test team was demonstrating the ability of a single GCS to control two UAVs. The first UAV was launched and climbed to a holding altitude, where it was to orbit at its lost-link rally point after link was switched to the second UAV's frequency. As the second UAV became airborne, the crew realized the first UAV's rally point location was incorrectly set 600 miles away (data entry error by 10 degrees of latitude). The first UAV flew beyond RF line of sight and was lost before the test team could re-acquire link.

## 6.4 Independent Flight Termination Systems

**Scenario:** Inadvertent or incorrect activation of the independent FTS results in loss of or damage to the vehicle.

- A UAV under test suddenly rolled and went into an inverted flat spin. The pilot commanded the FTS, which shuts the engine down and deploys a parachute. The parachute separated from the aircraft, and the vehicle spun into the ground. The FTS procedures were not well documented, and required the operator to follow a specific sequence to shut down the engine first and only then deploy the parachute. The parachute risers had contacted the spinning propeller blades and were cut.
- A UAV in flight and under test received an FTS arm-and-terminate command from another range performing ground tests on a different vehicle. The vehicle was lost.
- A UAV in flight and under test was configured to self-terminate if reception from a ground-based FTS transmitter was lost. The FTS transmitter momentarily stopped transmitting, and the vehicle self-terminated.
- An unmanned prototype of a tilt-rotor UAV crashed during tests. According to its builder, the UAV, which can hover like a helicopter or fly like a plane, went down after an unidentified radio signal triggered a self-destruct mechanism that shut the engine down.
- A UAV crashed on a test range after the unintentional FTS activation. The UAV was "damaged beyond repair due to a failure of the flight-termination ground equipment, which caused the aircraft's fail-safe flight termination mode to activate."[6] The automatic fail-safe system was "designed to irreversibly terminate flight"[7] so that the vehicle was not able to leave the range.

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[6] Graham Warwick. "Lockheed confirms P-175 Polecat UAV crash." *Flight Global*. March 20, 2007. Retrieved 13 October, 2015. Available at https://www.flightglobal.com/news/articles/lockheed-confirms-p-175-polecat-uav-crash-212700/.

[7] Amy Butler. "Lockheed's Polecat UCAV Demonstrator Crashes." Aviation Week & Space Technology. (19 March 2007.):44.

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# CHAPTER 7

# Aircraft Separation

One model of airspace management describes safety control as three layers of conflict management:

(1) Conflict management through organization of airspace (routes, types of airspace, etc.);
(2) Provisions for separation within the organized airspace; and
(3) Collision avoidance, when separation provisions have been compromised.

Understanding how each layer of conflict management has failed in previous UAV mishaps and hazardous events can provide a basis for assessing the current risk management capability.

Unsatisfactory outcomes when conflict management fails include:

- Midair collision;
- Near midair collision (NMAC);
- TCAS alert;
- In unassigned airspace;
- Not in contact, unknown status, possible undirected flight, risk unknown.

As shown in Figure 7-1, aircraft separation conflicts can occur while the UAV is on the ground (i.e., airfield) or during flight (i.e., airspace). Figure 7-2 shows the number and percentage of aircraft separation incidents by mishap barrier failure category and phase of flight.

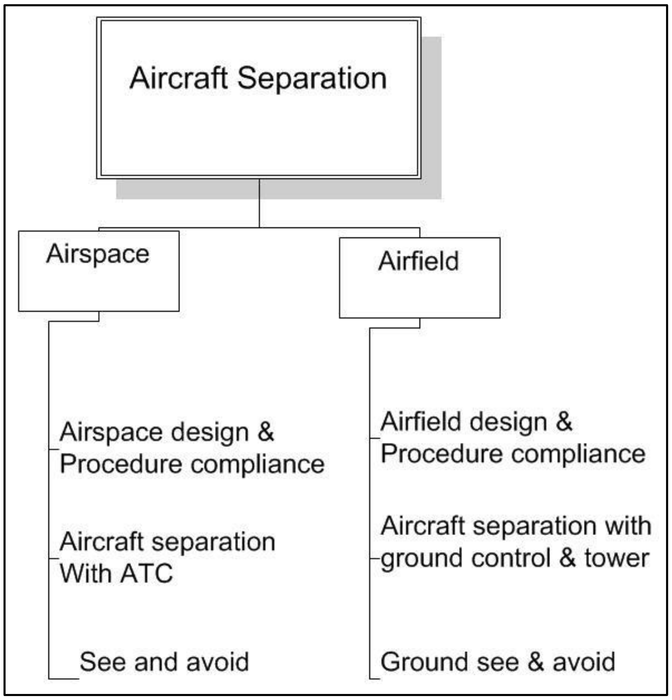

Figure 7-1. Taxonomy of Aircraft Separation Mishaps

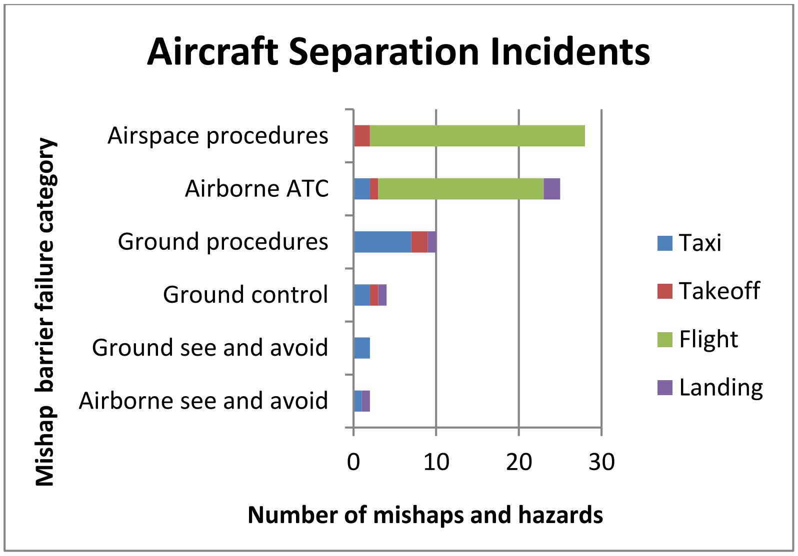

Figure 7-2. Distribution of Aircraft Separation Incidents

## 7.1 Mishaps Related to Airspace Design and Procedure Compliance

Air traffic conflict is managed in part by the design and implementation of flight routes, types of airspace, and traffic synchronization. Safe operation is maintained by flying the cleared flight plan and staying on assigned routes and in assigned areas.

**Scenario:** A vehicle system malfunction causes the vehicle to be outside of its assigned airspace or altitude, causing a hazardous situation.

- A UAV encountered a software flaw after it had lost link. The vehicle did not engage its emergency mission, but instead continued on a heading away from its assigned airspace and towards congested airspace. The crew was able to regain control using a second GCS to regain link.
- A UAV test article had a lost uplink failure that resulted in an undirected glide.
- Two different types of fixed-wing UAVs were involved in a near miss after one UAV had a ground station display failure that eliminated the operator's position awareness while returning to base. The air traffic controller on duty saw the vehicles closing and directed them apart.

**Scenario:** Activation of a UAV's emergency route results in flight outside of its assigned airspace or altitude, causing a hazardous situation.

- A UAV at 9000 ft MSL lost satellite link. The programmed emergency mission (lost-link mission) directed the UAV to climb to regain its line-of-sight link and then descend when link is re-established. In the process of climbing to 13,000 ft, the UAV triggered the TCAS resolution advisory of a light fixed-wing aircraft flying above it. The air traffic controller on duty was able to advise the light fixed-wing of the UAV's position, and the aircraft was able to monitor the UAV's position with TCAS. Analysis suggests the UAV operator mis-programmed the emergency mission altitude climb limit.
- A GCS experienced a rack lockup, requiring a reset while the UAV was in flight. The crew used an incorrect restart procedure that reset aircraft parameters, resulting in permanent loss of link. The crew did not have the most up-to-date, validated GCS rack

lockup reset checklist. The vehicle followed its emergency route for several cycles and eventually crashed.

- While controlling two UAVs simultaneously, a test team intentionally put one vehicle into lost link, but inadvertently set the rally point 600 miles away (data entry error by 10 degrees of latitude). The UAV flew beyond RF line of sight before the test team could re-acquire link. The UAV violated the airspace of a neighboring country before crashing into the sea on the other side *(see Section 6.3)*.

**Scenario:** A vehicle operator error or violation causes the vehicle to be outside of its assigned airspace or altitude, causing a hazardous situation.

- A manned, light fixed-wing aircraft was established in an orbit at 5000 ft MSL within its ATC-assigned operating zone. A UAV requested and received clearance to RTB at 5000 ft, but was advised of the active operating zone nearby. The UAV operator acknowledged, but failed to adequately monitor the UAV's position. The UAV drifted into the operating zone, causing a TCAS alert on the manned aircraft. The UAV passed within 1.4 NM of the manned aircraft at co-altitude.
- Three UAVs and a manned aircraft were cleared for operations within an operating zone controlled by one tactical control center. The vehicles were communicating with each other using voice and text-based chat circuits. A fourth UAV from another service was operating in adjacent airspace and was being controlled by a control center belonging to a third service. One UAV within the operating zone requested lower airspace, coordinated with the other aircraft within the operating zone, and received clearance from the corresponding tactical control center. The UAV descended through the operating zone into the adjacent airspace, co-altitude with the UAV in that area. The events met the criteria for an NMAC before the controllers monitoring the adjacent airspace were able to separate the vehicles. Neither of the two involved vehicles was aware of the other vehicle's position. Because the two involved UAVs belonged to different services, no real-time position information was available between the two platforms. The hazard investigator concluded the descending UAV operator lost situational awareness and descended without approval of the adjacent airspace control center, resulting in the NMAC. Differing modes of communication (voice vs. chat) resulted in the different vehicle operators having dissimilar situational awareness.
- On three occasions, the Warning Area monitoring facility observed unauthorized UAVs operating within Warning Area airspace.
- During after-hours test preparation, a non-participant helicopter, assuming the airfield was closed, performed several practice approaches. The test team was able to notify the helicopter of their presence by flashing the UAV lights, which caused the helicopter to depart the airfield.

**Scenario:** An error in airspace design causes the vehicle to be outside of its assigned airspace or altitude, causing a hazardous situation.

- A UAV was cleared to fly the tower pattern within tower airspace. A manned tactical aircraft was performing a tactical maneuver in adjoining range airspace (i.e., the two aircraft were operating in separate airspaces that share a common border). The two aircraft flew within 300 ft of each other with no visual contact until after the event. The manned aircrew violated tower airspace; however, the text and chart depicting the airspace boundary was ambiguous and confusing. There was no discussion of tower or range controllers' roles in the incident report. Inadequacy of see-and-avoid capability was discussed with a recommendation for a sense-and-avoid capability or TCAS in the UAV. Among the review board's recommendations were to fix the airspace documentation and establish a safety buffer between airspaces.

- According to North Atlantic Treaty Organization (NATO) Joint Air Power Competence Center in 2004, there have been at least three collisions between NATO helicopters and UAVs in southwest Asia due to inadequate airspace procedures.

**Scenario:** Loss of all contact with a UAV and no wreckage found indicates the vehicle may have caused an unrecognized hazardous airspace situation before crashing.

This scenario was experienced at least nine times.

- Communications link modem failure
- Unspecified cause (3)
- Lost link (2)
- Loss of satellite link
- Engine failure
- Electrical system (2)
- Weather
- Navigation system failure

## 7.2 Aircraft Separation with ATC

**Scenario:** Failure of ATC to recognize or take action with a potential conflict causes a potential for a hazardous airspace situation.

- A small passenger jet was given clearance by ATC to climb to cruise altitude on its heading. In the climb, the jet received a TCAS alert and spotted a UAV near its flight path and in a turn. The passenger jet maneuvered to avoid the oncoming UAV.
- A UAV was at 32,000 ft MSL and needed to cross a known jet route in order to RTB. The squadron's standard operating procedure for crossing jet routes involved ATC monitoring, scanning the jet route with visual sensors, and deconflicting with the data link. As the UAV began transiting the jet route, the UAV crew observed a co-altitude Boeing 747 in the jet route, 4 NM away. The UAV was commanded to descend to increase separation. No traffic calls or advisories were made by ATC. The hazard report states the data link display was frozen and ATC believed the UAV was at a different altitude.
- A UAV under test was flying at 7000 ft MSL with an accompanying observation aircraft. A non-participating general aviation aircraft was not in contact with ATC and started to follow the UAV and its chase. The air traffic controller on duty advised the UAV to descend and then to make several turns. The non-participant aircraft followed. The air traffic controller advised "it appears the aircraft is following you", and then the non-participant departed the area.

- A civilian airliner on approach to a large airport was involved in a nose-to-nose, near-miss encounter with a UAV on the UAV’s assigned route. The two aircraft missed each other by less than 200 feet and wake turbulence from the airliner caused the UAV to depart controlled flight. The airliner was unaffected; however, the UAV crashed in a populated area. A NATO spokesman attributed the incident to ATC failure.
- Two UAVs from different units were operating in airspace established for UAV exclusive use. Both UAVs established mutual deconfliction procedures through internet relay chat (mIRC). After several hours on station, one UAV stopped using chat for deconfliction. The vehicles converged to a point of 300 ft of vertical separation and 1/2 mile horizontal separation.
- Two UAV teams completed their missions in separate operating areas and each requested new assignment areas via their control and reporting center (CRC). The flight path to their separate destinations crossed, and the vehicles were at the same altitude. The CRC radar was only working intermittently and the CRC controllers did not notice the conflict. One of the UAVs had an airspace deconfliction tool, recognized the situation, and made an altitude change. The crew then contacted the CRC and the other UAV using mIRC. It was not until after the two UAVs passed each other that the CRC provided new transit altitude instruction.
- A UAV was returning from a five-hour mission to its assigned airfield and was instructed by ATC to report when established at a 10-mile base for the active runway. Two minutes later, a manned cargo aircraft was at seven miles on approach to the same runway, and was instructed to report 5 miles out. At 5 miles, the cargo aircraft struck the UAV. The cargo aircraft’s TCAS did not provide a warning even though the UAV had a functioning transponder. The cargo plane suffered leading-edge wing damage and the UAV was destroyed. The review board noted the following factors: Communication procedures - the UAV was on a UHF frequency and the cargo plane was on a VHF frequency, so neither pilot heard all of the other's transmissions; there was no local ATC radar facility; the tower controller did not follow local procedures regarding mixing UAVs and manned aircraft; the tower controller was newly qualified and alone in the tower; the manned aircraft’s TCAS did not provide a warning.
- A UAV operator requested a climb from 18,000 ft to 19,000 ft MSL within the operations area via mIRC, which the tactical control center approved also via chat. The approval went unnoticed and the UAV remained at 18,000 MSL while a second UAV checked in to the area and was also approved to operate at 18,000 MSL. When the tactical control center recognized that the first UAV had not yet climbed, the tactical control center deconflicted the two UAVs by altitude without incident. *(Note: the UAVs were operating with differing airspace deconfliction software; Falconview vs. Zeus.)*

**Scenario:** Incorrect or inaccurate ATC action causes a potential for a hazardous airspace situation.

- A small UAV was cleared by ATC for surveillance of an air base boundary at 400 ft above ground level (AGL) and below. A King Air (manned) aircraft was cleared to land on the airfield. At 400 ft AGL and 1/2 mile from the airfield, the King Air reported passing within 200 ft of the UAV. Investigation revealed Tower control failed to advise the landing aircraft that the UAV was operating in the vicinity. The incident is considered a mistake on the part of the tower controller.

- A UAV was on a takeoff roll after receiving clearance from Tower control. At the other end of the runway, a military truck crossed the runway without clearance. The tower controller assessed that the UAV would be airborne well before reaching the truck and did not cancel the takeoff clearance. The UAV pilot never saw the truck and took off safely without incident. The truck driver was aware crossing the runway without clearance was unauthorized.
- A UAV was orbiting in tactical airspace as assigned by the local tactical airspace controller. The UAV crew noticed another aircraft nearby (2 NM and co-altitude). A query to the controller indicated the other UAV had been assigned airspace that overlapped the first UAV's. Investigators determined the airspace controller's lack of attention to detail as the cause of overlapping assignments.

**Scenario:** Unclear or misunderstood ATC guidance causes a potential for a hazardous airspace situation.

- Two UAVs were launched in sequence from the same runway. Due to non-standard and ambiguous terminology from Tower control, the first UAV turned toward the other UAV after takeoff, creating potential for collision. The tower controller then recognized the potential hazardous situation and directed the first UAV to a specific altitude and heading. The UAVs departed the tower airspace without further incident.
- Two UAVs were operating in a tower pattern. One of the UAV operators misheard Tower control instructions to extend before turning downwind. The UAV turned early rather than late as instructed, reducing separation between aircraft to within 500 ft. The tower controller turned his attention to another aircraft that was cleared for takeoff and did not monitor the pattern visually. Both UAVs continued on their planned missions without further incident.
- Two UAVs were operating in the tower pattern. One UAV used non-standard terminology to request an orbit, which confused the tower controller. Both UAVs ended up in close proximity at the same altitude.
- A UAV operator was cleared to taxi behind another UAV preparing to take off. After the other UAV took off, the first UAV was directed to taxi up to the runway and hold short. The UAV taxied onto the active runway in position for takeoff. The UAV operator failed to read back the proper clearance, and the tower controller failed to realize the UAV operator had not read back the proper clearance. The controller cleared another aircraft to touch and go on the same runway the UAV was on. Upon hearing the other aircraft was cleared for a touch-and-go, the UAV operator announced they were also on the runway. The tower controller then directed the aircraft on final to go around. The UAV operator on the runway then obtained takeoff clearance and departed tower airspace without further incident.
- A small UAV requested recovery clearance from Tower control and was cleared to land at their discretion. The UAV intended to overfly the south end of the runway but was advised of a helicopter conducting a hover check in that area. The UAV operator adjusted his heading to cross over mid-field, but did not update Tower. A second helicopter was cleared to take off and cross the runway at mid field. The UAV struck the helicopter rotors and was destroyed. The helicopter was able to make a controlled landing with damage to its rotor tips. The airfield was designated as Class G

(uncontrolled) rather than Class D because the ATC radar had not yet been checked and certified.

- A UAV operating in a local pattern was instructed by Tower control to extend downwind in order to increase separation with another UAV also in the pattern. The UAV operator acknowledged, and the tower controller turned his attention to a third UAV preparing to take off. The first UAV turned onto final, which positioned it close to the second UAV at the same altitude. Tower instructed the second UAV to descend in order to increase separation and cancelled the third UAV's takeoff clearance. One factor cited was that the first UAV's Falconview program, which displays aircraft positions in the ground station, was not working, which reduced the UAV operator's situational awareness.
- A UAV was operating in an assigned operating zone, as cleared via radio by the local terminal controllers. The area outside the operating zone was controlled by a tactical controlling agency via mIRC. The UAV contacted the terminal controllers and verbally requested descent from 15,000 to 12,000 due to weather. The terminal controllers directed the UAV to contact the tactical controlling agency for permission to descend outside the operating zone. On a separate frequency, terminal controllers cleared a second UAV into the operating zone at the same altitude. The first UAV noticed the second UAV on Falconview and was able to deconflict.

## 7.3 See and Avoid

**Scenario:** Inadequate ability of a UAV to see and avoid results in an unsafe situation.

A fighter aircraft collided with a large UAV while both were in a landing pattern. Pattern procedures had been established as a right-turn pattern for UAVs and left-turn pattern for manned aircraft; however, the manned fighter made an approach to the inactive runway, which was perpendicular to the active runway, nose high with limited forward visibility and did not see the larger UAV ahead. After impact, the fighter landed safely with damage. The UAV entered a spin and landed in a populated area, causing extensive burn injuries to a child.

## 7.4 Airfield Design and Procedure Compliance

**Scenario:** A UAV failure or operator error causes the vehicle to travel outside the approved taxi route, causing a hazardous situation.

- A UAV was commanded to taxi for takeoff based on a pre-programmed mission plan. As it taxied, ground chase observed the vehicle was making incorrect turns and called for engine shutdown. The vehicle was towed back to the hangar without further incident. The investigation found that an incorrect mission plan had been loaded.
- A nervous junior UAV operator inadvertently engaged the automatic start program and did not know how to stop it. The vehicle accelerated across the airfield ramp until it impacted a parked transport aircraft.
- An operator in a second shadowing ground station skipped a step in the ground station startup checklist, which resulted in the GCS transmitter being turned on. This resulted in the shadowing GCS, rather than the controlling GCS, having control of the vehicle. The vehicle then responded to the second GCS's current settings, accelerated on the ground, departed the prepared surface, and impacted a fence *(see Section 6.2)*.

- An operator inadvertently selected autopilot pre-programmed mode rather than cooling fan. The vehicle attempted to go to an airborne waypoint while taxiing and ran off the taxiway surface, hitting a runway light *(also relates to an event in Section 3.1)*.

## 7.5 Aircraft Separation with Ground Control and Tower

**Scenario:** Lack of ground control taking action to deal with a potential conflict causes a hazardous airfield ground situation.

- A Security Forces vehicle did not notice a taxiing UAV and failed to properly give way, forcing the UAV to stop 30 ft from the vehicle. The Security Forces vehicle had only one radio that was tuned to the security force net (standard procedure at the time) rather than the airfield ramp net. The procedure has since been updated to require a second radio with airfield ramp net. The driver was also retrained and recertified for airfield driving.
- A similar event occurred when another Security Forces vehicle did not realize the red light approaching belonged to a UAV and turned onto the taxiway, forcing the UAV to come to a sudden stop.
- A painting contractor assigned to paint lines on the airfield taxiway lost situational awareness and continued onto the active runway while a UAV was on approach. The local tower was able to contact the UAV on final and direct it to go around.
- Two UAVs collided on an active runway in what was described as a “procedural” incident. No further information was available in the news article cited.

**Scenario:** Incorrect or incomplete ground control guidance causes a hazardous airfield ground situation.

One minute after a tower controller cleared a UAV for takeoff, the ground controller cleared an airfield maintenance vehicle to cross the active runway at the intersection. The UAV rotated well before the crossing ground vehicle. The investigation board felt the ground controller was potentially task-saturated.

**Scenario:** Unclear or misunderstood ground control guidance causes a hazardous airfield ground situation.

- Thirty seconds after a host nation tower controller cleared a UAV for takeoff, the host nation ground controller, in local language, cleared a host nation airfield support vehicle onto the same active runway. The UAV was able to rotate and climb out before encountering the ground vehicle, but came within approximately 150 feet of the vehicle.
- After landing, a UAV was proceeding to the taxiway at the end of the active runway while a second UAV was cleared to taxi for takeoff from the same taxiway. Ground control had attempted to stop the landing UAV’s taxi three times; however, the landing UAV was still in the process of changing to ground control’s frequency when the operator noticed the second UAV in front of them from the nose-aligned camera display. The landing UAV avoided collision by turning to the edge of the runway.
- A military utility vehicle was assigned to deliver cargo to the other side of the airfield. The driver contacted the tower for permission to cross the runway. The tower controller instructed the truck driver to hold short of the runway for a UAV on final approach to the runway; however, the transmission was distorted. The driver asked the control tower to

repeat the instructions, which the driver misunderstood as clear to proceed, and crossed the active runway. Tower directed the UAV to go around due to the vehicle on the runway.

- A foreign control tower cleared a UAV to line up on the runway prior to takeoff. The UAV operator checked both ends of the runway and observed an airliner being towed down the runway. The UAV operator notified tower of the towed aircraft and maintained vehicle position on the taxiway until the airliner had passed.
- A foreign civilian control tower cleared a light civil aircraft to land, do a 180-degree turn on the runway, and exit to the civilian ramp. While the manned aircraft was still on the runway, the Tower controller cleared a military UAV from the military ramp onto the runway into position and hold. The UAV crew monitored the progress of the manned aircraft as it headed towards them at the end of the runway and observed it pass the entrance to the civilian ramp. The tower had a discussion with the manned aircraft in French. The UAV taxied to the side of the runway to make room for the manned aircraft to pass on the runway. The UAV was then cleared for takeoff and departed.

## 7.6 Ground See and Avoid

**Scenario:** The reduced ability of a UAV to see and avoid other aircraft on the ground leads to a hazardous situation.

- A UAV was cleared to taxi back to the ramp after landing at the same time that a single-seat fighter on the ramp was cleared to taxi to the runway. The fighter saw the UAV approaching and turning towards his aircraft and called a warning on ground frequency, which prompted the UAV operator to stop the vehicle within a few feet of hitting the manned aircraft. The UAV did not see the fighter on the ramp until after the turn.
- Two teleoperated UAVs collided on the ground on the active runway. The cause of the collision was not described in the news report.
- A teleoperated UAV taxiing back to the hangar nearly collided with an F/A-18 taxiing in the other direction. Last-minute maneuvering by the manned aircraft prevented the collision.
- An airfield has servicing vehicle spots for aircraft on the taxiway near the end of the runway. An automated UAV was preparing for launch on one of these spots, and a manned aircraft was being serviced on another nearby spot. After servicing the manned aircraft, its service truck drove in front of the UAV just as the UAV began taxiing. The UAV chase vehicle saw the service truck moving and blew its horn. The service truck stopped and backed up to its original position out of the UAVs path.
- A helicopter air-taxied close to a UAV that was taxiing back to its line at night on a busy, overseas airfield. The UAV was buffeted sufficiently enough for the operator to notice the movement on video. There was no damage to either vehicle. The investigator determined that either the helicopter pilot misjudged the distance as he overflew the UAV or did not see the UAV at all.
- A base security officer drove onto the taxiway at night as part of his routine patrol. He observed a red light on an aircraft, but did not recognize it as a UAV, and continued on patrol towards the vehicle. The UAV operator saw the security vehicle and stopped on the taxiway, at which time the security officer did a U-turn and exited the taxiway. The

UAV continued on without further incident.  Poor lighting was a factor.  The security officer was identified and corrective training was provided.

# APPENDIX A

# Degraded State Definitions

## A.1 Introduction

In this analysis, by convention, a mishap scenario occurs when a vehicle transitions from normal flight to loss of ability to maintain controlled flight. The types of mishap scenarios are categorized and described in the main taxonomy. This categorization and description provides a basis for reviewing UAV test proposals. Familiarity with a collection of mishap scenarios provides the following benefits:

- Increases likelihood that potential for a similar scenario will be recognized beforehand;
- Provides a basis for reviewing the adequacy of existing safety efforts;
- Provides a method to ensure a broad review of hazards;
- Provides a knowledge base for safety personnel in training.

Preventing mishaps in design and test is primarily the responsibility of system designers, system safety, and the test team. One range safety strategy is to review the mishap prevention efforts and question any deficiencies.

An alternative range safety strategy is to focus on **degraded states of flight** and ensure barriers and safeguards exist for each degraded state or that the degraded state of flight will not be encountered because corresponding prevention measures are in place and independently certified by airworthiness personnel.

This appendix categorizes and defines degraded states of flight based on mishap data. When possible, ICAO standard terminology[8] is used. The frequency of occurrence and correlation with specific mishap scenarios is also provided.

### A.1.1 What is a degraded state?

In our mishap taxonomy convention, a chain of events results in a mishap scenario (UAV's loss of ability to continue flying). Once that ability to maintain flight is compromised, the vehicle may enter into a sequence of degraded flight capability states leading to a final mishap consequence. Figure A-1 shows the timeline of a mishap scenario, with the chain of events from normal flight through the top-level event, degraded state, and finally end state, or mishap consequence.

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[8] International Civil Aviation Organization/Commercial Aviation Safety Team Common Taxonomy Team. Aviation Occurrence Categories: Definitions and Usage Notes. V. 4.6. October 2013. May be superseded by update. Retrieved 14 October 2015. http://www.intlaviationstandards.org/Documents/OccurrenceCategoryDefinitions.pdf.

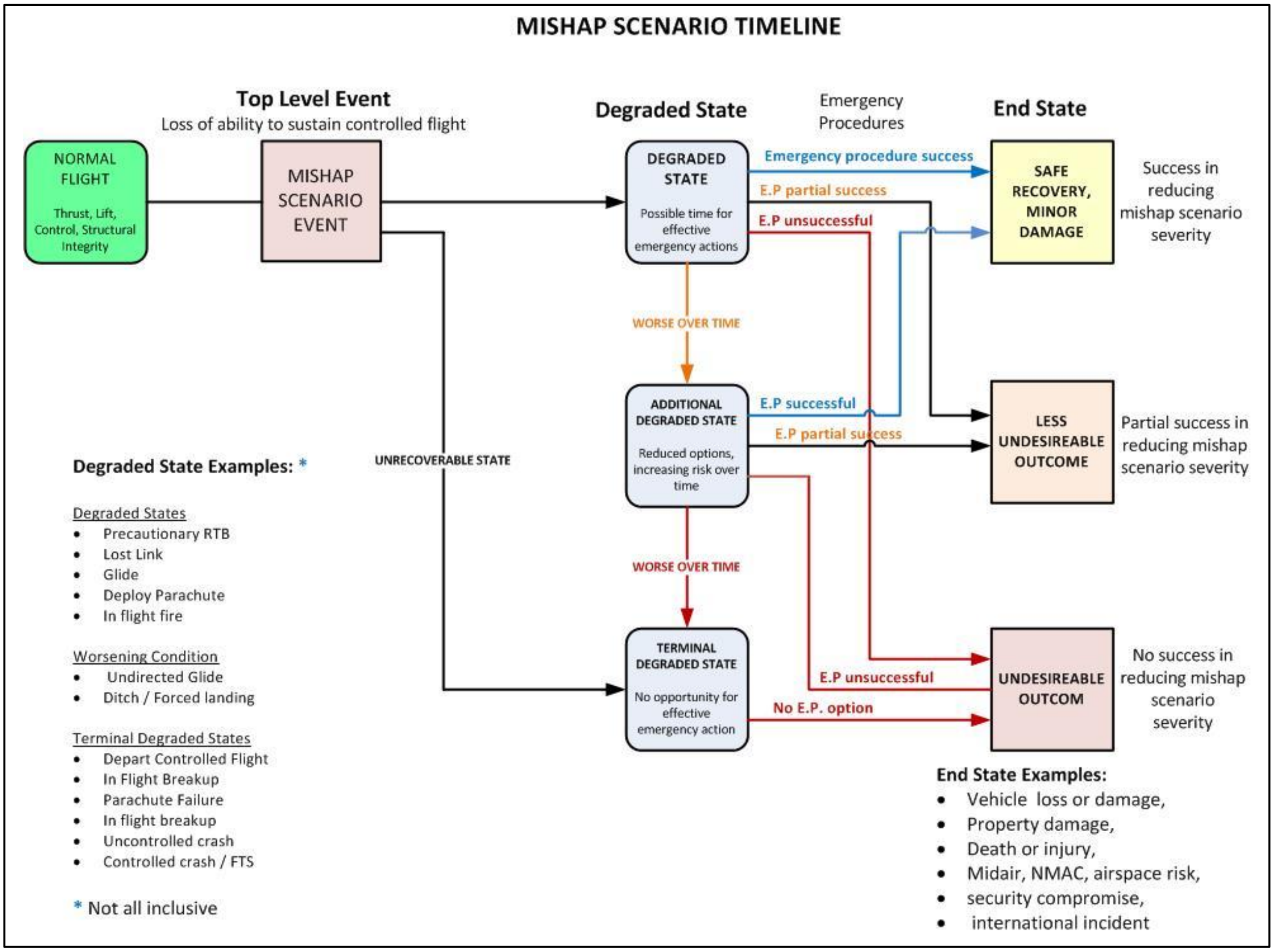

Figure A-1. Mishap Scenario Timeline

### A.1.2 Why are we concerned with degraded states?

Operational definitions of the degraded states allow us to more clearly recognize a range vulnerability or an actionable risk reduction opportunity. If we recognize a significant risk, we can take measures to limit or eliminate exposure, reduce probability of occurrence, or reduce severity of the outcome.

### A.1.3 Why are the degraded state definitions arranged this way?

These definitions are grouped by phase of flight (in flight, ground operations, takeoff, and landing) and special situations (arrested landing, parachute recovery, effect on airspace) that represent distinct problem categories from the perspective of the test range, as shown in Figure A-2. Figure A-3 shows the distribution of degraded states by category and phase of flight.

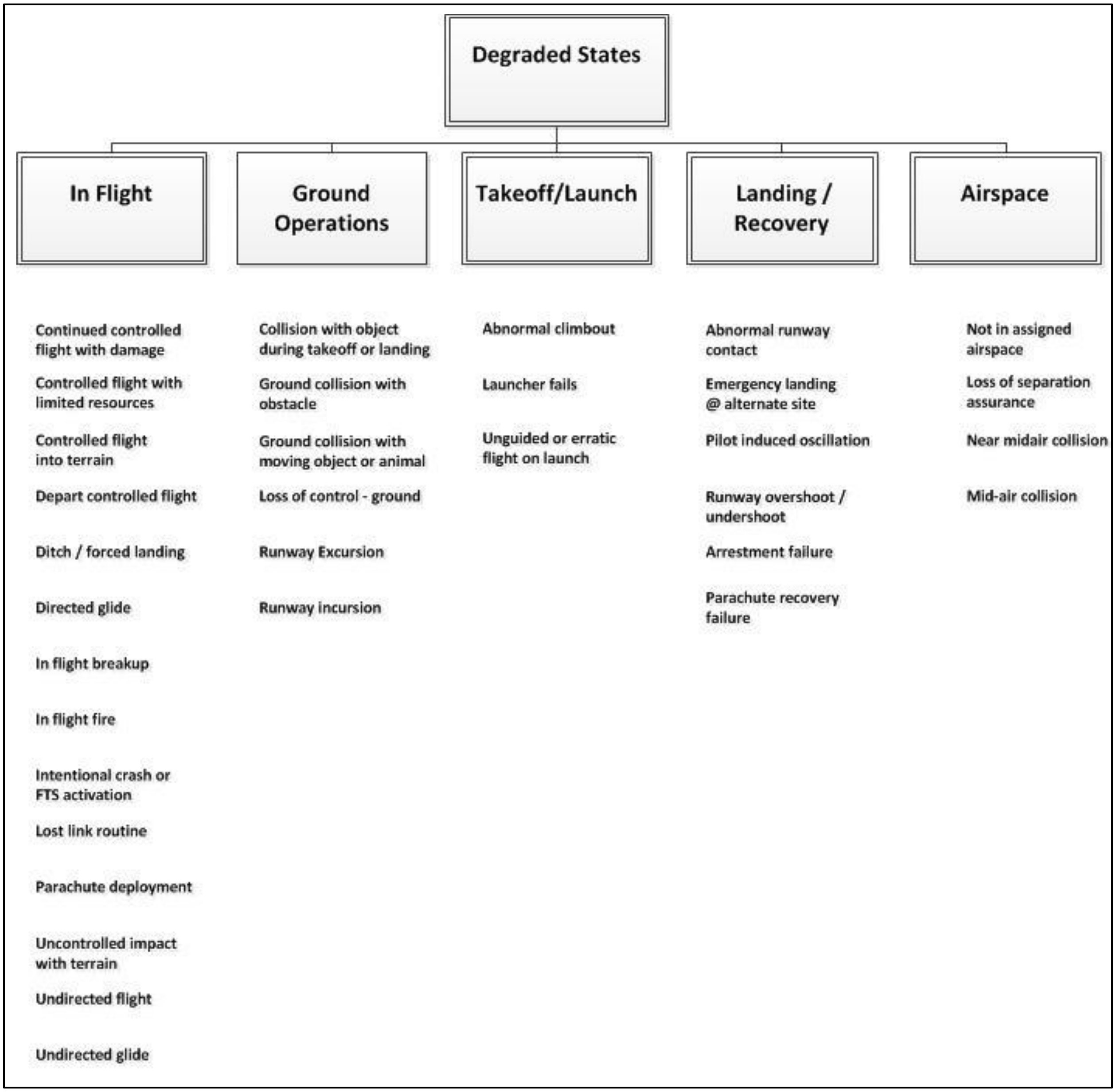

Figure A-2. Taxonomy of UAV Mishap Degraded States

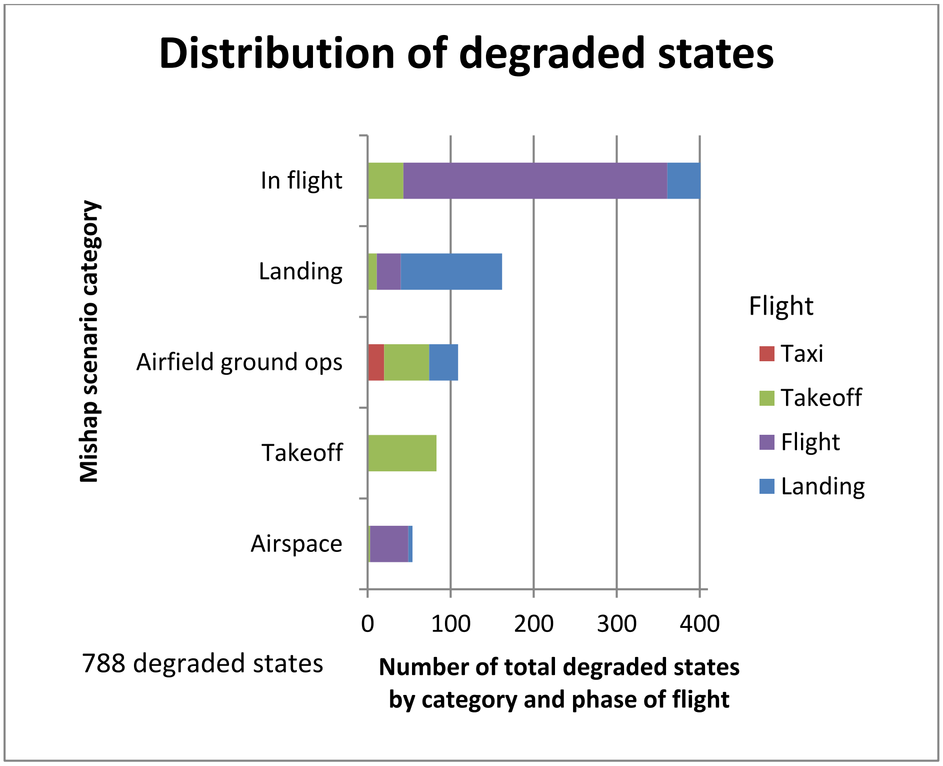

Figure A-3. Distribution of Degraded States by Scenario Category

## A.2 In-Flight Degraded States

In-flight degraded states are those degraded states and events primarily associated with a mishap scenario that begins in flight, but may continue though the landing phase. Figure A-4 shows the number of degraded states by mishap scenario category that occurred while a UAV was in flight.

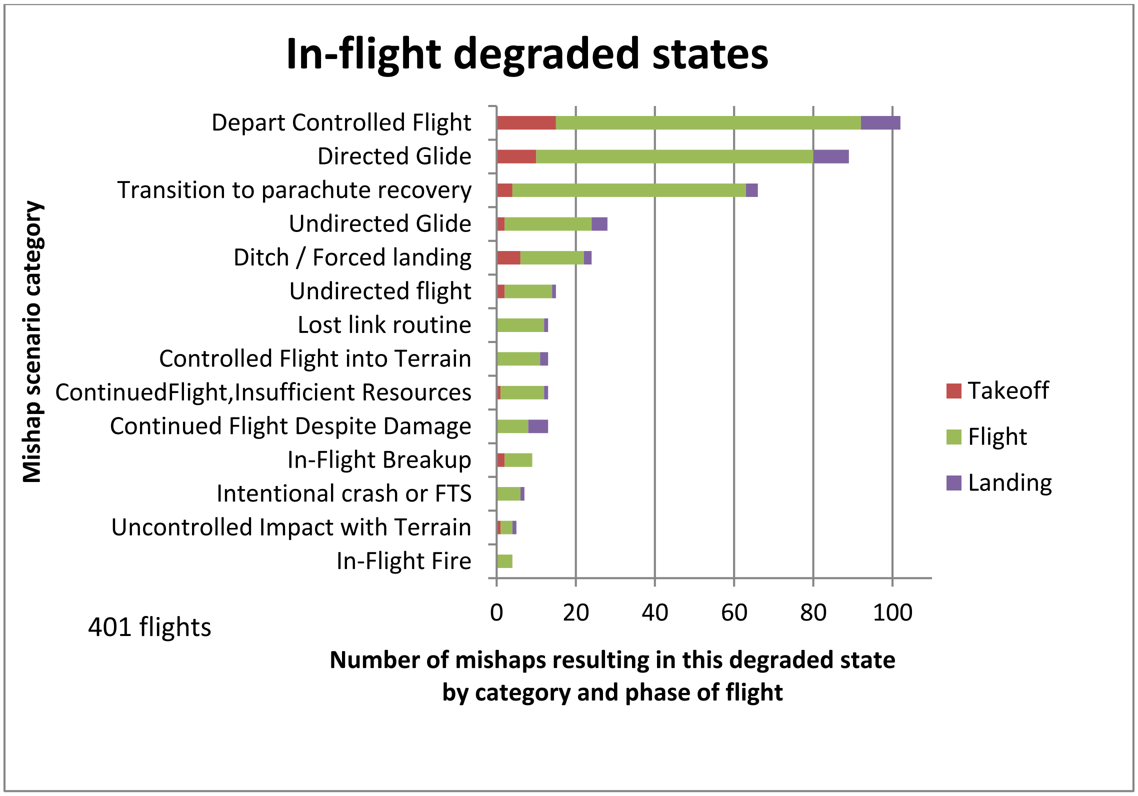

Figure A-4. Degraded States Occurring During In-Flight Phase

### A.2.1 Continued Controlled Flight Despite Damage

The vehicle continues flying in a controlled manner after minor damage or system warning. The vehicle is damaged or experiences a system failure that allows it to maintain controlled flight temporarily, making RTB possible. Figure A-5 shows the number of events by mishap scenario category in which a UAV entered a degraded state, but was able to continue controlled flight.

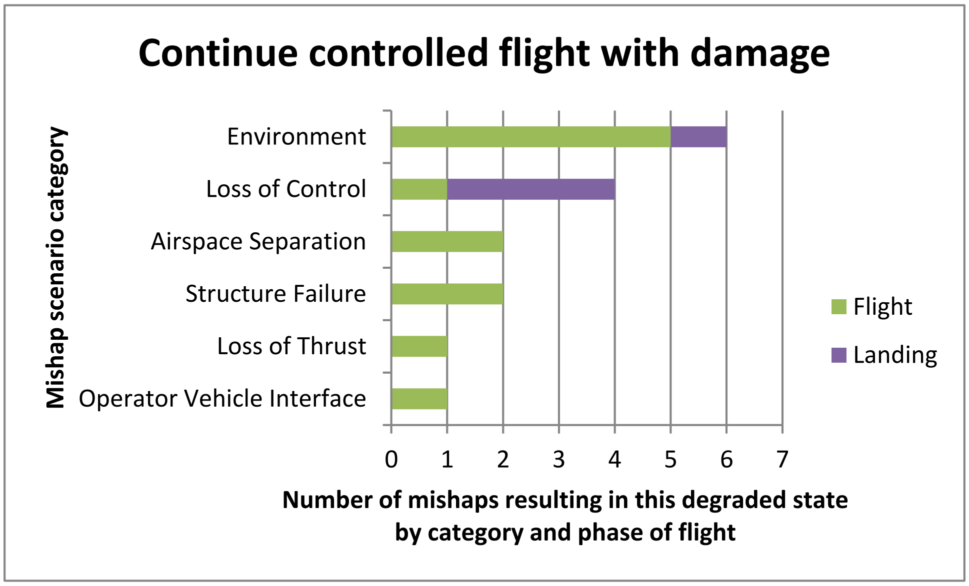

Figure A-5. Degraded State Mishaps with Continued Controlled Flight

The following mishap scenarios are associated with the continued controlled flight degraded state.

- There were five mishap scenarios involving structural damage in flight; all were able to RTB.
    - Vibration caused an engine cover to break loose, damaging the propeller.
    - Hail damaged the leading edge of the wing and engine.
    - A vehicle experienced lightning strike damage.
    - Minor damage occurred from a bird strike.
    - A vehicle experienced a hard landing and nose gear damage on landing, but regained flight. The crew was able to set up for another landing on the runway, which resulted in additional damage to the vehicle.
- There were four mishaps involving loss of sufficient precision control to safely land the vehicle. In each case, the loss-of-control event occurred in flight, but the vehicle was able to RTB and perform a landing approach. Significant vehicle damage occurred during landing.
    - The C-band uplink failed and landing was performed using satellite link.
    - Loss of GPS caused two vehicles to be damaged on landing.
    - Icing damage reduced controllability of a vertical-takeoff UAV. It was able to return but did not have adequate control to land safely.
- Two NMACs resulted in no damage to the vehicles involved and both were able to return safely to base.
- A hazard report described how sand and dust in the air did not cause any crashes, but did cause excessive engine wear.

Operators can attempt to recover the vehicle from a degraded state and transition to continue controlled flight state. Two instances of near midair and one runway overshoot occurrence transitioned to the continue controlled flight state and were recovered safely.

Degraded states can transition to worse situations. Several mishap events resulting in continue controlled flight states have degraded further into one instance each of depart controlled flight, forced landing, runway overshoot, and abnormal runway contact, resulting in loss of or damage to the vehicle.

### A.2.2 Continued Controlled Flight with Insufficient Resources

The vehicle is currently under control, but flight-critical resources such as fuel, lubricating oil, battery power (for electric vehicles), or electrical system power source are insufficient to RTB.

Examples:

- Fuel planning, fuel leaks, or engine performance is anticipated to cause fuel exhaustion or fuel starvation before RTB.
- Battery failure or poor battery performance may reduce time remaining in controlled flight.
- The operator mistakenly stops electrical power load shedding and drains battery power more quickly, resulting in loss of control before arrival at base.
- Lubrication stores may be inadequate for RTB due to planning error or leaks.

- Continued flight due to crew error or failure to recognize situation may cause vehicle loss.

Figure A-6 shows the number of incidents of controlled flight with insufficient resources by mishap category and phase of flight.

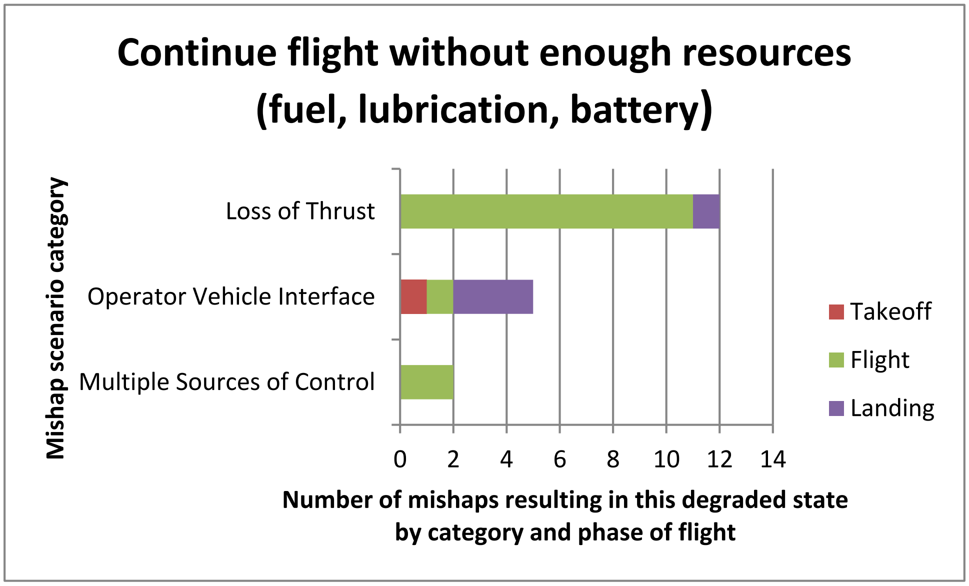

Figure A-6. Degraded State Mishaps for Continued Flight with Insufficient Resources

The following mishap scenarios are associated with the continued controlled flight with insufficient resources degraded state.

- Seven mishaps were caused when loss of electrical generator power or voltage regulator failure caused continued flight on battery power only, but the battery was not sufficient to return to a safe landing site.
- Four mishaps were caused when lubricating oil ran out.
- Fuel contamination caused a vehicle’s engine to fail and to begin to lose altitude just after launch. It was recovered by parachute.

The continued controlled flight with insufficient resources state has gotten worse on 12 occasions to the following degraded states:

- Depart controlled flight (2);
- Undirected flight (1);
- Uncontrolled crash (1);
- Runway overshoot/undershoot (2);
- Precautionary landing at alternate airfield (2);
- Fail to engage arresting gear (2);
- Parachute fails to open or attempt too late (2).

### A.2.3 Controlled Flight into Terrain

This category only applies to in-flight collision with terrain, water, or obstacle that occurs without any indication of loss of control. Collision with an object on takeoff or landing is categorized separately (see Section 3.1 and Section 3.4) consistent with ICAO categorization. This includes collisions with objects extending above the surface (towers, trees, cables, etc.). Figure A-7 shows the number of events by mishap scenario category and phase of flight that result in CFIT.

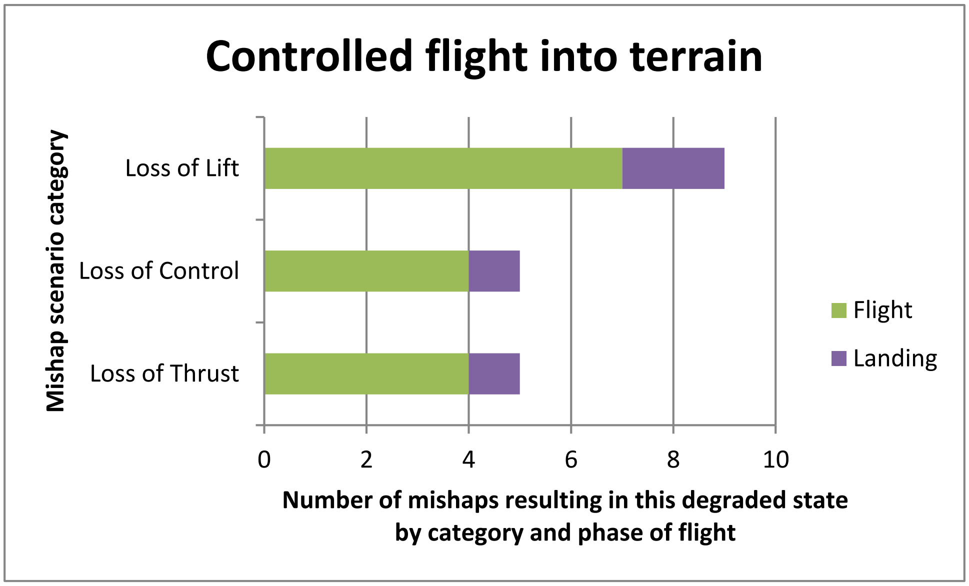

Figure A-7. Controlled Flight into Terrain Mishaps

The CFIT state is typically the last event of a mishap sequence. On one occasion the parachute was deployed but failed to open.

### A.2.4 Depart Controlled Flight

The vehicle is no longer able to maintain and control yaw, pitch, or roll. The vehicle may still have thrust. The final outcomes from this degraded state are ground impact, in-flight breakup, or attempted parachute recovery. Stalls and uncontrolled climbs in flight (i.e., after launch and initial climb out) are also included. Uncontrolled climb, stall, and loss of thrust on takeoff are addressed in Section A.4. Figure A-8 shows the number of departure from controlled flight mishaps by scenario category and phase of flight.

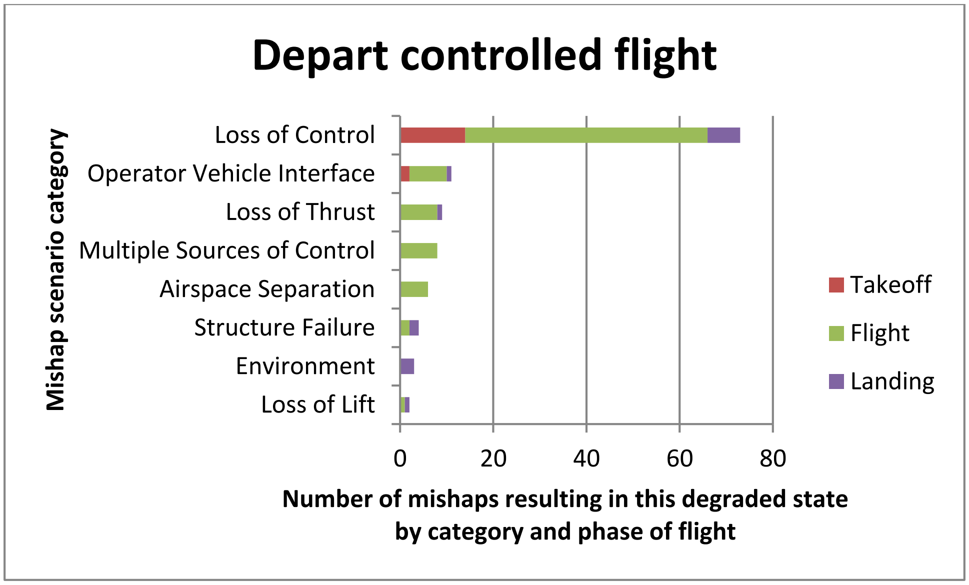

Figure A-8. Departure from Controlled Flight Mishaps

Mishap scenarios exhibiting the depart controlled flight state have degraded further on 10 occasions:

- In-flight breakup (1);
- Transition to parachute (2);
- Parachute fails to open (4);
- Parachute attempt too late (2);
- Runway overshoot/undershoot (1).

### A.2.5 Ditch/Forced Landing on Non-Runway Surface

The operator is unable to return to a controlled landing at an airfield and is forced to attempt landing on an unprepared surface or at sea. Figure A-9 shows the number of mishaps resulting in a forced landing or ditch on a non-runway surface by scenario category and phase of flight.

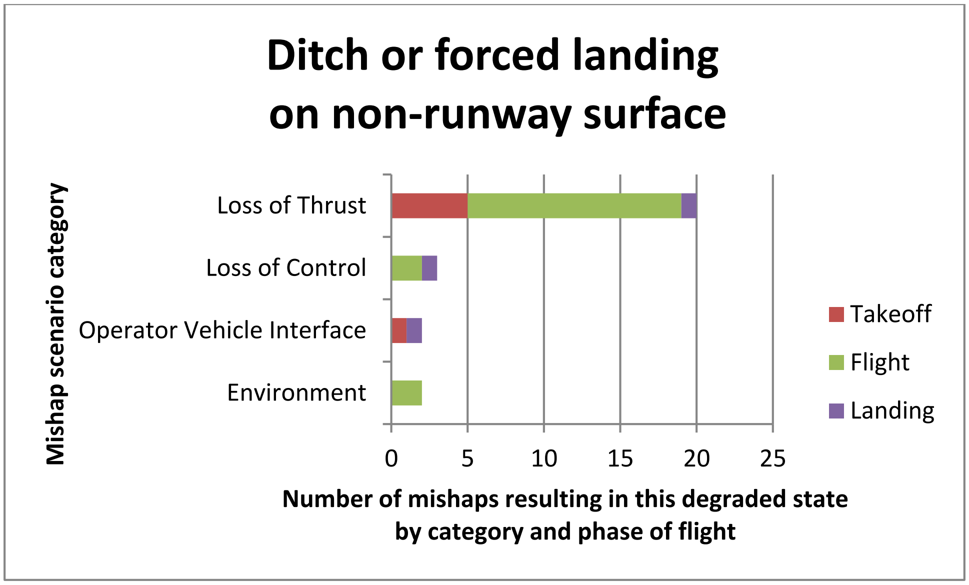

Figure A-9. Ditch/Forced Landing on Non-Runway Surface Mishaps

### A.2.6 Directed Glide

The operator (or flight control computer) is able to direct the vehicle heading but not maintain altitude. Some control is maintained over yaw, pitch, and roll. Thrust is gone or insufficient to maintain altitude. Figure A-10 shows the number of directed glide mishaps by scenario category and phase of flight.

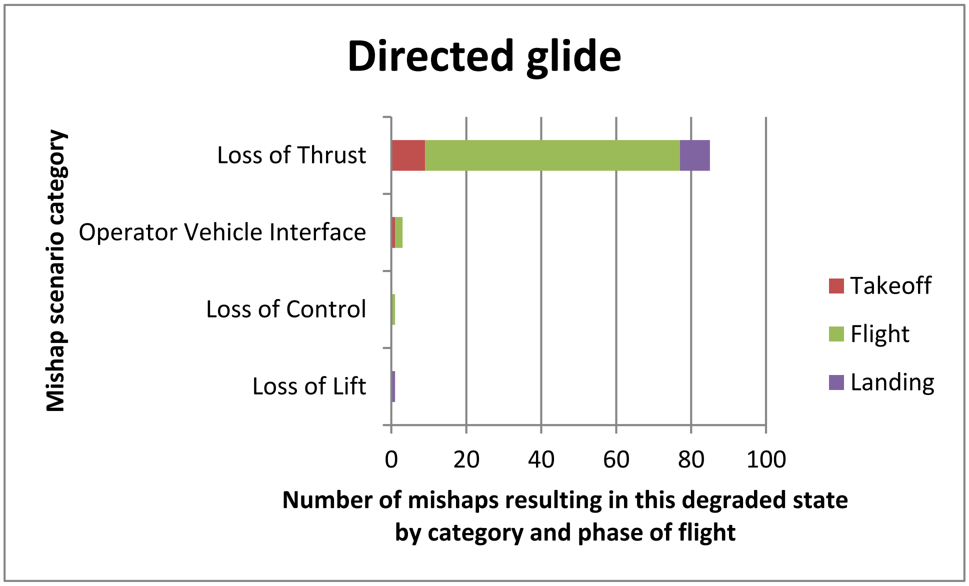

Figure A-10. Degraded State Mishaps with Direct Glide

The directed glide state has degraded further on 33 occasions:

- Depart controlled flight (1);
- Undirected glide (9);
- Transition to parachute (3);
- Attempt parachute too late (1);

- Ditch/forced landing (7);
- Intentional crash (5);
- Collide with obstacle on approach (1);
- Runway overshoot / undershoot (3);
- Abnormal runway contact (3).

### A.2.7 In-Flight Breakup

The vehicle comes apart into multiple pieces after material failure or exceeding operating limits. Figure A-11 shows the number of in-flight break-up mishaps by scenario category and phase of flight.

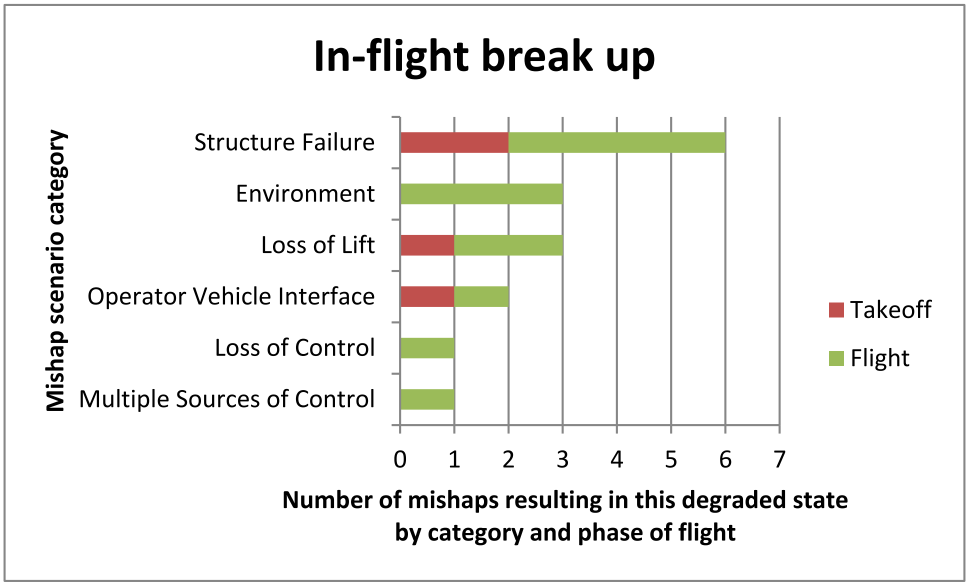

Figure A-11. In-Flight Break-Up Mishaps

The in-flight breakup state is typically the last event of a mishap sequence. Parachute recovery of some components is possible.

### A.2.8 In-Flight Fire

A fire that is not the result of impact occurs in the vehicle.

There were three events where the degraded state can be characterized as an in-flight fire. The in-flight fires were due to flammable fluids encountering an ignition source. Two events were related to lubricating oil leaks and one was due to a fuel leak in an engine bay. Figure A-12 shows the number of in-flight fire mishap scenarios.

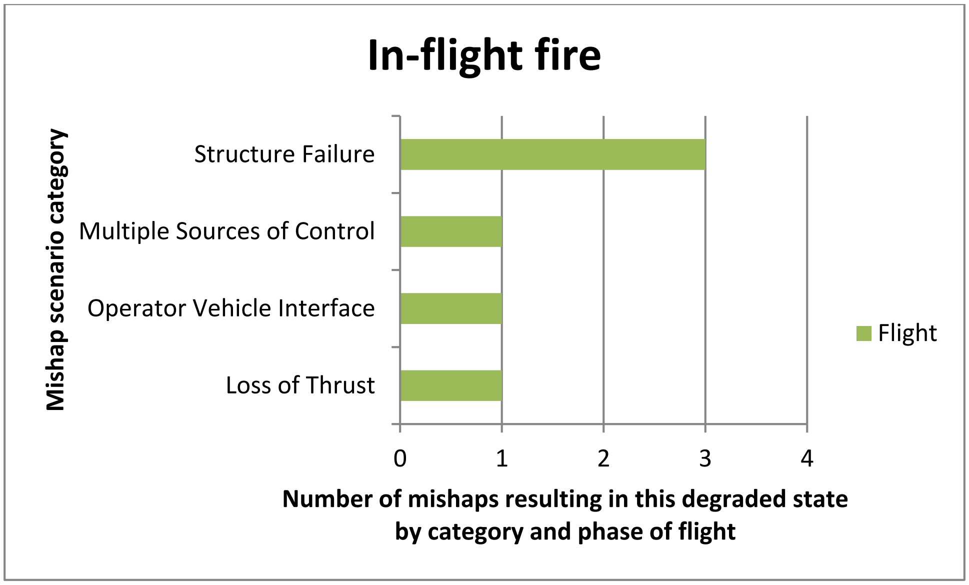

Figure A-12. Degraded State Mishaps with In-Flight Fire

The in-flight fire state has degraded further on three occasions:

- Depart controlled flight (2);
- Break up in flight (1).

### A.2.9 Intentional Crash or FTS Termination in Safe Location

If a vehicle is damaged and unable to RTB, one option is to crash in a known safe (unpopulated) location while the operator still has some control. Intentional crash has also been used to ensure the destruction of sensitive equipment when the vehicle is not able to make it to friendly territory.

“Flight termination” means to intentionally cause the vehicle to lose thrust and lose lift in the event of some loss of control, as in undirected flight, for example.

There were seven mishaps that were associated with either intentional crash or activation of an FTS. Figure A-13 shows the number of FTS or intentional crash mishaps by scenario category and phase of flight.

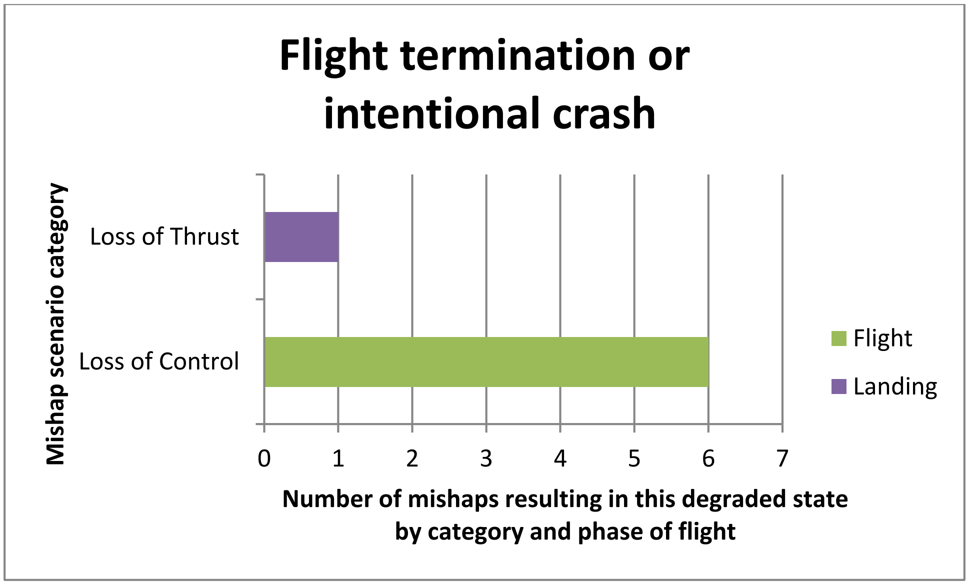

Figure A-13. Flight Termination/Intentional Crash Mishaps

### A.2.10 Lost-link routine

The vehicle is following the lost-link routine as designed or the emergency routine mission as planned. If loss of link is unplanned, the operator is unable to redirect the vehicle or modify the vehicle configuration as necessary to adjust to a changing situation. This is not a degraded state if lost link is intended as part of the mission.

The lost-link state has degraded further on 10 occasions:

- Depart controlled flight (2);
- Directed glide (1);
- Undirected glide (2);
- CFIT (3);
- Transition to parachute (1);
- Ditch/forced landing (1).

Figure A-14 shows the number of lost-link mishaps by scenario category and phase of flight.

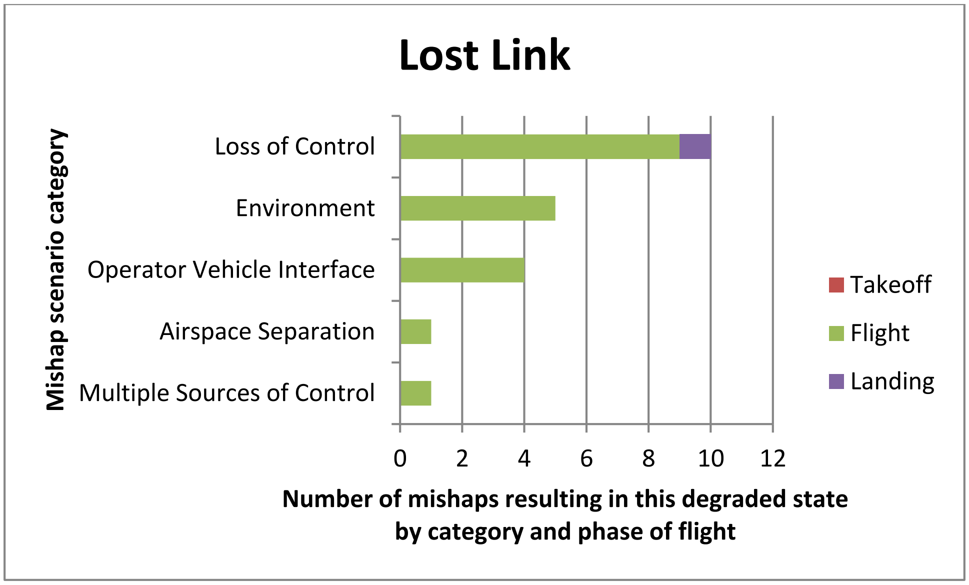

Figure A-14. Degraded State Mishaps with Lost Link

### A.2.11 Transition to parachute recovery (not in recovery area)

An unexpected or unplanned transition from normal flight to emergency or precautionary recovery under parachute occurs. Recovery may be successful or unsuccessful. Figure A-15 shows the number of parachute recovery attempts by scenario category and phase of flight.

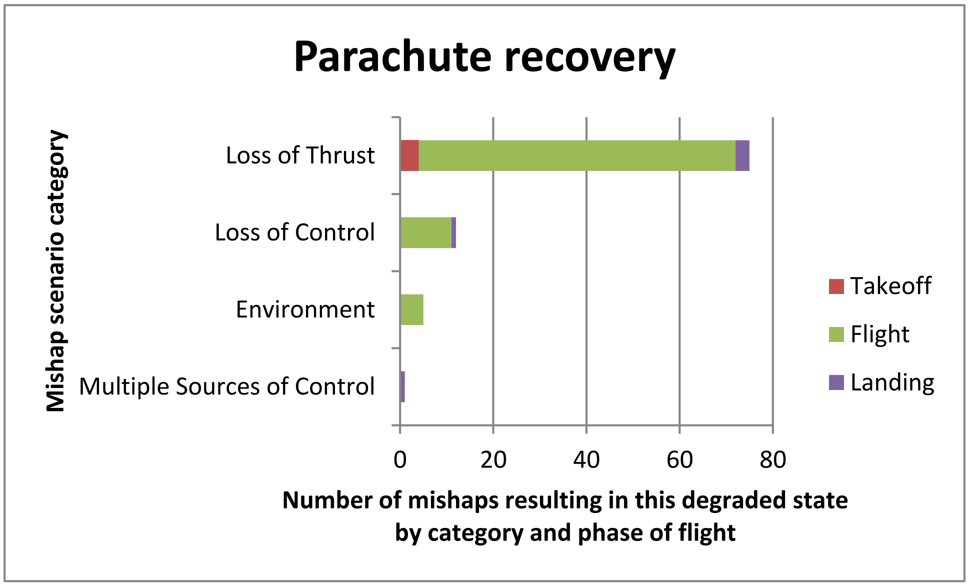

Figure A-15. Degraded State Mishaps with Transition to Attempted Parachute Recovery

### A.2.12 Uncontrolled Impact with Terrain

This degraded state occurs with any in-flight phase mishap involving surface impact not otherwise described by another degraded state. Figure A-16 shows the number of mishaps that ended with an uncontrolled impact with terrain by scenario category and phase of flight.

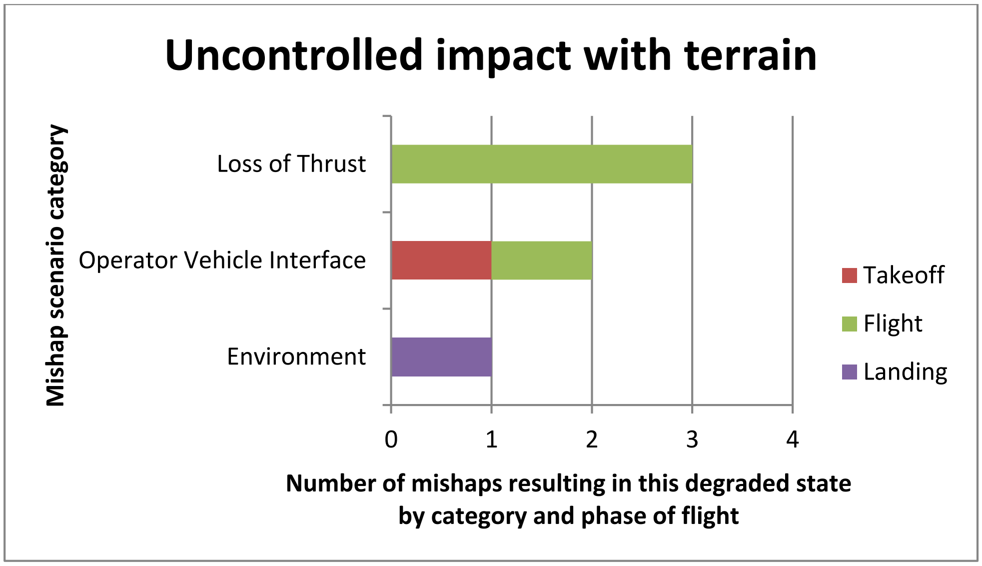

Figure A-16. Uncontrolled Impact with Terrain Mishaps

### A.2.13 Undirected Flight (flyaway)

The vehicle continues to maintain powered flight but is not responsive to operator commands. Figure A-17 shows the number of mishaps involving an undirected flight degraded state by scenario category and phase of flight.

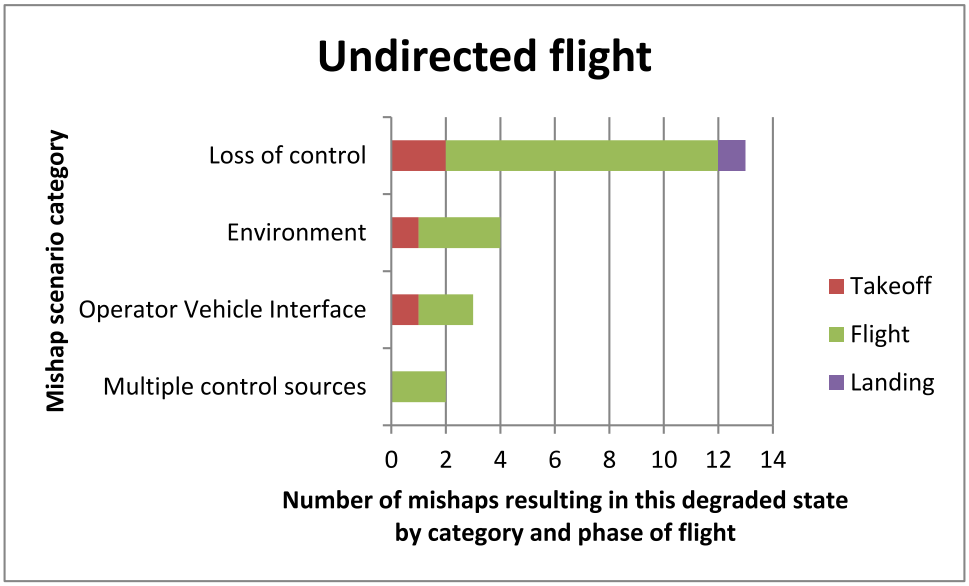

Figure A-17. Degraded State Mishaps with Undirected Flight

The undirected flight state has degraded further on six occasions:

- Undirected glide (1);
- CFIT (2);
- Collision with obstacle during approach (1);
- Leave assigned airspace (2).

### A.2.14 Undirected Glide

The operator (or flight control computer) is not able to direct the vehicle heading or maintain altitude. Inherent dynamic stability of the vehicle design may keep the vehicle from departing level flight. Thrust is gone or insufficient to maintain altitude. Figure A-18 shows the number of mishaps involving an undirected glide by scenario category and phase of flight.

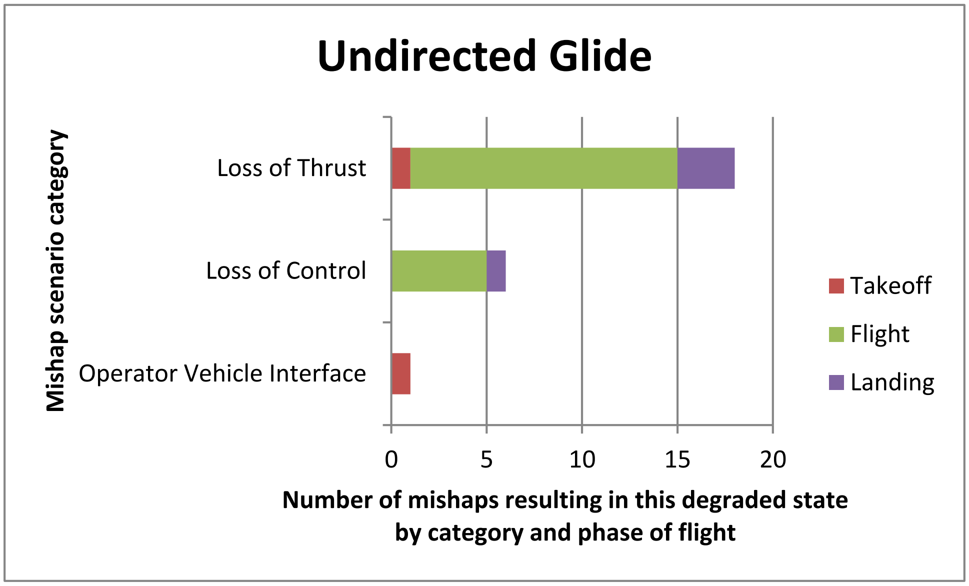

Figure A-18. Degraded State Mishaps with Undirected Glide

The undirected glide state typically results in an uncontrolled crash. Other outcomes included:

- Lost-link routine (1);
- Runway overshoot/undershoot (1);
- Parachute fails to open (1).

## A.3 Airfield Ground Operation Degraded States

Degraded state mishaps can also occur on the ground during takeoff/launch, landing, taxi, or standstill. Figure A-19 shows the number of airfield ground operations degraded state mishaps by scenario category and phase of flight.

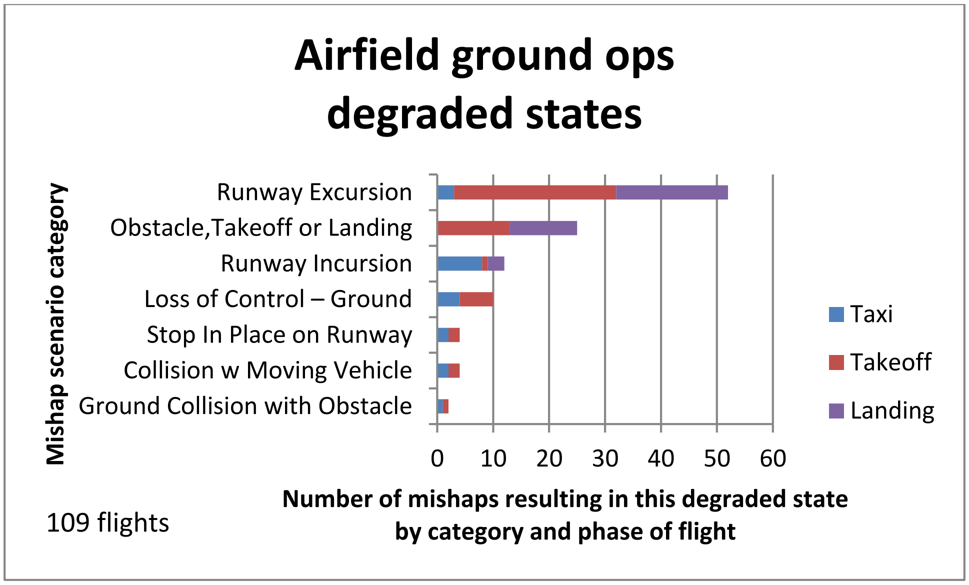

Figure A-19. Number of Ground Operations Degraded States Encountered

### A.3.1 Collision with Obstacle During Takeoff or Landing

The vehicle collides with an object while airborne, in controlled flight, after takeoff, or during landing approach. This includes collisions with vegetation, power cables, antennas, ships, buildings, etc. Figure A-20 shows the number of mishaps in which collision with an object on takeoff or landing caused a degraded state by scenario category.

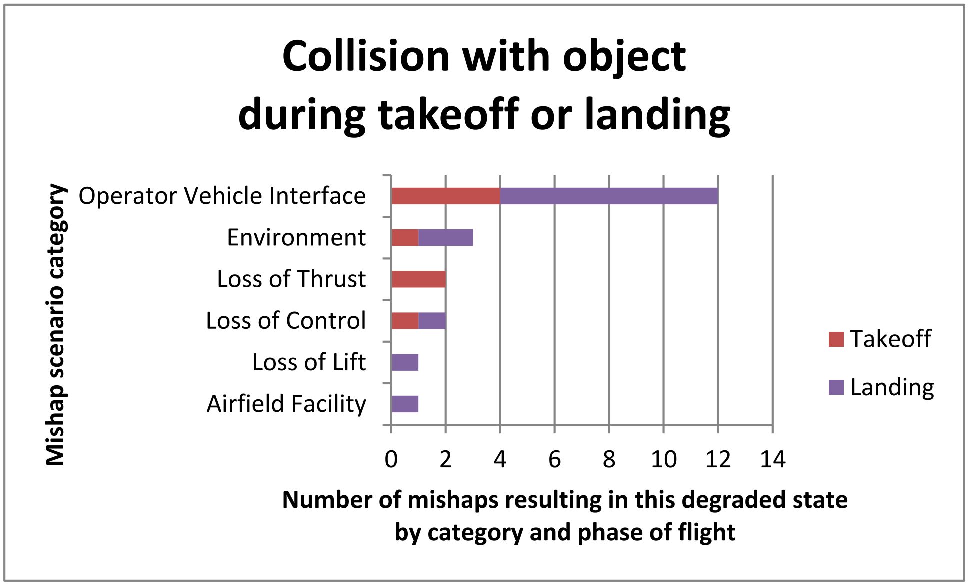

Figure A-20. Object Collision Mishaps

### A.3.2 Ground Collision with Obstacle

The vehicle collides with a stationary object while taxiing to or from a runway in use. This includes collisions with a parked aircraft, person, parked ground vehicle, obstacle, building, or structure while on the taxiway or runway surface.

There was one instance of a vehicle inadvertently being sent a launch command instead of shutdown on the parking ramp and driving itself into a parked aircraft.

### A.3.3 Ground Collision with Moving Vehicle or Animal

The vehicle collides with a moving object while taxiing to or from a runway in use. This includes collisions with other taxiing aircraft, moving ground vehicles, or animals.

- There was one instance of UAV/UAV collision on the taxiway, on the ground.
- There was one near collision of a taxiing UAV and a manned aircraft holding short waiting to access the taxiway.
- No UAV ground collisions with animals in our database were classified as mishaps. Further review may indicate collisions with animals were classified as hazards that we have not reviewed.

### A.3.4 Loss of Control – Ground

Aircraft control is lost while it is on the ground. Figure A-21 shows the number of loss-of-control mishaps that occurred while the UAV was on the ground by scenario category and phase of flight.

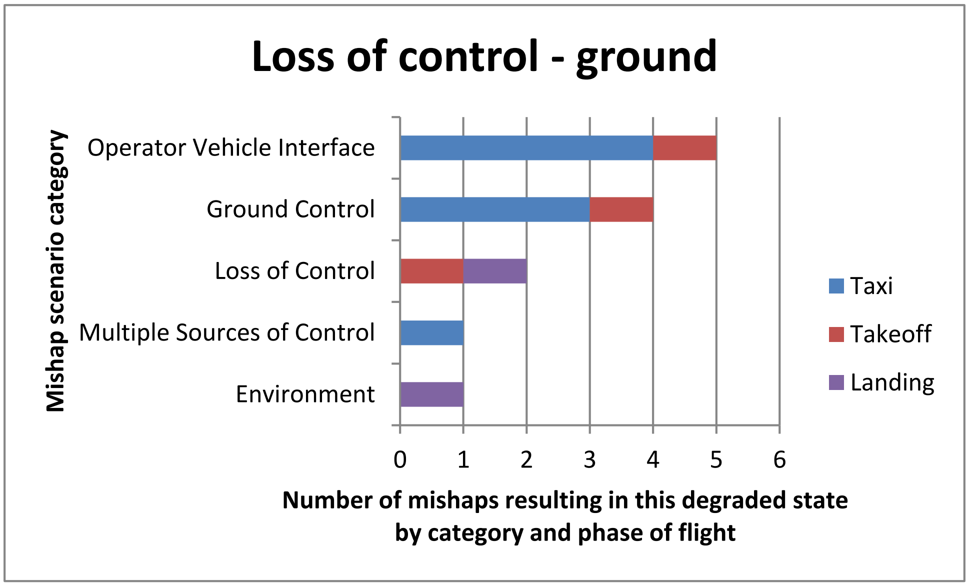

Figure A-21. Loss of Control Mishaps - Ground

### A.3.5 Runway Excursion

The vehicle veers off or overruns the runway surface during takeoff or landing. Figure A-22 shows the number of mishaps due to runway excursion by scenario category and phase of flight.

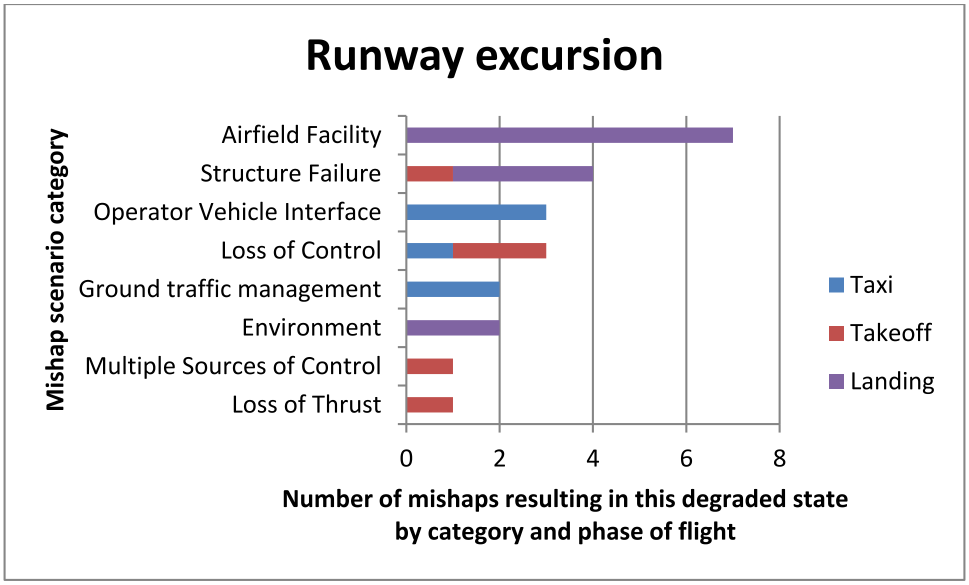

Figure A-22. Runway Excursion Mishaps

### A.3.6 Runway Incursion

An unauthorized aircraft, vehicle, or person is in the protected area of a surface designated for the landing or takeoff of aircraft.

This definition is based on ICAO taxonomy and airline experience. There were no categorized mishaps of this type in our sample, although one instance of ground UAV collision may have been. There was not enough information in the news report to verify this was the result of a runway incursion. Figure A-23 shows the number of degraded state events due to runway incursion by mishap scenario and phase of flight. While no categorized mishaps were in our data set, there were multiple reports that addressed this degraded state.

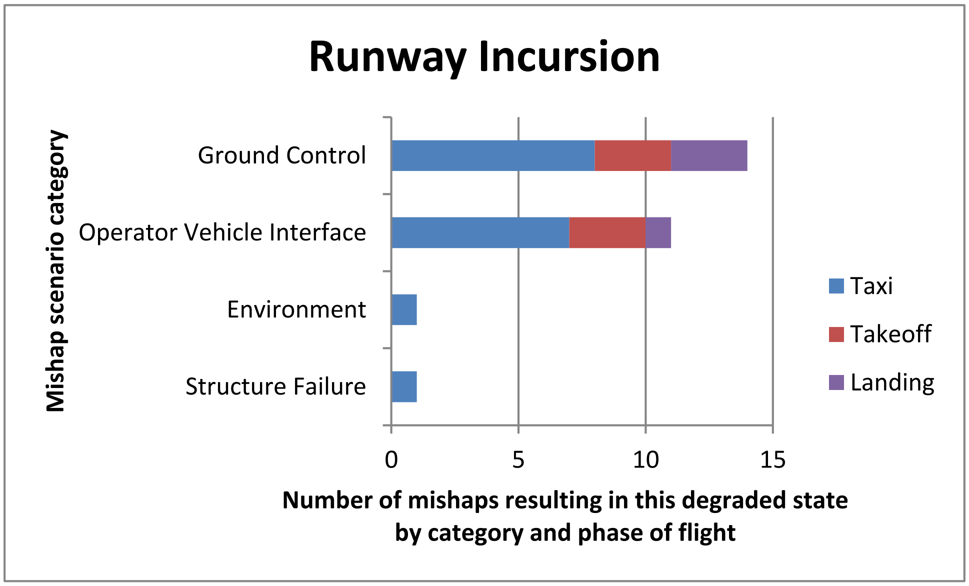

Figure A-23. Runway Incursion Degraded State Events

### A.3.7 Stop in Place on Runway

An unpredicted or uncontrolled vehicle stop occurs on a runway or taxiway. The vehicle may block other aircraft from launch or recovery.

There were two occurrences of note that resulted in hazard reports rather than mishap reports. It is a significant issue if it takes a long time to clear the runway for use by other aircraft. Figure A-24 shows the number of runway/taxiway hazards due to a vehicle stop in place by scenario category and phase of flight.

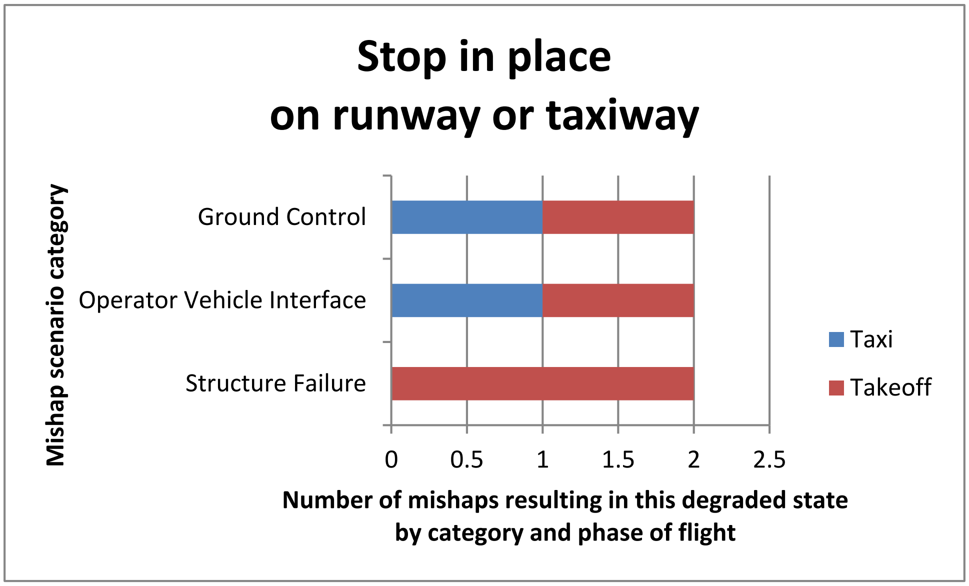

Figure A-24. Stop in Place on Runway/Taxiway Hazards

## A.4 Takeoff Degraded States

The vehicle encounters a degraded state on takeoff or launch. Figure A-25 shows the number of mishaps in which a degraded state occurred upon takeoff by scenario category.

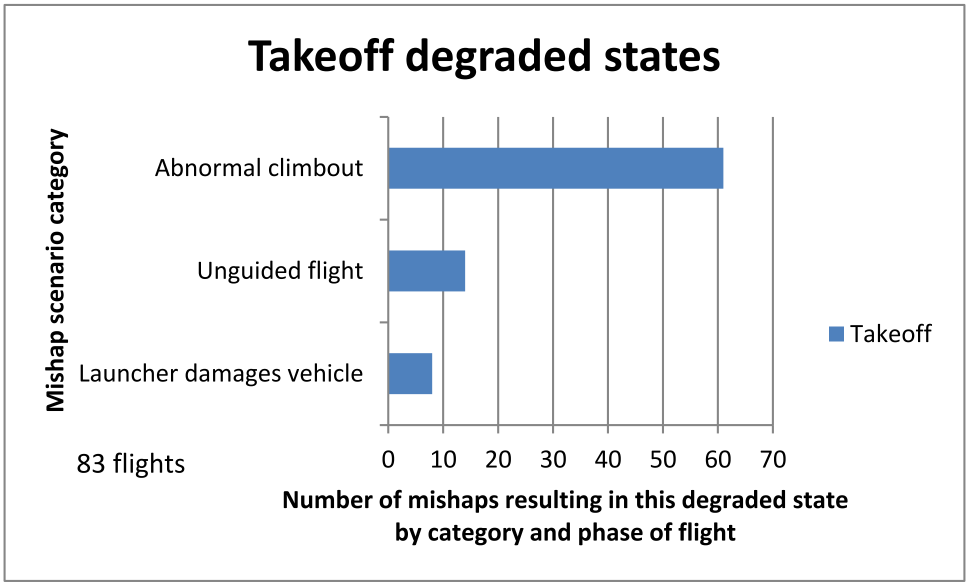

Figure A-25. Number of Takeoff Degraded States Encountered

### A.4.1 Abnormal Climbout

Vehicle launch or takeoff does not result in altitude increase necessary to safely depart from the airport or results in excessive climb and stall. Figure A-26 shows the number of mishaps in which an abnormal climbout on takeoff or launch occurred by scenario category.

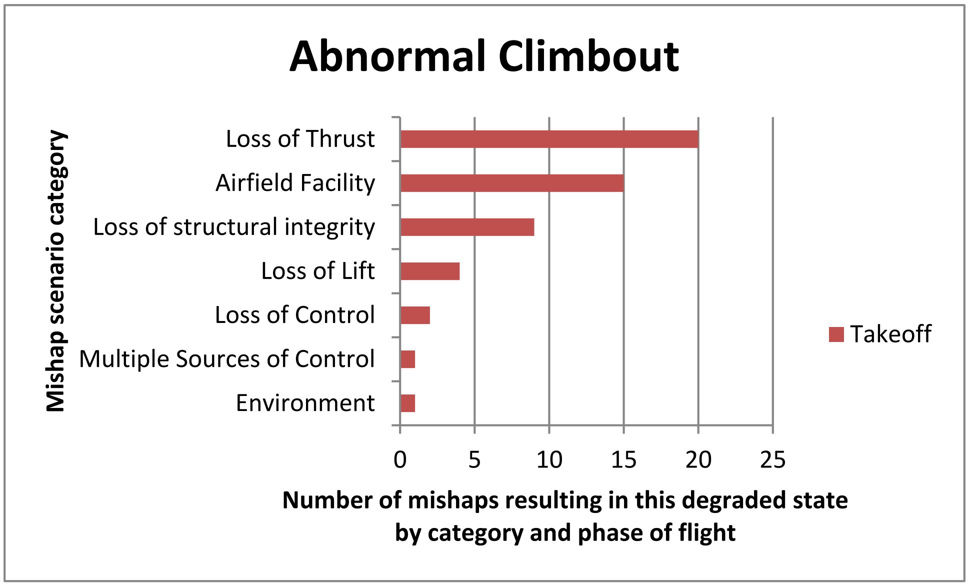

Figure A-26. Degraded State Mishaps with Abnormal Climbout

### A.4.2 Unguided Flight/Erratic Flight Path on Launch

Vehicle launch or takeoff does not result in consistent or predicted heading necessary to safely depart from the airport. Figure A-27 shows the number of mishaps in which unguided or erratic flight occurred on takeoff or launch by scenario category.

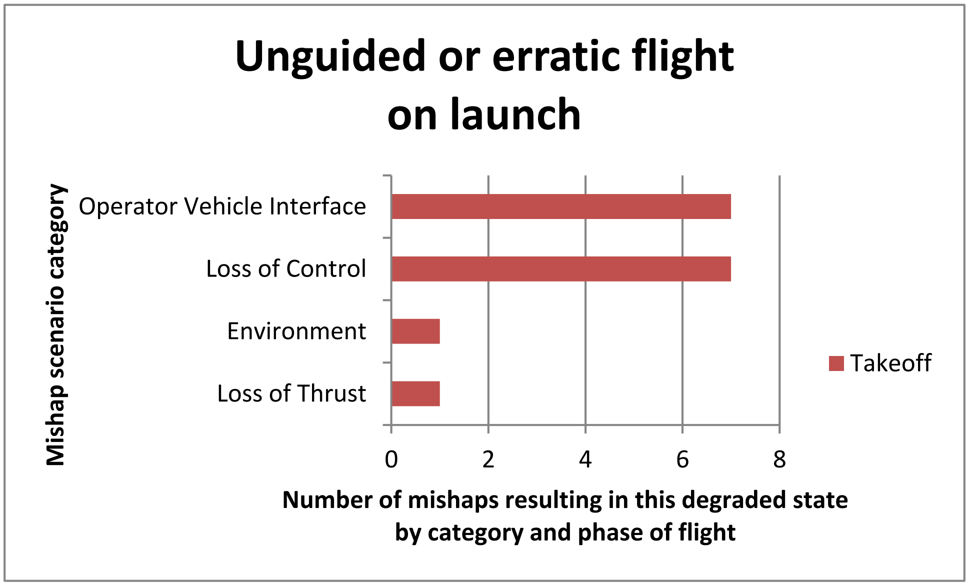

Figure A-27. Degraded State Mishaps with Unguided/Erratic Flight on Launch

### A.4.3 Launcher Damages Vehicle

The vehicle is damaged on launch and does not have sufficient thrust to climb or loses structure necessary to maintain lift or control. Figure A-28 shows the number of mishaps in which the vehicle launcher causes damage to the UAV on launch by scenario category.

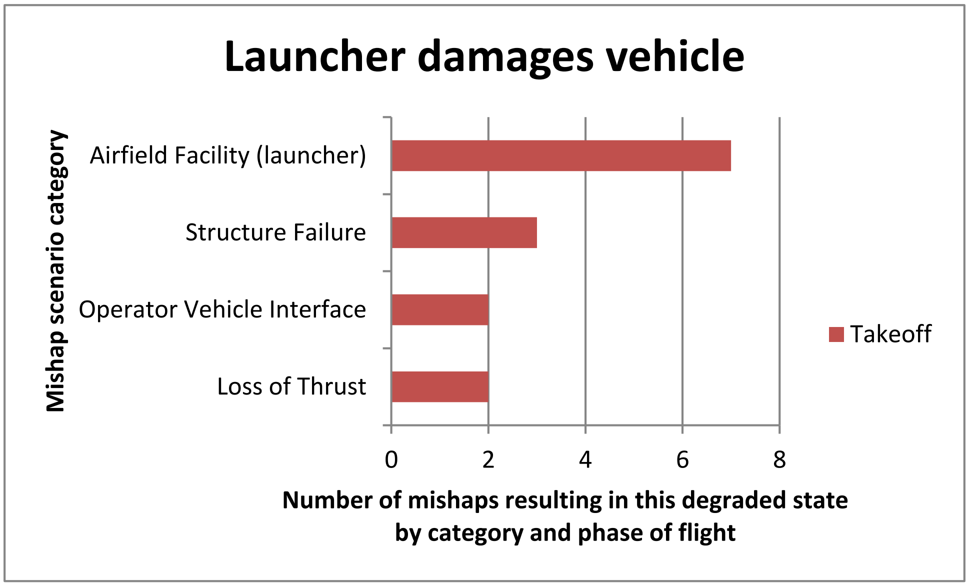

Figure A-28. Degraded State Mishaps with Vehicle Damage from Launcher

## A.5 Landing Degraded States

Landing degraded states are those degraded states and events primarily associated with a mishap scenario that begins during landing or an attempted landing. Figure A-29 shows the number of degraded states by scenario category that began while a UAV was in the landing phase of flight. The resultant mishap may have occurred in any phase of flight.

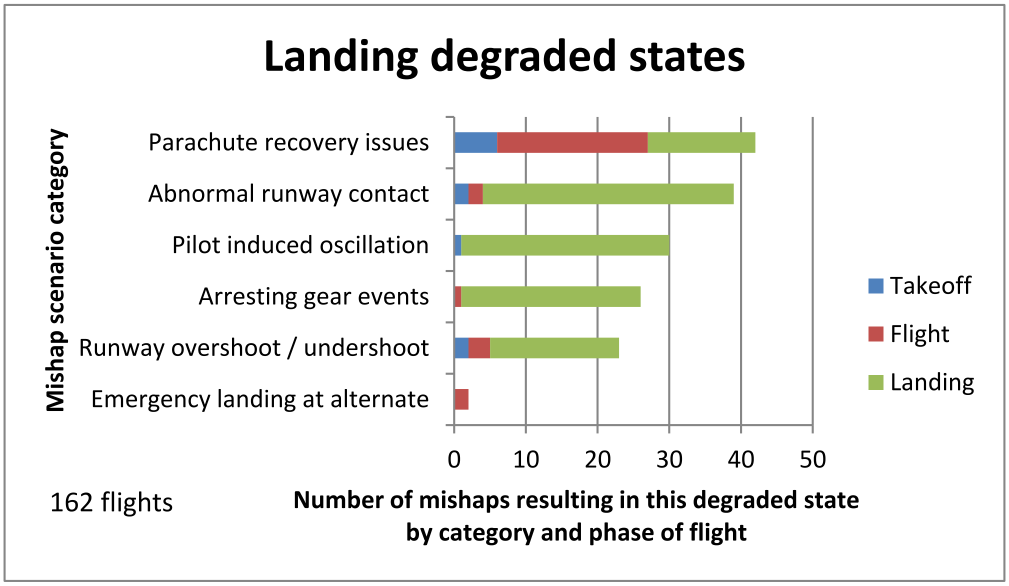

Figure A-29. Number of Landing Degraded States Encountered

### A.5.1 Abnormal Runway Contact

This degraded state is caused by a vehicle landing (or takeoff) that involves abnormal runway or landing surface contact. Figure A-30 shows the number of events in which abnormal runway contact caused a degraded state that led to a mishap. Events are shown by scenario category and phase of flight in which the mishap occurred.

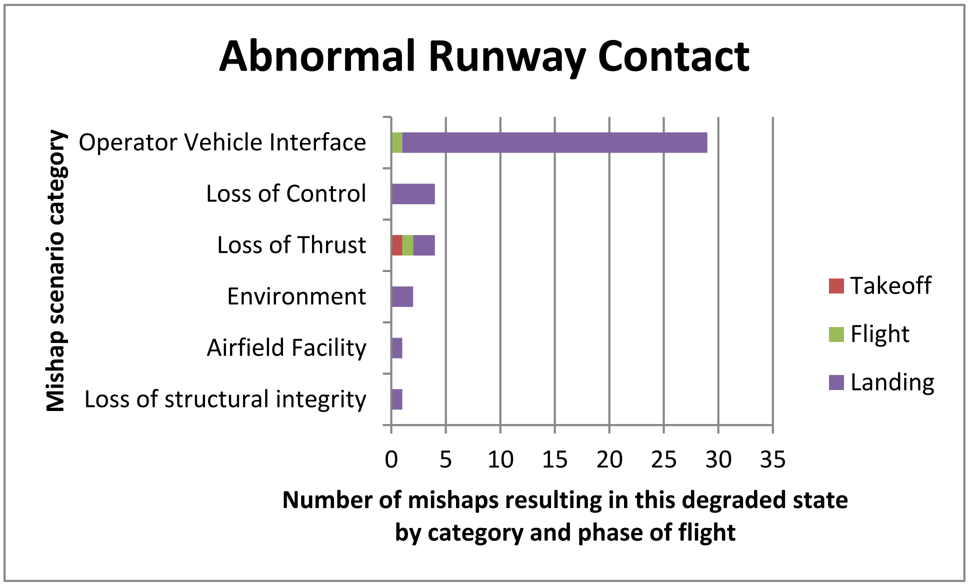

Figure A-30. Degraded State Mishaps with Abnormal Runway Contact

Examples include:

- Hard/heavy landings, long/fast landings, off-centerline landings, crabbed landings;
- Nose wheel first touchdown, tail strikes, wingtip strikes;
- Gear-up landings.

### A.5.2 Emergency or Precautionary Landing at Alternate Site

A landing at an alternate airfield is warranted due to actual or concern regarding degraded vehicle airworthiness.

There were only two events in our sample, both related to loss of engine lubrication.

### A.5.3 Pilot-Induced Oscillation

Pilot-in-the-loop oscillations result in increasing “porpoising” in the pitch axis. Frequently, PIO is associated with abnormal runway contact on landing, but is also possible on runway takeoff. Figure A-31 shows the number of events in which a PIO degraded state occurred that led to a mishap. Events are shown by scenario category and phase of flight.

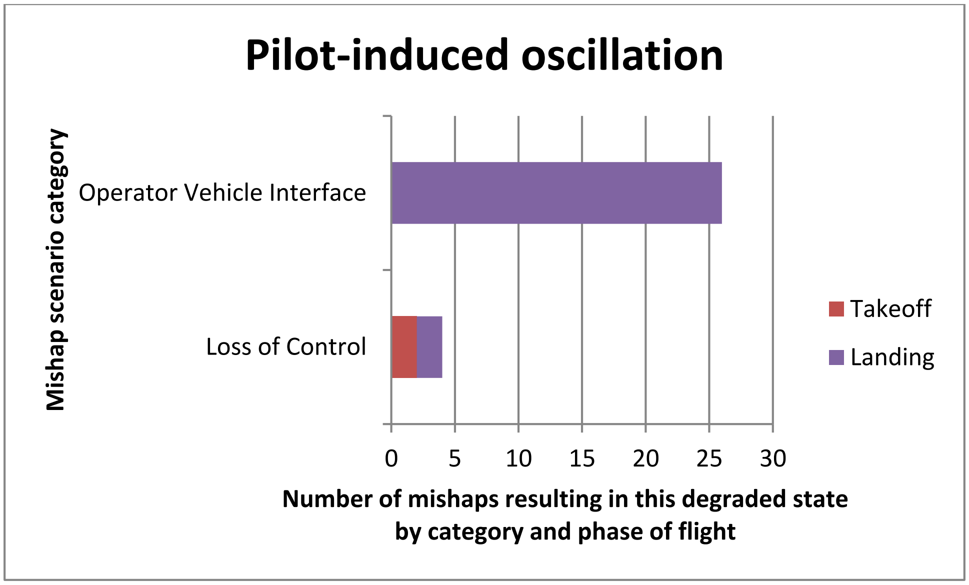

Figure A-31. Degraded State Mishaps with Pilot-Induced Oscillation

### A.5.4 Runway Overshoot/Undershoot

The vehicle touches down off of the runway or helipad surface in close proximity to the runway. Off-airport emergency landings are excluded (ICAO convention). Figure A-32 shows the number of runway overshoot or undershoot degraded state mishaps by scenario category and phase of flight.

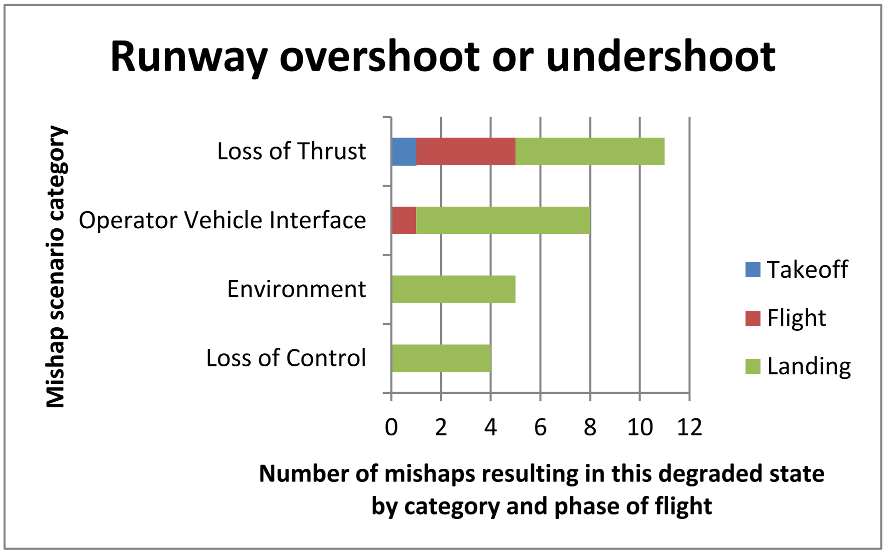

Figure A-32. Degraded State Mishaps with Runway Overshoot/Undershoot

### A.5.5 Arresting Gear Events

The UAV attempts an arrested landing and misses or engages in an unsuccessful manner. Figure A-33 shows the number and type of arresting gear degraded states.

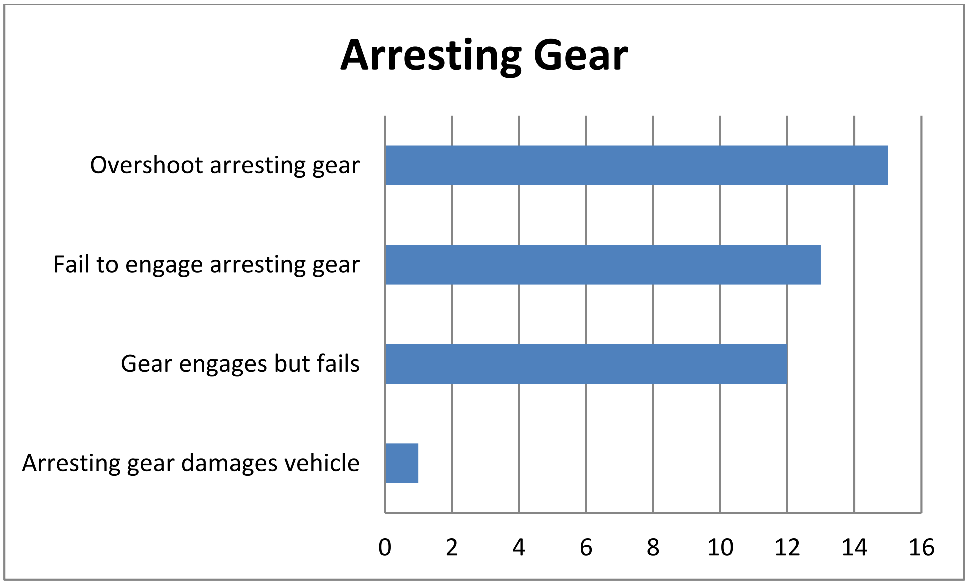

Figure A-33. Number and Type of Arresting Gear Degraded States Encountered

An arrested landing failure can be caused by a vehicle or vehicle system failure, an arresting gear failure, the environment, or a combination of factors. Figure A-34 shows the number of degraded state mishaps with arresting gear issues by scenario category.

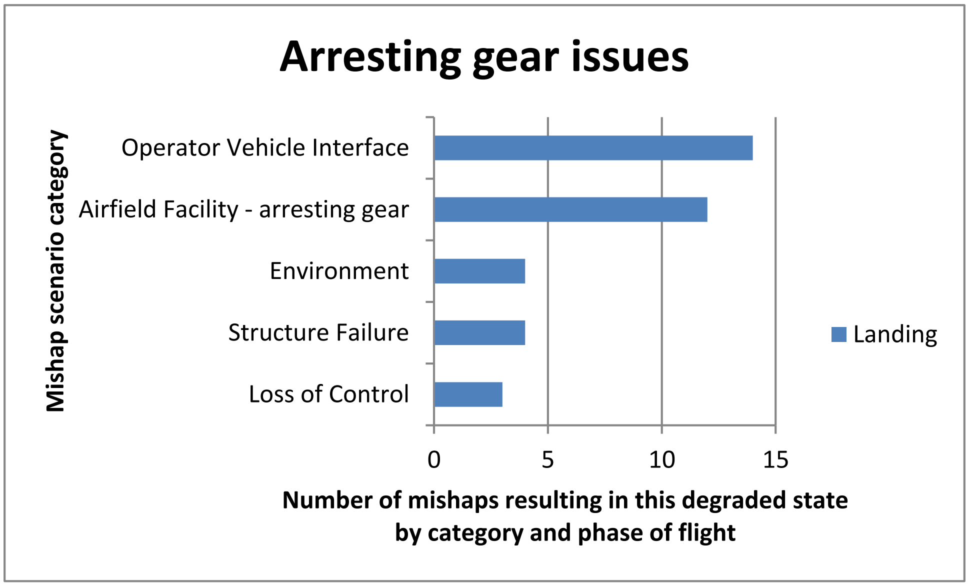

Figure A-34. Degraded State Mishaps with Arresting Gear Issues

- **Miss net/overshoot arresting gear:** The vehicle flies over the arresting cable or the arresting net.
- **Fail to engage arresting gear or net:** The vehicle passes over the arresting gear but does not catch the cable.
- **Fail to stop vehicle:** The arresting gear or net engages but fails to stop the vehicle.

- **Automatic landing system:** The automatic landing system is inoperative or unavailable during a landing approach.
- **Damage to vehicle:** The net or arresting gear damages the vehicle.

### A.5.6 Parachute Recovery Degraded States

A parachute recovery is attempted and fails or causes a mishap. Failures can be traced to the parachute recovery system, operator error, or external factors. Figure A-35 shows by scenario category and phase of flight the number of attempted parachute recoveries in which a failure caused a degraded state and led to a mishap.

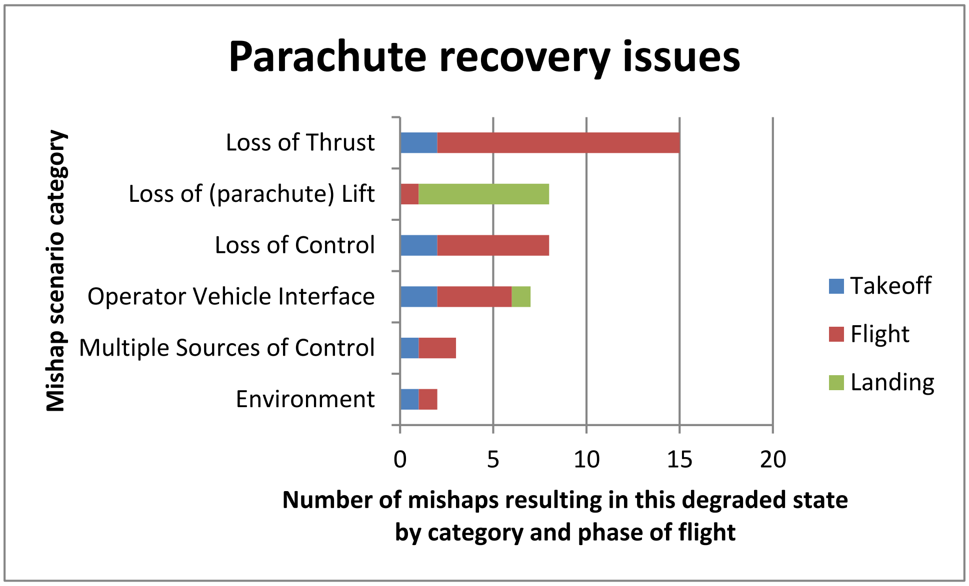

Figure A-35. Degraded State Mishaps with Parachute Recovery Issues

Figure A-36 shows the number and type of parachute degraded states that led to a mishap.

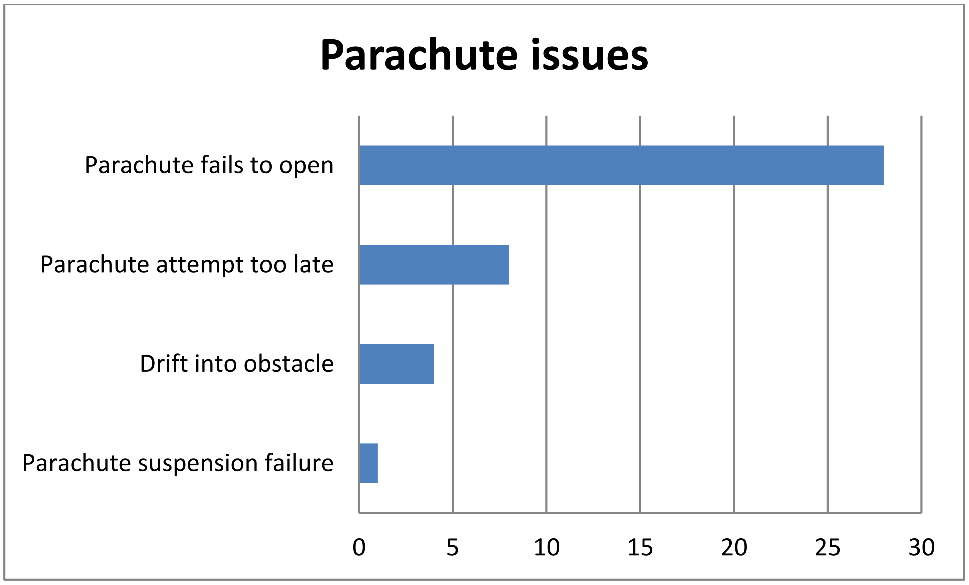

Figure A-36. Number and Type of Parachute Degraded States Encountered

A planned parachute recovery is not successful for one of the following reasons:

- Parachute fails to open;
- Parachute attempt too late, too close to ground;
- Vehicle drifts into obstacle or unsuitable landing area;
- Vehicle suspended in unusual or non-level attitude.

Unplanned or unexpected deployment of a parachute recovery system at other than the intended recovery site is addressed in Section 2.3.3.

## A.6 Airspace Operations Degraded States

Airspace operations degraded states address the vehicle, nearby vehicles, and the air traffic controlling authority.

The terms AIRPROX (air proximity issues), Loss of Separation, NMAC, and Midair Collision are used by ICAO. They also track TCAS and Airborne Collision Avoidance System alerts.

There is some commonality here with the airspace mishap scenarios; should we prevent the mishap (mishap scenario approach) or treat the outcome (degraded state approach)? Figure A-37 shows the number and type of airspace degraded states.

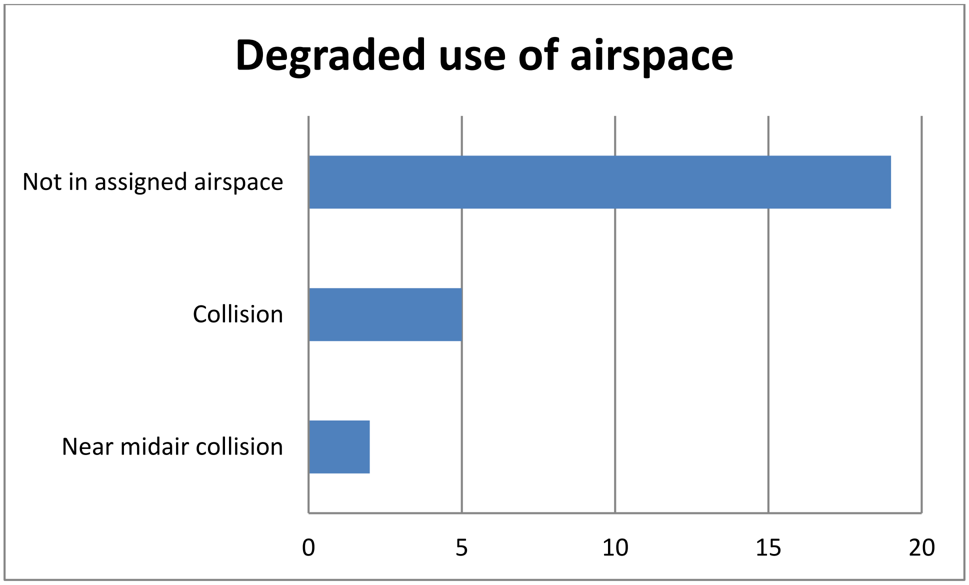

Figure A-37. Number and Type of Airspace Degraded States Encountered

### A.6.1 Unknown Airspace Status

The operator and/or ATC is no longer in contact with the vehicle. Risk is increased to other participants of the airspace because separation is no longer assured.

Not being in assigned airspace increases risk of collision with other aircraft or denies the use of that airspace to other aircraft. Figure A-38 shows by mishap scenario category the number of degraded states involving unknown airspace status.

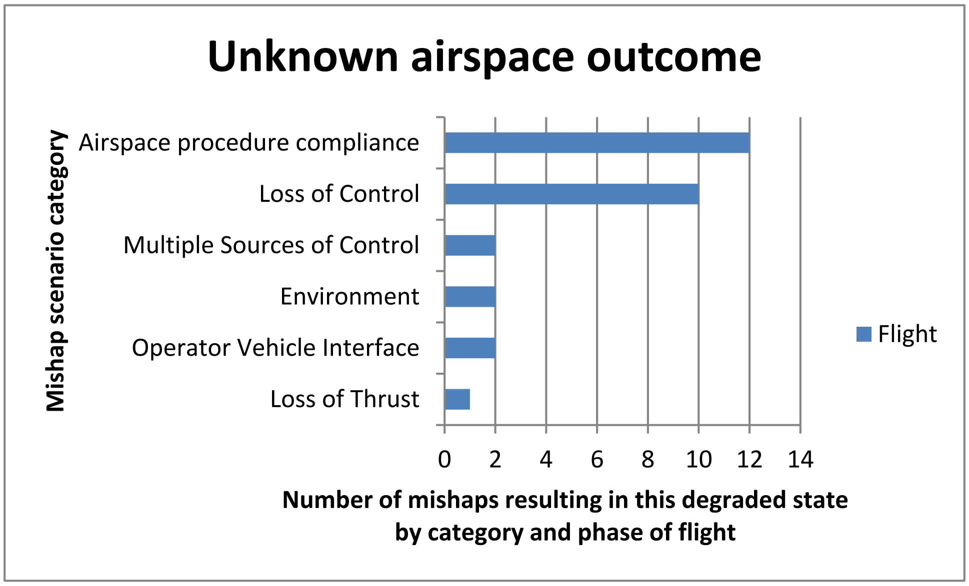

Figure A-38. Degraded State Mishaps with Unknown Airspace Status

### A.6.2 Loss of Airspace Separation Assurance

The vehicle was observed to be violating some safety provision of the airspace system, such as not on its assigned route or in assigned area, but did not come close enough to meet near-midair criteria. Figure A-39 shows by mishap scenario and category of flight the number of events in which airspace separation assurance was lost during UAV operations.

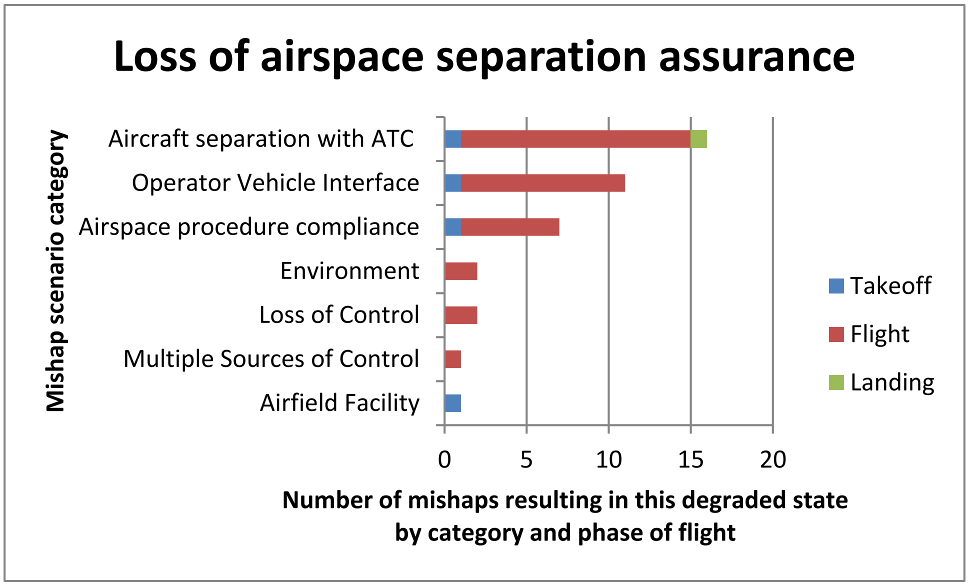

Figure A-39. Degraded State Mishaps with Loss of Airspace Separation Assurance

### A.6.3 Near Midair Collision

- A UAV has an unexpected encounter in proximity with another aircraft.
- The aircraft flew within 500 ft of each other.
- The aircrew took evasive action or would have taken action if circumstances allowed.
- Aircraft proximity triggers a TCAS resolution advisory.

Figure A-40 shows by scenario category the number of NMACs that occurred.

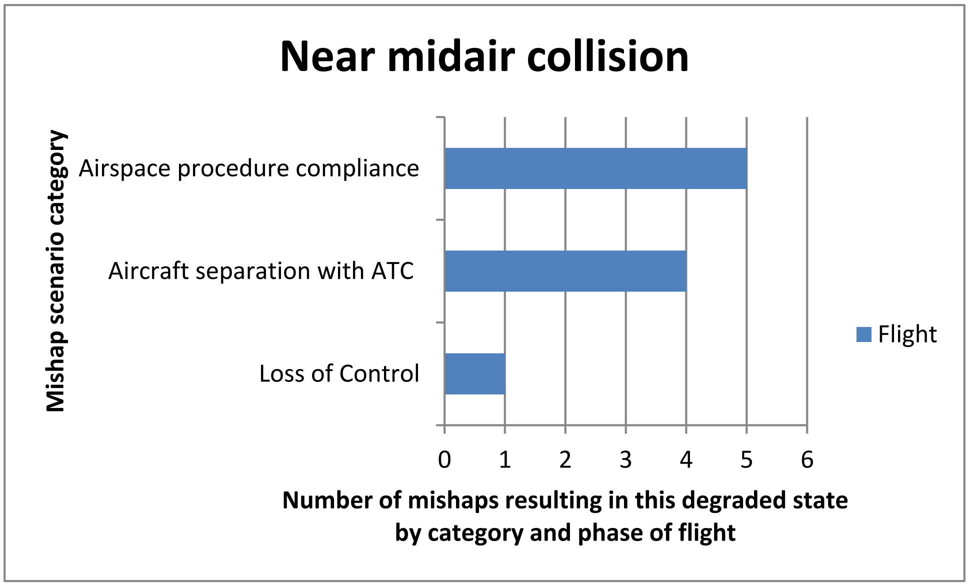

Figure A-40. Degraded State Mishaps with Near Midair Collision

### A.6.4 Midair Collision

A UAV impacts another vehicle in flight, resulting in damage to or loss of one or both vehicles. Figure A-41 shows by scenario category the number of midair collision mishaps.

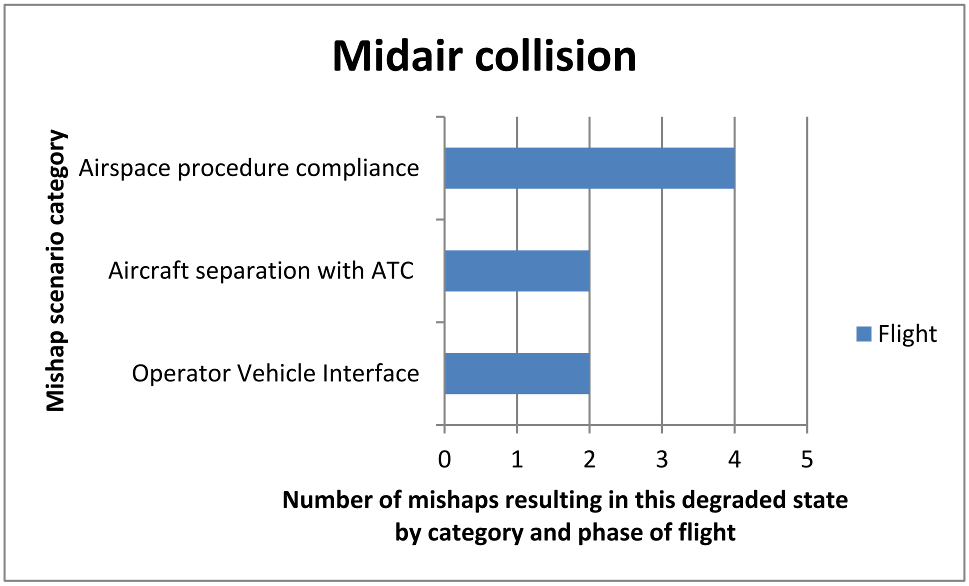

Figure A-41. Midair Collision Mishaps

# APPENDIX B

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# APPENDIX C

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