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Hazards Identification and Analysis for Unmanned Aircraft System Operations

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Many beneficial civilian applications of commercial and public small unmanned aircraft systems (sUAS) in low-altitude uncontrolled airspace have been proposed and are being developed. Associated with the proliferation of civil applications for sUAS is a paradigm shift from single-UAS visual operations in restricted airspace to multi-UAS beyond visual line of sight operations with increasing use of autonomous systems and operations under increasing levels of urban development and airspace usage. Ensuring the safety of sUAS operations requires an understanding of associated current and future hazards. This is challenging for sUAS operations due to insufficient mishap (accident and incident) reporting for sUAS and the rapid growth of new sUAS applications (or use cases) that have not yet been implemented. These applications include imaging, construction, photography and video, precision agriculture, security, public safety, mapping and surveying, inspections, environmental conservation, communications, parcel delivery, and humanitarian efforts such as delivery of medical supplies in developing nations. This paper will summarize research results in the identification of: 1.) Current hazards through the analysis of sUAS mishaps; and 2.) Future hazards through the analysis of a collection of sUAS use cases. The mishaps analysis will include the identification of mishap precursors and an analysis of their individual contributions to the mishaps as well as an analysis of worst-case hazards combinations and sequences. The future hazards are identified through an assessment and categorization of use cases for sUAS, the identification of associated paradigm shifts in terms of operations and new vehicle systems (both cross-cutting and for specific use case categories), the determination of future potential hazards (relative to the vehicle, ground control station, operations, and UTM system) arising from these paradigm shifts, and future potential impacts and outcomes (relative to the vehicle, other vehicles, people, ground infrastructure, and the environment). Key findings from these analyses are also summarized. The analysis results are then used to develop a set of combined (current and future) hazards for assessing risk.

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Nomenclature

BVLOS	=	beyond visual line of sight
MAC	=	mid-air collision
NMAC	=	near-mid-air collision
sUAS	=	small unmanned aircraft system
UAS	=	unmanned aircraft system
UTM	=	UAS traffic management
VLOS	=	within visual line of sight

I. Introduction

MANY beneficial civilian applications of commercial and public small unmanned aircraft systems (sUAS) in low-altitude uncontrolled airspace have been proposed and are being developed. These applications include delivery of goods, infrastructure monitoring, precision agriculture, search and rescue, and many others.[1] Figure 1 provides a graphical depiction of sUAS low-altitude operations.

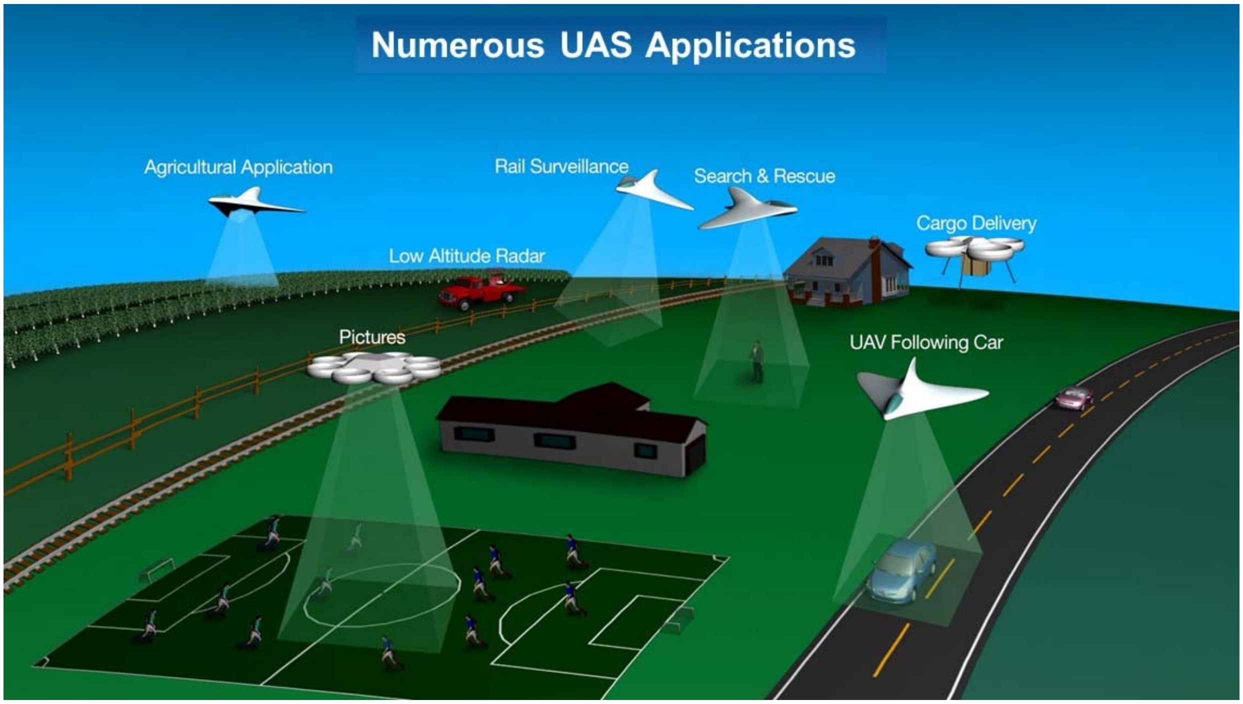


Figure 1. Depiction of sUAS Operations in Low-Altitude Airspace

These UAS operations will increasingly require interactions with an array of existing users of that airspace - general aviation aircraft, helicopters, gliders, balloons, and even parachutists. However, the safety of these existing operations cannot be reduced by the introduction of the new UAS operations. Currently, there is no automation infrastructure to accommodate the widespread use of UAS operations in uncontrolled airspace. The NASA Unmanned Aircraft System (UAS) Traffic Management (UTM) Project[2] seeks to facilitate the safe use of low-altitude airspace (below 500 feet) by operators of small UAS (sUAS of 55 lbs or less) for a wide variety of applications. The UTM system will enable safe and efficient low-altitude airspace operations by providing services such as airspace design, corridors, dynamic geo-fencing, severe weather and wind avoidance, congestion management, terrain avoidance, route planning, re-routing, separation management, sequencing, spacing, and contingency management. UTM is essential to enable the accelerated development and use of civilian sUAS applications. In its most mature form, the UTM system will be developed using autonomicity characteristics, which will include self-configuration, self-optimization and self-protection.

Associated with the proliferation of civil applications for UAS is a paradigm shift from single-UAS remotely piloted within visual line of sight operations in remote locations to multi-UAS BVLOS (beyond visual line of sight) operations with increasing use of autonomous systems and operations under increasing levels of urban development and airspace usage. Along with increasing levels of operational complexity and sophistication come increasing complexity of hazards sources and levels of safety / risk impacts. Ensuring safety can therefore be thought of as a multidimensional problem, and visualized in a 3-dimensional problem space as depicted in Figure 2.

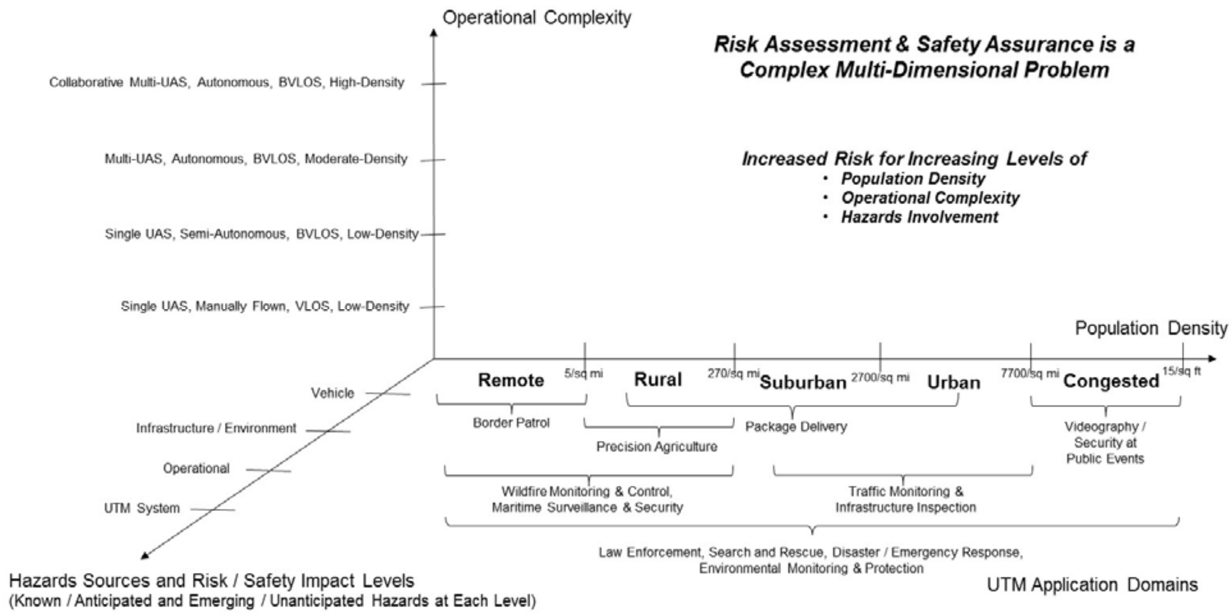


Figure 2. Multidimensional Problem Space for Assessing Risk and Ensuring the Safety of sUAS and UTM Operations [*]

As indicated in Figure 2, one dimension of the safety problem involves operational complexity, which increases with increasing numbers of UAS operations by a single operator, increasing use of autonomous systems and operations, and increasing density of operations within the UTM airspace (i.e., from low to high density of operations). Another dimension of the safety problem involves the population density (including remote, rural, suburban, urban, and congested) of the operational environment, and the proliferation of applications for sUAS being considered. An attempt is made in Figure 2 at mapping the various sUAS applications (or use cases) across the operational environments envisioned. The third dimension depicted in Figure 2 represents the hazards sources and levels of associated safety / risk impact, including at the vehicle level, infrastructure, environment, operational, and the UTM system. It should be noted that hazards at one level can affect not only that level but also others along this dimension. For example, a hazard at the vehicle level can impact safety and risk at the operational level.

The identification of safety hazards and associated risk is challenging for the emerging sUAS operations being proposed by a plethora of industries, government agencies, municipalities, and individuals. Safety and risk assessments associated with UAS operations have been the subject of a number of publications. [3, 4, 5, 6] These papers provide insights into hazards identification and risk analysis for unmanned aircraft, but do not actually perform a detailed hazards analysis for UAS in terms of current mishaps and future use cases. In Ref. [5], hazards are discussed in three domains: the UAS Design Domain, the UAS Flight Crew Domain, and the UAS Operational Domain – all of which should be considered in hazards identification for UAS. Hazards analyses for a specific sUAS have also been performed.[7]

This paper addresses the identification of current and future hazards associated with sUAS operations within a UTM system. Current hazards are identified by analyzing mishaps (incidents and accidents). Future hazards are identified by determining paradigm shifts associated with sUAS use case categories. A combined set of hazards can

[*] Population Densities from Demographia, http://www.demographia.com/db-intlsub.htm, downloaded 29 March 2016.

be developed based on the current and future hazards analyses, and a preliminary hazard set at the vehicle level is presented in this paper. The paper is organized as follows: Section II summarizes the current hazards analysis approach and results based on sUAS mishaps; Section III summarizes the future hazards identification process and results based on sUAS use cases; Section IV presents a preliminary set of current, future, and combined hazards at the vehicle level, which will be used in a preliminary risk assessment[8]; and Section V will present a summary of the results, conclusions, and future work.

II. Current Hazards Identification

In order to assess current hazards, sUAS accidents and incidents (i.e., mishaps) were collected into a database and then analyzed by the team in terms of mishap precursors, precursor sequences, and worst-case precursor combinations and sequences using an analysis approach developed and applied to transport aircraft loss of control mishaps[9, 10, 11]. This section presents the sUAS mishaps analysis results relative to the mishaps set (Sec. II.A), general statistics associated with the mishaps set (Sec. II.B), the mishaps precursor analysis (Sec. II.C), key findings (Sec. II.D), and further work to be done in this area (Sec. II.E).

A. sUAS Mishaps Set

As part of an on-going study, Unmanned Aerial Vehicle (UAV) mishap data have been collected from a variety of sources including government accident reports and media reports. These data were coded into an Access® database previously used in assessing manned aircraft loss-of-control events. This database is described elsewhere (see Refs. [10] and [11]).

Currently, there are 396 military and civilian mishaps entered into this UAV Mishap Database. For this study, only civilian UAVs weighing less than or equal to 55 lbs were considered. At the time we chose to freeze the data set, there were 104 mishaps. We discarded three questionable reports and one suspected duplicate. The remaining 100 reports were analyzed.

The data were classed into incidents and accidents using NTSB criteria.[12] For the UAVs in the study pool, vehicle damage to the UAV itself or ground property damage is not a factor in accident determination.[*] Thus for this study, the criteria for classifying a mishap as an accident are (1) serious injury or fatality to any person or (2) substantial damage to another aircraft. Any mishap that is not an accident is an incident. All of the mishaps classed as accidents included serious injuries or fatalities.

Of the 100 small UAV mishaps in the study group, there were 96 incidents, and 4 accidents (with two involving fatalities). Table 1 breaks down the data by primary cause. Note that "Flight Crew" refers to the Remote Pilot-in-Command, another pilot manipulating controls, and any visual observers designated by the pilot-in-command to see and avoid other air traffic or objects.

Table 1. Small UAS Mishaps Summarized by Primary Cause

Primary Cause	Incidents	Accidents	Fatal Accidents	Total
Flight Controls	15			15
Flight Crew	11	2	1	14
Propulsion	9			9
Lost Link	8			8
Software	6			6
Sensors	2			2
Remote Control	2			2
Wind Shear	2			2
Other	10			10
Undetermined	31		1	32
Total	**96**	**2**	**2**	**100**

[*] The accident criteria for UAVs weighing less than 300 lb does not include UAV damage.[12]

Two characteristics of UAVs are shown in the next two tables. Table 2 shows the configuration of the UAV (multirotor, fixed-wing, etc.) and Table 3 shows the breakdown by weight class.

Table 2 Small UAS Mishaps Summarized by Configuration

UAV Configuration	Incidents	Accidents	Fatal Accidents	Total
Multi-Rotor	33	2		35
Fixed-Wing	33			33
Helicopter	7		2	9
Hybrid	5			5
Thrust Vector	1			1
Not Reported	17			17
Total	**96**	**2**	**2**	**100**

Table 3 Small UAS Mishaps Summarized by Weight Class

UAV Weight Class	Incidents	Accidents	Fatal Accidents	Total
A: W <= 4.4 lb	49	2		51
B: 4.4 < W <= 20 lb	33		2	35
C: 20 < W<=55 lb	14			14
Total	**96**	**2**	**2**	**100**

Table 4 shows the purpose of the mishap flights.

Table 4. Small UAS Mishaps Summarized by Mission

Mission	Incidents	Accidents	Fatal Accidents	Total
Research & Development	34			34
Personal Use	23	2	2	27
Aerial Photography	9			9
Aerial Survey/Observation	6			6
Law Enforcement	6			6
Training	6			6
Illegal Activity	2			2
Other	3			3
Unknown	7			7
Total	**96**	**2**	**2**	**100**

Table 5 shows the outcome of the mishaps. Note that in the two non-fatal accidents, the UAS struck and injured people on the ground after colliding with either terrain or an obstacle on the ground.

Table 5 Small UAS Mishaps Summarized by Outcome

Primary Cause	Incidents	Accidents	Fatal Accidents	Total
Collision with Terrain Collision with Terrain Collision with Water Controlled Flight into Terrain	19	1		20

Collision with Obstacle Building Man-Made Structure Natural Obstacle	18	1		19
Uncontrolled Descent	13			13
Crash in Landing Area Abnormal Runway Contact Crash in Runway Safety Area Failed to Become Airborne Recovery System Failure	13			13
Return to Base Autonomous Commanded	10			10
Flight Termination Autonomous Commanded Intentional Crash in Safe Area	6			6
Collision with Person(s)	3		2	5
Landed without Further Incident	5			5
Airspace Conflict Airspace Conflict Near Midair Collision	3			3
Collision with Ground Vehicle	4			4
Unknown	2			2
Total	**96**	**2**	**2**	**100**

Please see Appendix A for a full listing of the sUAS mishaps set used in the analysis.

B. General Statistics

Some general statistics about the mishaps set are summarized in Figures 3 - 6. Figure 3 shows the severity of the sUAS mishaps in the set relative to the number of mishaps involving: fatalities; injuries to people on the ground; damage to ground infrastructure, objects, or ground vehicles; crashes into public areas; crashes away from a public area; landings with no reported damage; and undetermined.

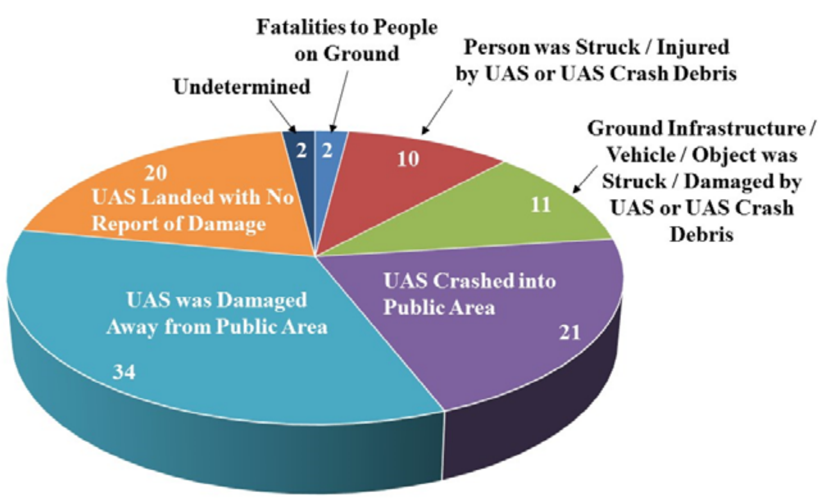


Figure 3. sUAS Mishap Statistics Relative to Severity

Figure 4 depicts the mishap results in terms of the numbers of: intentional groundings; flights that landed successfully; unsuccessful landings (controlled and uncontrolled); unsuccessful launches, liftoffs, or takeoffs; collisions with objects on the ground; mid-air or near-mid-air collisions (MAC/NMAC); and unknown outcomes. Note that "Uncontrolled Descent / Landing" included destabilized approaches and landings.

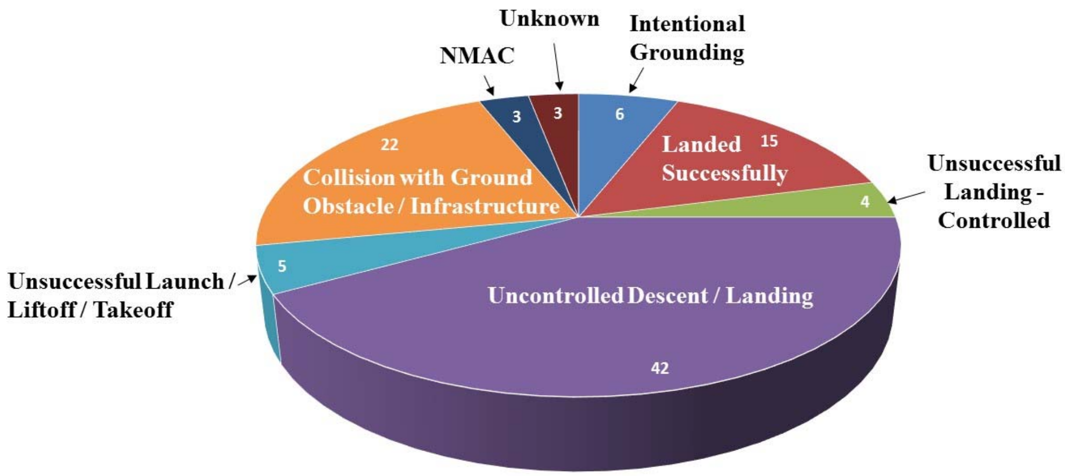


Figure 4. sUAS Mishap Statistics Relative to Result

Figure 5 summarizes the sUAS mishaps by category, including: aircraft loss of control (LOC); lost link; MAC/NMAC; Collision with Surface Terrain; Collisions with Objects or People on the Ground; Abnormal Runway Contact; Loss of Navigation Capability; and Other / Unknown.

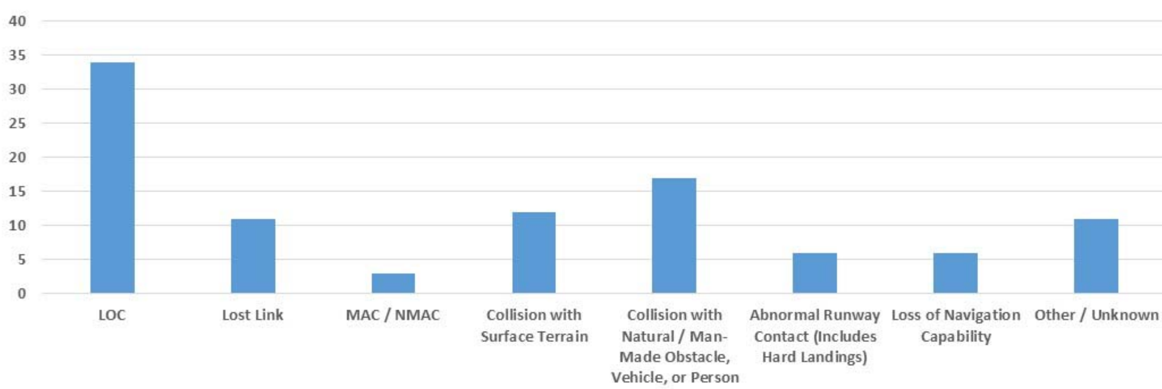


Figure 5. sUAS Mishap Statistics Relative to Mishap Category

Figure 6 summarizes the number of mishaps in terms of causal and contributing factors. It should be noted that aircraft loss of control (LOC) in this paper is defined as motion that is: outside the normal operating flight envelopes; not predictably altered by pilot control inputs; characterized by nonlinear effects, such as kinematic/inertial coupling; disproportionately large responses to small state variable changes, or oscillatory/divergent behavior; likely to result in high angular rates and displacements; and characterized by the inability to maintain heading, altitude, and wings-level flight.[13] LOC also includes situations in which the flight path is outside of acceptable tracking tolerances and cannot be predictably controlled by pilot (or autoflight system) inputs.[14] LOC is therefore fundamentally a dynamics and control problem. It is important to note that LOC need not be unrecoverable, but ***if left unaddressed it may become unrecoverable***. LOC is also a complex problem in that there are many causal and contributing factors that can lead to LOC [15, 16, 17, 18]. The primary causes include: entry into a vehicle upset condition; reduction or loss of control effectiveness; changes to the vehicle dynamic response in relation to handling/flying qualities; and combinations of these causes. There are numerous factors that have led or contributed to LOC. These can be grouped into three major categories: adverse onboard conditions, external hazards and disturbances, and abnormal flight conditions (or vehicle upsets).

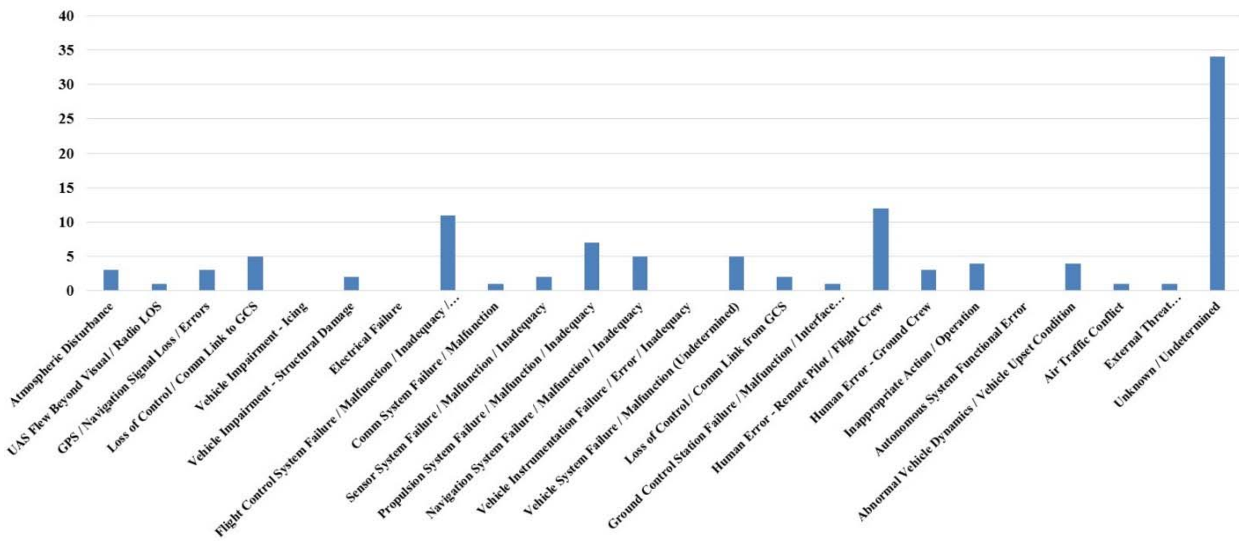


Figure 6. sUAS Mishaps Statistics Relative Causal and Contributing Factors

The next subsection provides a detailed analysis of the sUAS mishap causal and contributing factors (or precursors).

C. Analysis of Mishap Precursors

This section presents a detailed analysis of the sUAS mishap precursors in terms of their individual contributions (Sec. II.C.1), worst-case combinations (Sec. II.C.2), and worst-case sequences (Sec. II.C.3). The precursors used in the analysis are defined in Table 6. The mishap precursors were organized into the following categories: Adverse Aircraft Conditions; Adverse Ground Support Conditions; Environmental Hazards and External Disturbances; and Abnormal Vehicle Dynamics and Flight Conditions. Subcategories for each precursor category are shown in Table 6 as well as the precursors within each subcategory.

An analysis process similar to that described in Ref. [11] was performed for the set of 100 sUAS mishaps summarized in Section II.A and Appendix A. The accident analysis methodology was based on the sequential precursor model, which defines an accident as a series of connected events that ultimately lead to an undesired outcome. If a precursor event can be eliminated by an intervention, the mishap can be prevented. For this study, the methodology was designed to identify dominant precursors for each sUAS mishap and the associated temporal sequencing. In contrast to typical root cause analysis, the precursors were selected by identifying all relevant hazards that sequentially led to the mishap (as opposed to the primary / root cause). This analysis approach facilitates the identification and development of effective mitigation strategies. A team consensus approach was used in reviewing each mishap report and recording the precursor sequences in an analysis spreadsheet with comments added for each precursor from the associated details in the report. A set of flags was also used by the team relative to Lost Link, Fly-Away, LOC, System Failures, Airspace Intrusion / Air Traffic Control (ATC) Impact, Remote Pilot Distraction, and Potential Human-Machine Interface Issues. The flag entry for each mishap was designated “Yes”, “No”, or “Not Enough Information (NEI)”, and a comment from the report was included for positive entries. The flags were used to facilitate sorting the mishaps set in order to compare mishaps involving these flagged conditions. Appendix B provides the spreadsheet entry for Mishap No. 39 as an example. The precursor sequences thus recorded were used to assess individual precursor contributions to the mishap set, and worst-case precursor combinations and sequences. The results of these analyses are presented in the following subsections.

Table 6. sUAS Mishap Precursors by Category and Subcategory

Precursor Categories	Precursor Subcategories	Precursors
Adverse Aircraft Conditions	System & Components Failure/Malfunction	• Flight Control Component Failure / Malfunction • Control System Design / Validation Inadequacy • Control System Operational Error (e.g., response to sensor errors) • System Operational / Software Verification Error • Propulsion System Failure / Malfunction • Navigation System Failure / Malfunction • Sensor / Sensor System Failure / Malfunction • System Failure / Malfunction (Non-Control Component) • System Failure / Malfunction (Undetermined) • Loss of Control / Communication Link
	Vehicle Impairment	• Improper Maintenance / Manufacturing • Airframe Structural Damage
Adverse Ground Support Conditions	Remote Pilot / Flight Crew Error	• Pilot / Flight Crew Decision Error or Poor Judgment • Operation In / Near Restricted Airspace • Loss of Attitude State Awareness / Spatial Disorientation (SD) • Aggressive Maneuver • Abnormal / Inadvertent Control Input • Improper / Ineffective / Unsuccessful Recovery • Inadequate Crew Resource Monitoring / Management • Improper / Incorrect / Inappropriate Procedure /Action
	Ground Control Station (GCS) Failure / Inadequacy	• Lost Communications / Control Link • GCS Power / Electrical System
	Ground Support	• Ground Support Crew Error or Improper / Incorrect Procedure • Ground Recovery System Failure
Environmental Hazards / External Hazards & Disturbances	Adverse Navigational Environment	• Flight Beyond Visual / Radio Line of Sight • Loss of GPS Signal • Erroneous GPS Signal
	Weather & Atmospheric Conditions	• Wind • Wind Shear
	External Threat	• Fixed Obstacle • Another Aircraft in Close Proximity • Conflict with Wildlife (Bird)
Abnormal Vehicle Dynamics & Flight Conditions	Abnormal Vehicle Dynamics	• Uncommanded Motion • Oscillatory Vehicle Response • Abnormal Control for Trim / Flight and/or Control Asymmetry • Abnormal / Counterintuitive Control Response
	Vehicle Upset Conditions	• Abnormal Attitude • Abnormal Airspeed • Undesired Abrupt Dynamic Response • Unsuccessful Launch • Abnormal Flight Trajectory • Uncontrolled Descent • Stall / Departure

1. Individual Precursors

A summary of the number of occurrences of each precursor from Table 6 is provided in Tables 7 – 10 relative to each precursor category. That is, Table 7 summarizes the number of occurrences of Adverse Onboard Conditions, Table 8 summarizes these results for Adverse Ground Support Conditions, Table 9 summarizes the occurrences for Environmental and External Conditions, and Table 10 summarizes the occurrences of Abnormal Vehicle Dynamics and Upset Conditions.

As indicated in Table 7, approximately half of the mishaps (52) involved Adverse Onboard conditions, with nearly all of these (49) resulting from system failures, malfunctions, or design / validation inadequacy. The number of occurrences of the particular system failures within this subcategory was fairly evenly distributed. Vehicle impairment only contributed to 3 of the 52 occurrences in this category.

Table 7. Number of Mishaps Resulting from Precursors under Adverse Onboard Conditions

Adverse Onboard Conditions		Number of Occurrences
Subcategory	**Precursor**	
System Failures / Malfunctions / Inadequacy		**49**
	Flight Control Component Failure / Malfunction	4
	Control System Design / Validation Inadequacy	4
	Control System Operational Error (includes response to erroneous sensor inputs)	4
	System Operational Error (Software Verification Error)	4
	Propulsion System Failure / Malfunction	8
	Navigation System Failure / Malfunction / Impairment	6
	Sensor / Sensor System Failure / Malfunction / Inadequacy	4
	System / Subsystem Failure / Malfunction (Non-Control Component)	3
	System Failure / Malfunction / Error (Undetermined – Includes Intermittent Problems)	6
	Lost Control / Communications Link	6
Vehicle Impairment		**3**
	Improper Maintenance / Manufacturing	1
	Airframe Structural Damage	2
Total		**52**

Table 8. Number of Mishaps Resulting from Precursors Adverse Ground Support Conditions

Adverse Ground Support Conditions		Number of Occurrences
Subcategory	**Precursor**	
Remote Pilot / Flight Crew Error		**25**
	Pilot / Flight Crew Decision Error / Poor Judgment	4
	Operation In / Near Restricted Airspace	9
	Loss of Attitude State Awareness	1
	Aggressive Maneuver	1
	Abnormal / Inadvertent Control Input / Maneuver	1
	Improper / Ineffective / Unsuccessful Recovery	1
	Inadequate Crew Resource Monitoring / Management	1
	Improper / Incorrect / Inappropriate Procedure / Action	7
Ground Control Station Failure / Inadequacy		**5**
	Lost Communications / Control Link from GCS	4
	GCS Power / Electrical System	1
Ground Support		**3**
	Ground Support Crew Error or Improper / Incorrect Procedure	2
	Ground Recovery System Failure	1
Total		**33**

Table 8 indicates that one-third (33) of the mishaps involved adverse conditions at the ground control station (GCS), with 25 of these associated with remote pilot or flight crew errors. Note that "Flight Crew" refers to the Remote Pilot-in-Command, another pilot manipulating controls, and any visual observers designated by the pilot-in-command to see and avoid other air traffic or objects. Only a few mishaps involved GCS system failures (5) and ground support errors (3). Ground support crew included personnel responsible for maintenance and setting up the sUAS prior to flight.

Table 9 indicates that relatively few mishaps (12) were associated with adverse environmental or external conditions. However, it should be noted that very few reports included wind or weather conditions so this statistic could be falsely conservative. Based on the mishap reports, these were fairly evenly distributed between Adverse Navigational Environment (5), Weather & Atmospheric Conditions (3), and External Threat (4).

Table 9. Number of Mishaps Resulting from Precursors under Environmental / External Conditions

Environmental / External Conditions		Number of Occurrences
Subcategory	**Precursor**	
Adverse Navigational Environment		**5**
	Flight Beyond Visual / Radio Line of Sight	2
	Loss of GPS Signal	2
	Erroneous GPS Signal	1
Weather & Atmospheric Conditions		**3**
	Wind	2
	Wind Shear	1
External Threat		**4**
	Fixed Obstacle	2
	Another Aircraft in Close Proximity to sUAS	1
	Conflict with a Bird	1
Total		**12**

As indicated in Table 10, approximately half (52) of the mishaps involved Adverse Vehicle Dynamics and Upset Conditions, with many of these involving Vehicle Upsets (38) and significantly fewer mishaps involving Abnormal Vehicle Dynamics (14). Of the Vehicle Upset precursors, nearly half involved Uncontrolled Descent (16) – which was the largest precursor contribution in this subcategory.

Table 10. Number of Mishaps Resulting from Precursors under Abnormal Vehicle Dynamics and Upsets

Abnormal Vehicle Dynamics / Vehicle Upset Conditions		Number of Occurrences
Subcategory	**Precursor**	
Abnormal Vehicle Dynamics		**14**
	Uncommanded Motions	6
	Oscillatory Vehicle Response	6
	Abnormal Control for Trim / Flight and/or Control Asymmetry	1
	Abnormal / Counterintuitive Control Response	1
Vehicle Upset Condition		**38**
	Abnormal Attitude	2
	Abnormal Airspeed (Includes Low Energy)	1
	Undesired Abrupt Dynamic Response	2
	Unsuccessful Launch of sUAV	5
	Abnormal Flight Trajectory	1
	Uncontrolled Descent	16
	Stall / Departure	1
Total		**52**

Appendix C provides a full listing of individual precursor occurrences and includes precursor outcomes, mishap class, and mishap consequences.

While individual precursor occurrences are interesting to review, it is not an indicator of how these precursors combined or sequenced in time within this set of mishaps. These are considered in the following subsections.

2. *Worst-Case Precursor Combinations*

In order to assess precursor combinations, three dimensional scatter plots were generated using Matlab, as shown in Figure 7, where each dimension represented a separate precursor category. Note that the "Adverse External Conditions" axis includes the two categories "Adverse Ground Support Conditions" and "Environmental / External Conditions". The identification of worst-case combinations was facilitated by sizing the data spheres proportionally to the number of mishaps, and color-coding the spheres by the number of unsuccessful landings (as indicated in the legend). As indicated in Figure 7, the worst-case combination of precursor categories (relative to both number of mishaps and number of unsuccessful landings) involved "None / Unknown" in each dimension. This is an indicator of the lack of information provided in many of the sUAS mishap reports.

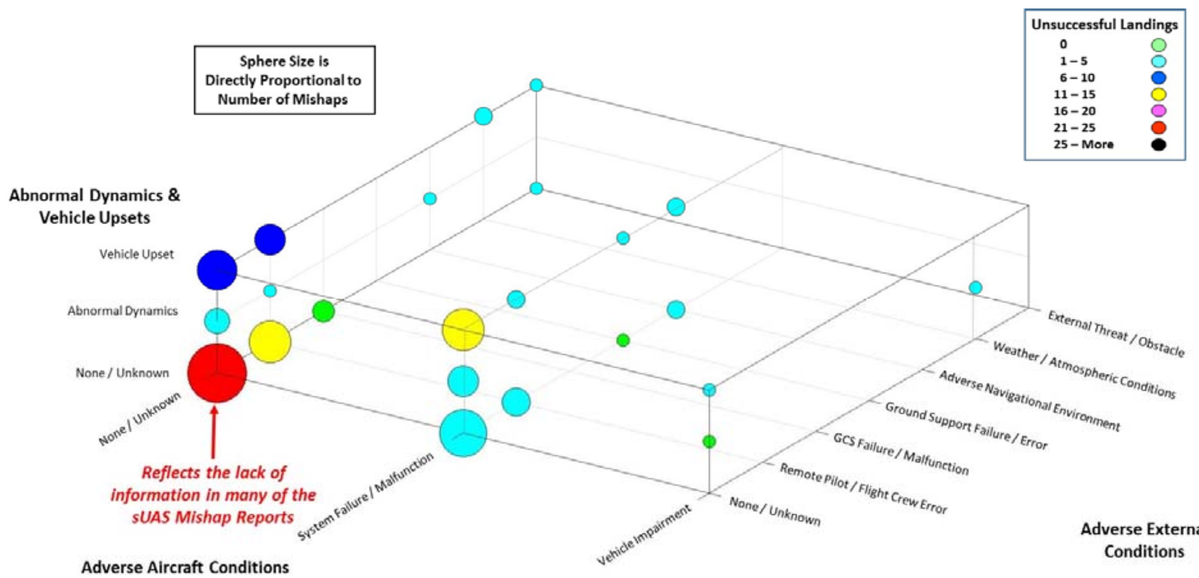
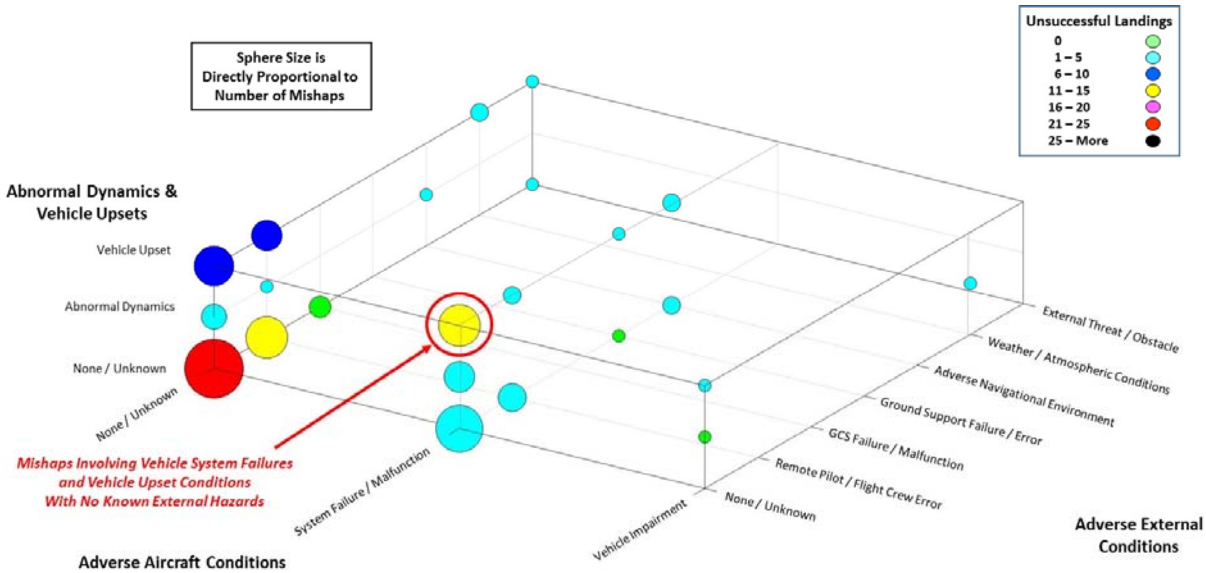


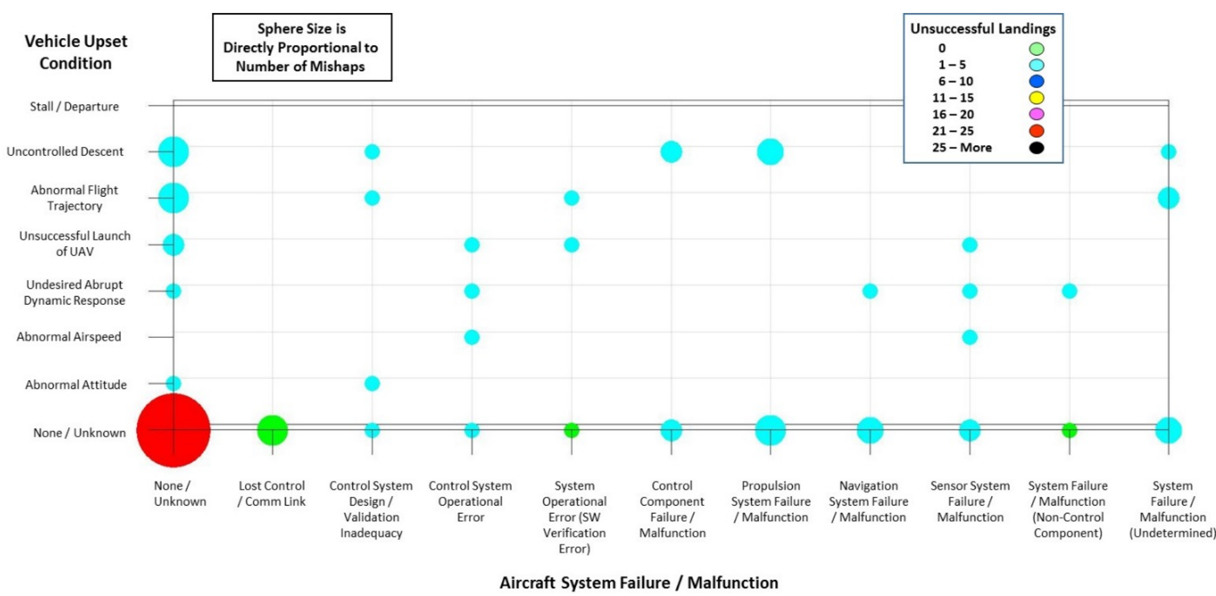
Figure 7. Worst-Case Precursor Category / Subcategory Combinations Associated with sUAS Mishaps Set

Figures 8 and 9 illustrate the utility of this analysis technique in that worst-case precursor combinations at the Category and Subcategory levels can also be assessed at the precursor level. For example, Figure 8 illustrates an analysis of the combination involving Vehicle System Failures and Vehicle Upset Conditions with No Known External Hazards. As illustrated in Figure 8b, this enables an assessment of specific failures relative to resulting upset conditions. Similarly, Figure 9 provides an analysis of the combination involving Remote Pilot Error and Vehicle Upset Conditions with No Known Adverse Aircraft Conditions. Figure 9b enables an analysis of upset conditions resulting from specific actions taken by the remote pilot. It should be noted that Figures 8b and 9b are both two-dimensional scatter plots resulting from the two-dimensional combinations selected in Figures 8a and 9a, respectively. Had an interior three-dimensional combination been selected, the precursor-level scatter plot would have been three-dimensional.

While scatter plots provide a means of visually identifying worst-case precursor combinations in terms of the number of associated mishaps and some user-defined metric (e.g., unsuccessful landings), it does not provide any information about the temporal sequencing of the precursor combinations. This is addressed in the following subsection.

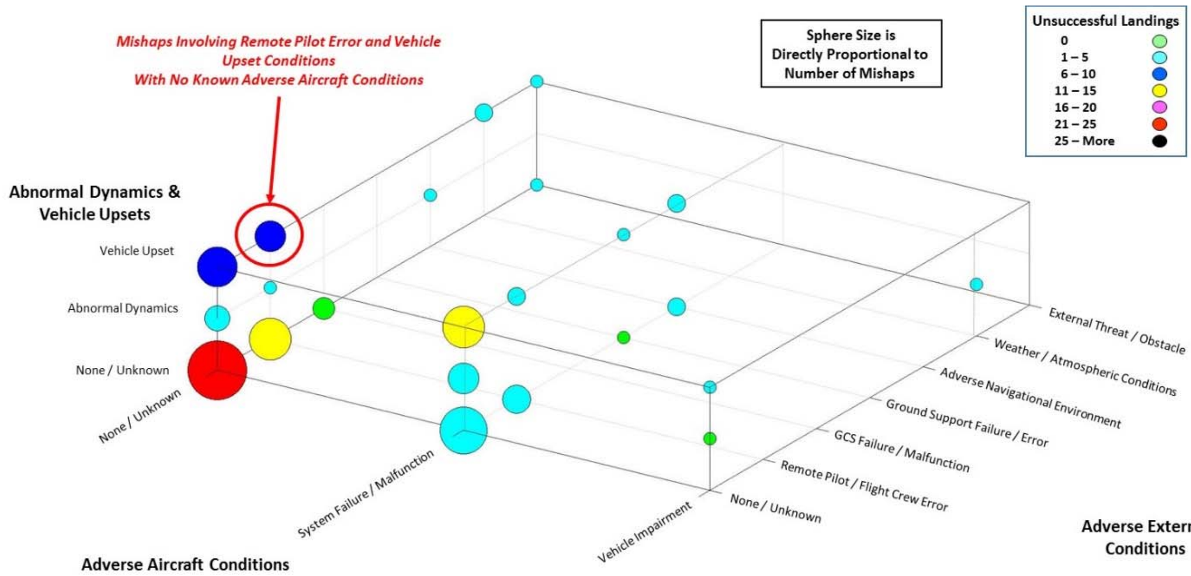


a. Worst-Case Precursors at the Sub-Category Level

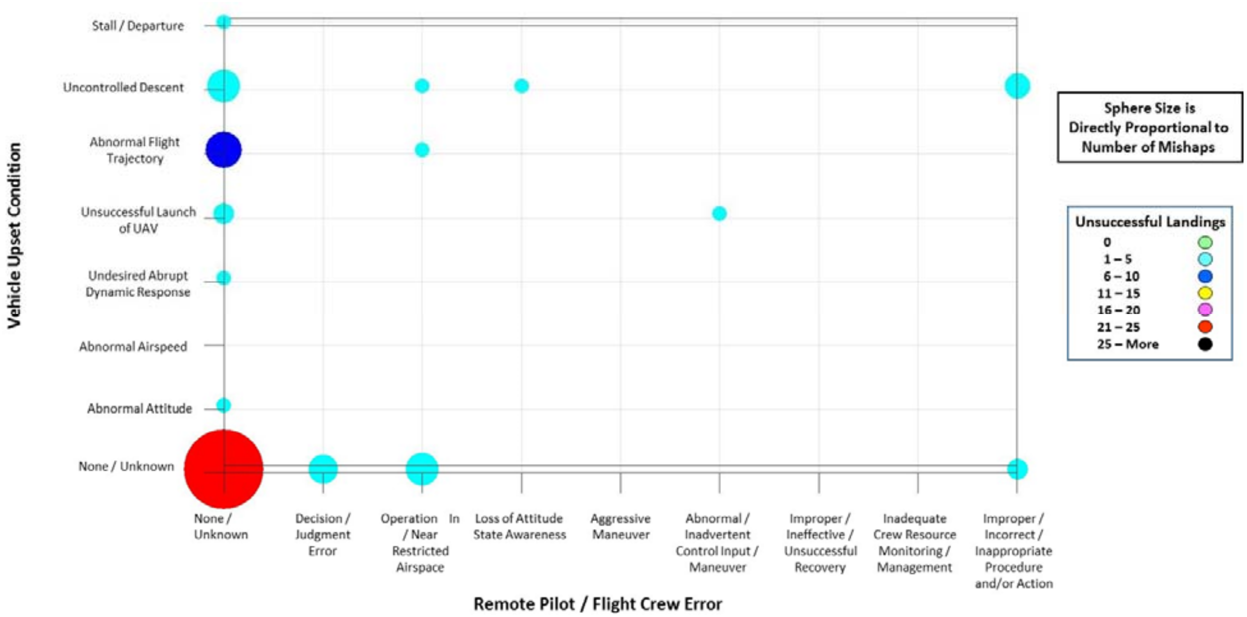


b. Worst-Case Precursor Combinations for the Sub-Category Combination Indicated in (a.)

Figure 8. Worst-Case Precursor Combinations for a Selected Sub-Category Combination



a. Worst-Case Precursors at the Sub-Category Level



b. Worst-Case Precursor Combinations for the Sub-Category Combination Indicated in (a.)

Figure 9. Worst-Case Precursor Combinations for a Selected Sub-Category Combination

3. Worst-Case Precursor Sequences

Worst-case precursor sequences were identified relative to the number of unsuccessful landings and intentional groundings. These sequences were generated for each initiating precursor from the consensus-based precursor analysis. This analysis identified the series of events or actions that comprised the mishap in a temporal order. Some mishaps were described using only one or two events, while some required as many as nine events or actions. Table 6 showed all of the specific precursors that were identified, within categories and subcategories. For each mishap, a data record was created which contained the specific precursors (including category and subcategory identifiers) that were identified for that particular mishap, in the determined temporal order, using a separate variable for each precursor. The data record also included a general indicator of the mishap outcome: intentional grounding, successful landing, unsuccessful landing, and undetermined. Unsuccessful landings included collisions with terrain or obstacle following loss of control, as well as hard landings and collisions with obstacles during the approach for a normal landing. Sixty-two of these unique sequences applied to only one mishap. For sequences that were applied to more than one mishap, the number of mishap outcomes for all mishaps with that particular precursor sequence were summarized. All precursor sequences were sorted and grouped according to the initial precursor. Table 11 defines the acronyms used in generating these sequences.

Table 11. Acronyms Used in sUAS Precursor Sequences

Acronym	Definition
AAOC	Adverse Aircraft Onboard Conditions
ADVUC	Abnormal Dynamics and Vehicle Upset Conditions
AVD	Adverse Vehicle Dynamics
AOBI / GSC	Adverse Off-Board Infrastructure / Ground Support Conditions
ANE	Adverse Navigational Environment
EHEHD	Environmental Hazards / External Hazards & Disturbances
GCS	Ground Control Station
RPFCAI	Remote Pilot / Flight Crew Action or Inaction
SCFMI	System & Component Failure, Malfunction, or Inadequacy
VI	Vehicle Impairment
VUC	Vehicle Upset Condition
WAC	Weather & Atmospheric Conditions

Figure 10 provides example sequences initiated by Onboard System Failures, with a catalogue to the right indicating the total number of sequences each diagram represents as well as which sequences resulted in an unsuccessful landing, intentional grounding, or a successful landing. A full listing of the sequences generated for the sUAS mishaps analyzed in this study is provided in Appendix D. From a review of the sequence diagrams of Appendix D, there were not many common sequences for the mishaps in this set. Another point to note from the sequences of Appendix D is that the lack of detail in many of the reports resulted in some sequences being initiated by atypical precursors. In particular, there are sequences that appear to be initiated by "Abnormal Vehicle Dynamics" and Vehicle Upset Conditions" both of which usually result from some other adverse condition (e.g., onboard system failure, adverse environmental condition, etc.). Similarly, there are some sequences in Appendix D that are initiated by a "Collision", which is typically an outcome of a mishap.

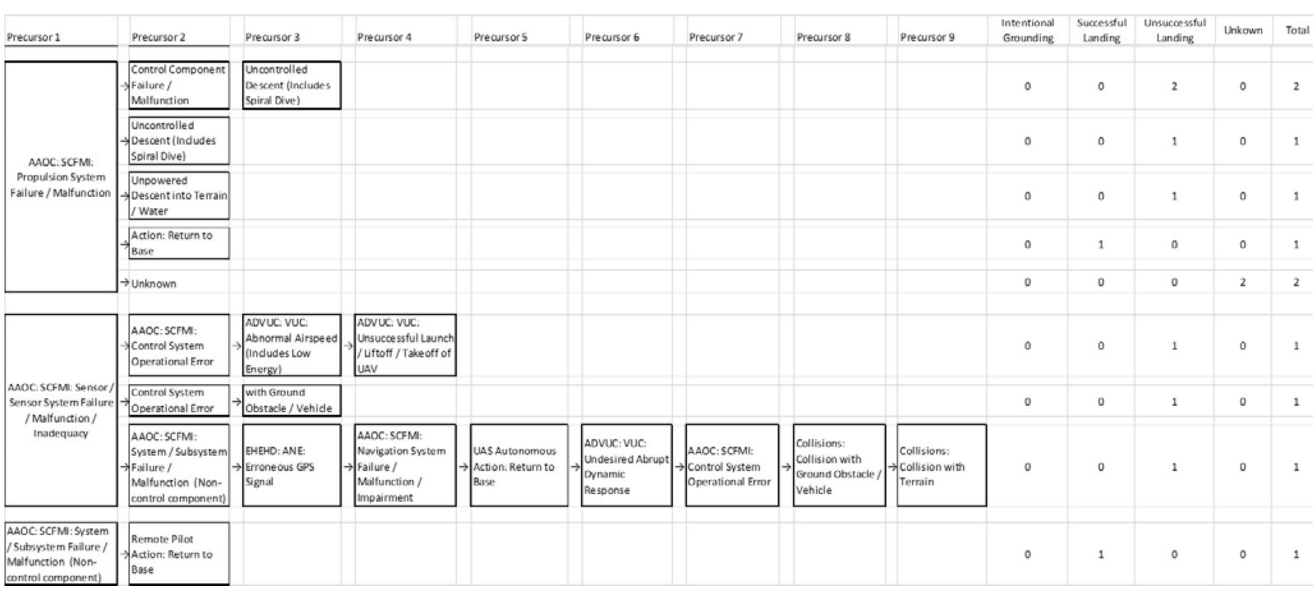


Figure 10. Selected Precursor Sequences Initiated by Onboard System Failures

In general, the poor level of detail provided in many of the sUAS mishap reports made it difficult to obtain useful analysis results. This is discussed further as a key finding in the next section.

D. Key Findings from the Mishaps Analysis

Some key findings from the sUAS mishaps analysis are summarized below.

1. **A lack of detail in sUAS mishaps reporting masks / deters identification of current hazards.**

   There is a general lack of information provided in many sUAS mishap reports that were reviewed for the analysis of this paper. In some cases, we requested and obtained police reports associated with mishaps that occurred in public. In other cases, we utilized information obtained from the FAA related to mishaps that occurred under a Certificate of Authorization (COA) to fly in a particular test site. A few of the reports were obtained from the National Transportation Safety Board (NTSB).

   This lack of detail in sUAS mishap reports makes it difficult to perform meaningful analyses and benefit from these past events for improving the safety of future operations. Significant benefit could be derived from a Standardized Mishaps Reporting System for sUAS, with a standard set of information provided about the mishap and the sequence of events that led up to it.

   The analysis of other mishap reports (e.g., for military UAS, helicopters, and/or general aviation aircraft) may provide a means of filling in gaps and identifying UAS hazards and mitigation strategies that are applicable to commercial sUAS operations.

2. **An increasing prevalence of hobbyist / amateur sUAS operations in the mishaps set of this paper resulted in an increasing incidence of human injury / fatalities and ground infrastructure damage.**

   The first few years of mishaps in the data set analyzed herein predominantly arose from research flights conducted by academia and government agencies under a COA with the FAA. The latter few years of mishap reports predominantly resulted from hobbyist and amateur activities. The mishap reports associated with COAs were generally better than those that were not authorized through any channel of operation. There was a much higher incidence of property damage, personal injury, and even a couple of fatalities in these hobbyist / amateur operations.

   This correlation underscores the need to develop detailed safety requirements and recommendations at all levels of sUAS operation (i.e., vehicle level through operational system level) to reduce known and anticipated risks.

3. **Aircraft loss of control (LOC) is a key hazard / risk for sUAS (as with all other vehicle classes).**

   Aircraft Loss of Control (LOC) occurred for a large proportion of the mishaps analyzed in this study (i.e., in 38 of the 100 mishaps analyzed). Moreover, due to the lack of detailed information in the mishap reports, this estimate could be conservative. This is not surprising in that LOC is a significant contributor to accidents in nearly all (if not all) aircraft and operational classes being flown.

   It is recommended (especially for safety-critical operations that pose a high risk to persons and property) that resilient systems be developed for sUAS that enable LOC prevention / recovery and are effective, implementable and affordable.

4. **Very little is known about multirotor sUAS off-nominal vehicle dynamics & upset phenomena.**

   While significant study has been conducted in analyzing fixed wing aircraft off-nominal vehicle dynamics and upset phenomena[19, 20], very little is known about off-nominal vehicle dynamics and upset phenomena associated with multirotor sUAS. High-fidelity vehicle simulation models for multirotor aircraft are needed to characterize nominal and off-nominal vehicle behavior. From these high-fidelity models, mitigation systems (e.g., for LOC prevention and recovery) can be developed and evaluated. Moreover, low-order models can be derived for trajectory prediction under off-nominal conditions.

For these reasons, vehicle dynamics simulation models are being developed in related research for multirotor sUAS, as well as trajectory prediction models that can be implemented in real-time.[21]

5. **Current hazards identified for manned aircraft do not necessarily translate to UAS.**

Unmanned aircraft have unique attributes that have to be analyzed and identified specifically for UAS operations. Safety assessments performed for sUAS need to account for these attributes (e.g., a lack of sensory information provided to the remote pilot, and an increasing reliance on autonomous systems).

E. Future Research

Future work in this area will focus on filling in gaps from the sUAS mishaps analysis. This will include further mishaps analyses from relevant mishap sets (e.g., military UAS, helicopters, and/or general aviation aircraft). Failure mode effects analyses will also be performed at all levels of operation (e.g., vehicle, operational, and UTM System functional levels).

III. Future Hazards Analysis

The operation of sUAS is an emerging commercial enterprise and may introduce safety risks that cannot be revealed by analyzing current and past mishaps. It is, therefore, important to identify future potential hazards and safety risks associated with this emerging operation. This section summarizes the future hazards analysis process, results, and key findings.

A. Identification of Future Potential Hazards

This section summarizes the process used in identifying future potential hazards (Sec. III.A.1), provides a summary of the use cases and categories used in the analysis (Sec. III.A.2), and presents the results of the analysis (Sec. III.A.3). Key findings of this study are also provided in this section (Sec. III.B), as well as future work (Sec. III.C).

1. Future Hazards Identification Process

In an effort to identify future potential safety hazards, sUAS use cases were collected from NASA industry partners, government agencies, and through a literature review. The process followed for identifying future potential safety hazards is depicted in Figure 11. The collection of sUAS use cases were organized into Use Case Categories from which the team, through a consensus-based brainstorming process, identified paradigm shifts away from current operations involving remotely piloted sUAS within visual line of sight (VLOS). The paradigm shifts involved new operations and new vehicle systems, some of which were cross-cutting over many use case categories. From these paradigm shifts, the team identified (again through a consensus-based brainstorming process) potential hazards and impacts / outcomes of the hazards. Future potential hazards were identified at the vehicle, ground control station / infrastructure, operational, and UTM system functional levels. Potential impacts / outcomes of the hazards were identified relative to the UAS, other UAS, other vehicles (both air and ground), people (in manned aircraft and on the ground), infrastructure and ground assets, and the environment.

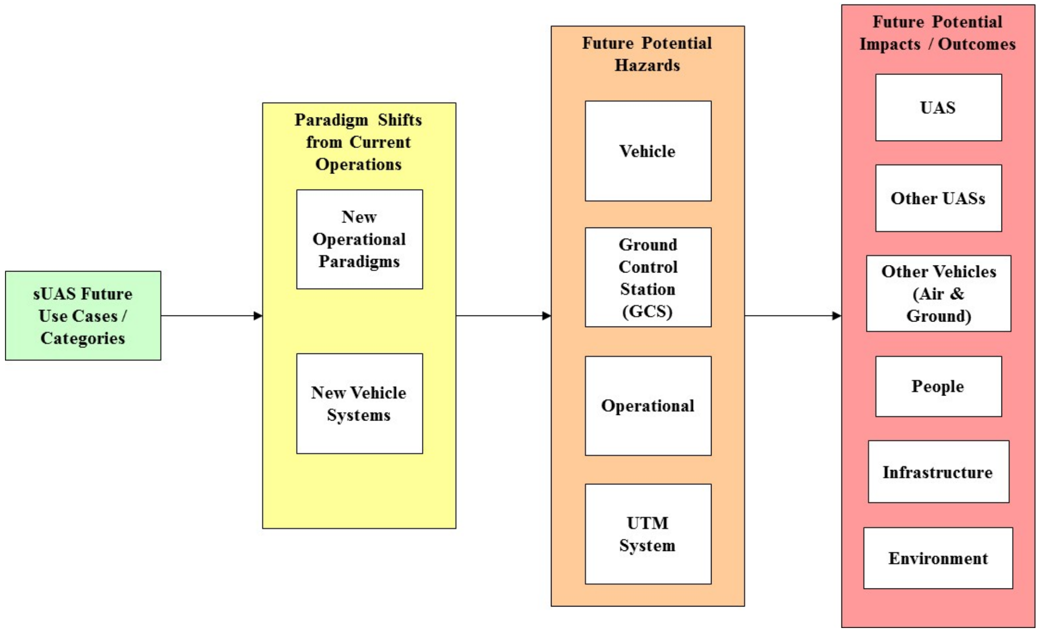


Figure 11. Future Hazards Identification Process

2. Use Case Summary

Future sUAS Use Case descriptions were collected from industry, government agencies, and academia (through a literature review[22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34]). Information requested in the use case descriptions included: Use Case Title; sUAS Business Interest / Use Case Context; Use Case Description; Operational Objectives for use of sUAS in UTM Environment; sUAS Vehicle Types to be Operated (e.g., fixed wing, multirotor, etc.); Number of sUAS to be Operated Simultaneously; Method of sUAS Operation (e.g., from a ground station, multiple ground stations, within or beyond visual line of sight, altitude above ground level, vehicle cruise velocity, etc.); Operational Management Structure; Level of Autonomy to be Employed (at the Vehicle and Operational levels); Safety Hazards / Risks Already Identified; Safety Strategies being Taken for the Planned sUAS Operation (e.g., human factors, training, level of required resilience to system failures, etc.); and Other Relevant Information. More than 100 Use Case descriptions were obtained with varying levels of detail in the above information classes. These use cases were compiled into use case categories for the analysis, and these are summarized in Table 12.

Table 12. Summary of Use Case Categories Used in Future Hazards Identification Process

Use Case Category	Description
Videography at Public Events	Includes Sporting Events, Fireworks Displays, Parades, Festivals, etc.
Security at Public Events & Counter UAS Operations	Monitoring, Detection, & Mitigation of Security Threats & Rogue UAS
Infrastructure Inspection	Critical Infrastructure – Includes Dams, Canals, Railroads, Bridges, Mines, Power Distribution Lines, Oil Pipelines, Onshore Oil and Gas Facilities, Offshore Oil Platforms, and Wind Turbine Blades, etc.
Search & Rescue	Includes Missing Persons, Missing Airplane, Missing Ship, Survivors from a Shipwreck or Aircraft Accident, etc.

Disaster Response	Includes Widespread Events Associated with Landslides, Mudslides, Hurricanes, Floods, Tornadoes, Earthquakes, etc., and Includes Volcano Inspection / Monitoring after Eruption Event, Avalanche Monitoring / Control, Flood Mapping, etc.
Emergency Response	Includes Localized Events such as Aircraft Accidents, Multi-Vehicle Collisions, etc.
Monitoring & Patrol	Includes Border Patrol, Individual / Group / Vehicle Identification and Tracking, Maritime Patrol along Coastal Border Regions, Intelligence, Surveillance, and Reconnaissance of an Area or Building of Interest, etc.
Maritime Surveillance & Security	Includes: Surveillance, Situational Awareness, and Security of Ports, Waterways, and the Coast; Security zone enforcement (e.g., deterring unauthorized vessels from entering a security zone); Airborne patrol of waterfront facilities (marinas, boat launch sites, etc.); Vessel inspection prior to boarding; Facility security inspections; Airborne wide-area surveillance in ports and/or offshore for potential terrorist activity; Drug interdiction
Wildfire Monitoring & Control	Includes Coordinated Multi-Vehicle (Air and Ground) Operations
Law Enforcement	Includes Aerial Photography for Suspect Tracking, Motor Vehicle Accident Response, Crime Scene Investigation, Accident Scene Investigation, Search and Rescue of Missing Persons (Amber Alerts, ...), etc.
Package / Cargo Delivery	Includes Package Delivery to Individual Consumers in Rural / Suburban / Urban Environment, and Delivery of Emergency Medical Supplies in Remote Locations
Imaging / Data Acquisition / Survey of Public / Private Land	Includes Construction Site Inspection, Terrain Mapping, Land Surveys for Future Construction, etc.
Environmental and Wildlife Monitoring & Protection	Includes Wildlife Inventory and Monitoring, Atmosphere / Environment Data Collection and Monitoring, Air and Water Quality/Pollution Monitoring, Climate Change Analysis, Volcano Inspection / Monitoring, Landscape Monitoring, etc.
Precision Agriculture	Includes Crop Dusting, Inspection, Vegetation Inventory and Monitoring, etc.

It should be noted that several potential use cases involved operations inside buildings. These were determined by the team to be beyond the scope of this study and were therefore not included in the analysis presented in this paper.

3. Future Hazards Identification

Paradigm shifts for the above use case categories were identified at the operational and vehicle levels from which future potential hazards and outcomes were identified. Cross-cutting paradigm shifts that were applicable to multiple use case categories were also identified and included: Multiple and Collaborative UAS Operations (i.e., multiple sUAS operated simultaneously by a single operator); Beyond Visual Line of Sight (BVLOS); Increasing Levels of Terrorist Sophistication & Threat; Increasing Use of Autonomous and Semi-Autonomous Operational and Vehicle Systems; Increasing Reliance on Algorithms and Data that are Difficult to Validate; Increasing Reliance on Software without the Ability to Adequately Verify its Correctness; and Proliferation of New sUAS Operators with Relatively Low Levels of Experience. Safety-Critical Operations within High Population Areas was also considered separately as a cross-cutting use case category. Table 13 provides example future hazards identified for Multi-UAS Operations, and Table 14 provides similar results for Monitoring & Patrol. A full listing of several example future potential hazards and their impacts from the use case analysis spreadsheet are provided in Appendix E.

Table 13. Example Future Hazards Identified for Multi-UAS Operations

Future Use Case / Category	Paradigm Shifts from Current Operations		Future Potential Hazards			
	New Operational Paradigms	New Vehicle Systems	Vehicle-Level Hazards	Ground Control Station (GCS) / Infrastructure	Operational	UTM / USS System
All / Many	Multiple UAS Operations			Poor Interfaces / Displays for Multiple Vehicle Operations (Situational Awareness, Safety Monitoring, Surveillance Information Processing, Detection Notification, etc.)		
All / Many	Multiple UAS Operations			Poor Interface for Switching Between Manual and Autonomous UAV Control for Selected UAV (e.g., under Vehicle Impairment) Leading to Unanticipated Mode Changes and/or Transient Control Input Signals		
All / Many	Multiple UAS Operations			Inability / Ineffective Means to Manually Take Control Of UAV with Issues while Continuing to Monitor the Remaining UAS in Operation		
All / Many	Multiple UAS Operations				Poor Management and/or Multi-Sector Coordination of Multiple UAVs	
All / Many	Multiple UAS Operations				Pilot Overload & Loss of Situational Awareness under Multiple UAV Operations	
All / Many	Multiple UAS Operations				Poor Safety Monitoring of Multiple UAVs	
All / Many	Multiple UAS Operations					UTM System Allows Entry into Restricted Airspace
All / Many	Multiple UAS Operations					UTM System Allows Entry into Secured Airspace by Unauthenticated (Rogue) UAS
All / Many	Multiple UAS Operations		Loss of Navigation Capability by One or More UASs			
All / Many	Multiple UAS Operations				GPS Outage During Operation	

All / Many	Multiple UAS Operations					Inadequate / Faulty Multiple UAS Coordination for Cooperative Missions and/or Across Multiple Independent Missions
All / Many	Multiple UAS Operations				Communication Interference Among Multi-UAS Operators (e.g., Electromagnetic Interference and/or Using Same Frequency for Communication)	

Table 14. Example Future Hazards Identified for Monitoring & Patrol

Future Use Case / Category	Paradigm Shifts from Current Operations		Future Potential Hazards			
	New Operational Paradigms	New Vehicle Systems	Vehicle-Level Hazards	Ground Control Station (GCS) / Infrastructure	Operational	UTM / USS System
Monitoring & Patrol (e.g., Border Patrol, Individual / Group / Vehicle Identification and Tracking, Maritime Patrol along Coastal Border Regions, Intelligence, Surveillance, and Reconnaissance of an Area or Building of Interest, etc.)		Use of Weaponized Vehicles	Payload Failure (e.g., Weapons) resulting in CG Shift / Incomplete Release / Vehicle Instability			
		Use of Weaponized Vehicles	Erroneous / Inadvertent Discharge of Weapons			
	Launch and Recovery of UAS from a Moving Vehicle Ground Control Station (GCS)			Lost Link with Mobile GCS		
	Operation under Uncertain Conditions				Weather Conditions (e.g., Fog, Rain, Dust, Snow, etc.) Compromise Sensors Used in Monitoring and Patrol	
	Coordination Across Multiple Municipalities and/or Jurisdictions					Ineffective Coordination by UTM System Among Multiple Operators In the Same Vicinity (DHS, Police, News Media, etc.)

B. Key Findings

Some key findings from the future hazards analysis are summarized below.

1. **Numerous Future Use Cases were Identified and Additional Growth in New Applications is Anticipated**

   A large number of sUAS use cases were identified for this study, which implies a large number of intended operations being planned for sUAS. It is therefore anticipated that additional operations will be planned in the future. The identification of Future Potential Safety Risks and Hazards must therefore be continually updated to incorporate new / emerging use cases.

2. **A Significant Number of Cross-Cutting Paradigm Shifts were Identified that are Applicable Across Numerous Future Use Cases / Applications.**

   Safety inadequacies to reduce risk in cross-cutting application areas could have broad impacts / outcomes. These include the following:

   - Multi-UAS Operations (No Current Guidelines for Safe Operations)
   - Increasing Use of Autonomous & Semi-Autonomous Systems (No Current Guidelines for V&V)
   - Use of sUAS for Low-Altitude / Urban Applications (High Susceptibility to Uncertain Weather & Boundary Layer Wind Effects)
   - Safety-Critical Operations (No Current Guidelines or Requirements for Resilience, Redundancy, etc.)
   - Increasing Levels of Terrorist Sophistication & Threat (sUAS Operations May Be an Easy Target)
   - Proliferation of New UAS Operators with Minimal Experience (No Currently Available Guidelines for Safe Operations)

3. **Paradigm Shifts in Specific Use Case / Application Areas are Also Significant**

   There are numerous opportunities for new ways to introduce old problems (e.g., LOC). One example includes payload shifts / instabilities associated with package delivery, disaster relief, videography, etc.

   There are also numerous opportunities to introduce new problems. Some example include:

   - Crash of Weaponized Vehicles Poses High Risk to Infrastructure / People (e.g., Monitoring & Patrol, Law Enforcement, etc.)
   - Safety-Critical Applications with High Risk of the Unexpected Pose High Risk to People and/or Infrastructure (e.g., Package / Cargo Delivery, etc.)
   - Transport of Toxic Chemicals Poses High Risk to People and the Environment (e.g., Wildfire Monitoring & Control, Agriculture, Aerial Insect Control, etc.)

C. Future Research

Further work in the identification of future hazards includes a functional failure mode effects analysis relative to new systems (vehicle level and operational level – including the UTM system and UTM Service Suppliers). Additional future potential safety hazards may still remain to be identified using different approaches or even using the approach presented in this paper by other teams of analysts.

IV. Preliminary Hazards Sets Defined for Assessing Risk

In order to assess risks associated with sUAS operations, the current and future analysis results presented in Sections II and III had to be distilled down to a combined set of hazards to use in the preliminary risk assessment.

This section summarizes key definitions used in defining the hazards sets, and presents the current, future, and combined hazards sets. The combined hazards set is used for a preliminary risk assessment (see Ref. [8]).

A. Hazards Set Formulation

In order to formulate a combined hazards set to be used in assessing risk, the sUAS mishaps analysis results and the sUAS use case analysis results needed to be distilled down to a current and future hazards set, respectively, from which a combined hazards set could be determined. This required defining the term "hazard" more formally. The following definitions were used in this process.

Hazard – Any real or potential condition that can cause: injury, illness, or death to people; damage to or loss of a system, equipment, or property; or damage to the environment. A hazard is a prerequisite to an accident or incident. For unmanned aircraft weighing less than 300 lbs, damage to the unmanned aircraft itself is not considered.

Accident – An unplanned event or series of events that results in death, injury, or damage to, or loss of, equipment or property.

Incident – An occurrence other than an accident that affects or could affect the safety of operations.

Cause – One or several mechanisms that trigger the hazard that may result in an accident or incident; the origin of a hazard.

Furthermore, it was determined that the preliminary risk assessment would focus on the vehicle level in terms of hazards and risk/safety impacts. Thus, the preliminary hazards sets developed herein are focused at the vehicle level. Figure 12 depicts the problem subspace that was the focus of this effort.

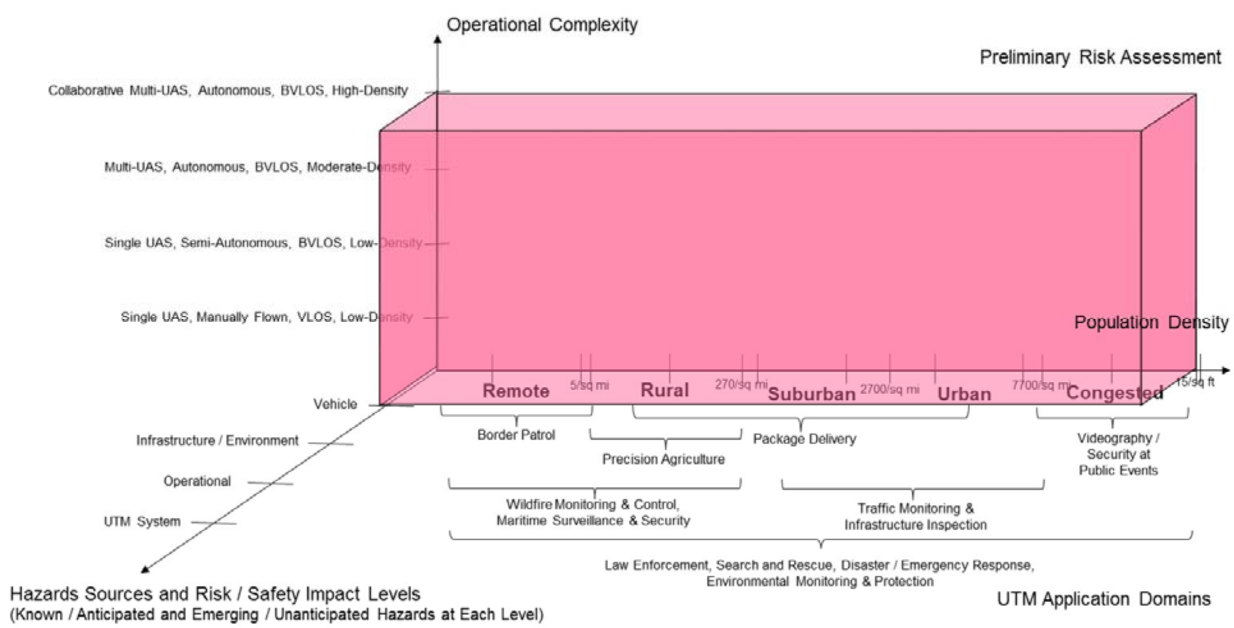


Figure 12. Problem Subspace Utilized in Defining the Hazards Set to be Used in the Preliminary Risk Assessment

The following subsections present the results of this work.

B. Current Hazards Set

The current hazards set defined using the definitions and problem subspace of Section IV.A are shown in Table 15. A full set of tables, including causal and contributing factors, operational state, result, impacts, and hazardous outcomes are provided in Appendix F (see Tables F.1-a and F.1-b).

Table 15. Current Hazards Set Based on the Mishaps Analysis

Category	Hazard
Single UAS Manually Controlled by Remote Pilot under VLOS Operations	Aircraft Loss of Control (LOC)
	Aircraft Fly-Away / Geofence Non-Conformance
	Lost Communication / Control Link
	Loss of Navigation Capability
	Failure / Inability to Avoid Collision with Terrain and/or Fixed / Moving Obstacles
	Unsuccessful Landing

C. Future Hazards Set

The future hazards set defined using the definitions and problem subspace of Section IV.A are shown below in Table 16. A full set of tables, including causal and contributing factors, operational state, result, impacts, and hazardous outcomes are provided in Appendix F (see Tables F.2-a – F.2-d).

Table 16. Future Hazards Set Based on the Use Case Analysis

Category	Hazard
Single UAS Manually Controlled Semi-Autonomously under BVLOS Operations	Aircraft Loss of Control (LOC)
	Aircraft Fly-Away / Geofence Non-Conformance
	Lost Communication / Control Link
	Loss of Navigation Capability
	Failure / Inability to Avoid Collision with Terrain and/or Fixed / Moving Obstacles
	Unintentional / Unsuccessful Flight Termination
	Hostile Remote Takeover and Control of UAS
	Rogue / Noncompliant UAS
	Rogue / Noncompliant UAS (Weaponized)
	Hostile Ground-Based Attack of UAS (e.g., Using High-Powered Rifle, UAS Counter Measure Devices, etc.)
	Unintentional / Erroneous Discharge of Weapons, Explosives, Chemicals, etc.
	Erroneous Autonomous Decisions / Actions by UAS Compromise Vehicle / Operational Safety
Multi-UAS & Collaborative UAS Controlled Autonomously under BVLOS Operations	Cascading Failures in Multi-UAS and Collaborative Missions

D. Combined Hazards Set

A combined hazards set for use in a preliminary risk assessment at the vehicle level was developed by combining the current and future hazards sets presented in Sections IV.B and IV.C. Table 17 summarizes this combined hazards set. A full set of combined hazards tables, including use case / category, operational state, causal / contributing factors, result, impacts, and hazardous outcomes are provided in Appendix F (see Tables F.3-a – F.3-i). The "Use Case / Category" column in these tables corresponds to the "Population Density / sUAS Application Domain" dimension of Figure 12, and the "Operational State" column corresponds to the "Operational Complexity" dimension of Figure 12.

Table 17. Combined Hazards Set Used in a Preliminary Risk Assessment (Ref. [8])

Hazard No.	Hazard
VH-1	Aircraft Loss of Control (LOC)
VH-2	Aircraft Fly-Away / Geofence Non-Conformance
VH-3	Lost Communication / Control Link
VH-4	Loss of Navigation Capability
VH-5	Unsuccessful Landing
VH-6	Unintentional / Unsuccessful Flight Termination
VH-7	Failure / Inability to Avoid Collision with Terrain and/or Fixed / Moving Obstacles
VH-8	Hostile Remote Takeover and Control of UAS
VH-9	Rogue / Noncompliant UAS
VH-10	Rogue / Noncompliant UAS (Weaponized)
VH-11	Hostile Ground-Based Attack of UAS (e.g., Using High-Powered Rifle, UAS Counter Measure Devices, etc.)
VH-12	Unintentional / Erroneous Discharge of Weapons, Explosives, Chemicals, etc.
VH-13	Erroneous Autonomous Decisions / Actions by UAS Compromise Vehicle / Operational Safety
VH-14	Cascading Failures in Multi-UAS and Collaborative Missions

It should be noted that the preliminary risk assessment of Ref. [8] focuses on VH-1 through VH-7.

V. Conclusion

This paper has presented results from a hazard analysis for sUAS operations within the UTM system. Current hazards were identified through an analysis of sUAS mishaps, which included an assessment of precursor sequences for each mishap, individual mishap precursors, worst-case precursor combinations, and worst-case sequences. Future hazards were identified by analyzing sUAS use cases collected from industry, government agencies, and academia in terms of paradigm shifts identified at the operational and vehicle system levels. Future hazards were identified relative the vehicle, ground control station and associated infrastructure, operational considerations, and the UTM system. Key findings from these studies were also presented. One such finding relative to current hazards identification is that significant value could be derived from improved sUAS mishap reporting in terms of level of detail and information provided. The results from these analyses were distilled down into an actionable set of current and future hazards, from which a combined set of hazards was obtained at the vehicle level. This combined hazards set is used in a preliminary risk assessment. Future work will include the development of a full set of combined hazards at all levels defined in the problem space.

Appendix A: sUAS Mishaps Set

No	Date	Aircraft	Arr	Cl	Oper	Mission	Location	Dam	A/I	Phase	Outcome	Occurrence	FA	LC	LL	AT
1	9/30/2010	Wasp-III	FW	A	NMSU	Research & Development	Las Cruces NM	U	I	Unknown	Unknown	Flight Controls		LC		
2	12/14/2010	ADS-Orbiter	FW	C	Mexico	Law Enforcement	El Paso TX	U	I	Unknown	Parachute Deployed	Loss-of-Control	FA	LC		AT
3	4/6/2011	Airstar	FW	C	NASA	Research & Development	Aberdeen Airfield	S	I	Landing	Abnormal Rwy Contact	Atmospheric Disturbance		LC		
4	5/6/2011	QZ-2	H	B	NASA	Research & Development	Crows Landing	N	I	Enroute	Return to Base	Lost Link			LL	
5	5/8/2011	QZ-2	H	B	NASA	Research & Development	Crows Landing	S	U	Landing	Abnormal Rwy Contact	Software		LC		
6	7/6/2011	RQ-16	VT	B	MDPD	Training	Everglades FL	U	i	Landing	Flight Termination	GPS Stabilization		LC		
7	7/13/2011	Aeryon-Scout	MR	A	UAA	Research & Development	Gulf of Alaska	N	I	Unknown	Return to Base	Remote Control Fault			LL	
8	7/20/2011	NexSTAR	FW	B	UofCo	Research & Development	Table Mountain	S	I	Initial climb	Crash on Runway	Pilot Lost of Control		LC		
9	7/22/2011	QZ-2	H	B	NASA	Research & Development	Moffett Field	S	U	Hover	Uncontrolled Descent	Software		LC		
10	8/18/2011	Maveric	FW	A	DOE	Public Use	Gallaher Bend TN	N	I	Unknown	Flight Termination	Navigation				
11	9/23/2011	Shadow-Hawk	RW	C	Vanguar	Demonstration	Houston TX	U	U	Unknown	Collision w/Vehicle	Unknown				
12	10/13/2011	Textron-Mk 4.7	FW	C	KSU	Research & Development	Lindsborg KS	S	I	Takeoff	Failed to Takeoff	Blocked Static Port		LC		
13	11/8/2011	RQ-11B	FW	A	DOI	Aerial Survey	81W8 X 38N10	N	I	Unknown	Return to Base	Power Loss				
14	12/11/2011	Dragen-fly-X-6	MR	A	SPD	Law Enforcement	Seattle WA	N	I	Takeoff	Failed to Takeoff	Software		LC		
15	1/6/2012	Dragan-fly-X-4	MR	B	TxSU	Research & Development	Texas St Univ	S	I	Unknown	Landed w/o Incident	Maintenance				
16	1/13/2012	Aeryon-Scout	MR	A	UofAK	Research & Development	Nome AK	N	I	Initial climb	Landed w/o Incident	Sensors		LC		
17	1/18/2012	QZ-2	H	B	NASA	Research & Development	Moffett Field	S	U	Landing	Abnormal Rwy Contact	Unknown		LC		
18	2/13/2012	Desert-Hawk	FW	B	LMCO	Research & Development	Oswego NY	N	I	Enroute	Return to Base	Lost Link			LL	
19	3/19/2012	Maveric	FW	A	MTSU	Research & Development	35N11 X 88W00	S	I	Unknown	Return to Base	Lost Link			LL	
20	4/18/2012	Cutlass	FW	B	NMIMT	Research & Development	Socorro NM	D	I	Enroute	Flight Termination	GPS Stabilization				
21	4/30/2012	Maveric	FW	A	MTSU	Research & Development	35N17 X 88W01	S	I	Initial climb	Return to Base	Flt Control Actuator				
22	6/19/2012	RQ-11B	FW	A	DOI	Aerial Survey	Port Angeles WA	U	I	Enroute	Collision w/Obstacle	Collision w/Person				AT
23	8/22/2012	Shadow-Hawk	RW	C	MCSD	Law Enforce	Lake Conroe	S	I	Initial climb	Flight Termination	Deviation fr Procedures				

No	Date	Aircraft	Arr	Cl	Oper	Mission	Location	Dam	A/I	Phase	Outcome	Occurrence	FA	LC	LL	AT
24	8/24/2012	CropCam	FW	B	UofND	Research & Development	11 NM SW CKN	S	I	Takeoff	Failed to Takeoff	Unknown				
25	9/25/2012	QZ-2	H	B	NASA	Research & Development	Moffett Field	U	U	Maneuvering	Uncontrolled Descent	Aircraft Oscillations		LC		
26	9/26/2012	BAT-3	FW	C	NMSU	Research & Development	Jomada	S	I	Initial climb	Abnormal Rwy Contact	Unknown				
27	9/28/2012	CropCam	FW	B	KSU	Research & Development	SW St Thomas	S	I	Initial climb	Collision w/Terrain	Uncommanded Bank		LC		
28	10/3/2012	Penguin-B	FW	C	KSU	Research & Development		U	I	Approach	Abnormal Rwy Contact	Software		LC		
29	3/14/2013	Smart-Sonde	FW	B	UofOK	Research & Development	34N58 X 97W31	N	I	Unknown	Landed w/o Incident	Flt Control System				
30	4/24/2013	Smart-Sonde	FW	B	UofOK	Research & Development	IRW VOR 165 rad	S	I	Unknown	Return to Base	Software			LL	
31	5/7/2013	NOVA-III	FW	B	MTSU	Research & Development	ISR Group Range	N	I	Climb	Return to Base	Remote Control Fault			LL	
32	5/22/2013	Draganfly-X-4	MR	B	DBPD	Law Enforcement	29N10 X 81W40	U	I	Unknown	Uncontrolled Descent	Blade Separation		LC		
33	5/29/2013	Shadow-Hawk	RW	C	MTSU	Research & Development	Savannah TN	S	I	Unknown	Landed w/o Incident	Autopilot		LC		
34	6/21/2013	Procerus	MR	A	NASA	Research & Development	43N19 X 106W14	U	I	Unknown	Uncontrolled Descent	Propulsion Failure		LC		
35	7/11/2013	Gaui-F-X7	RW	B		Personal Use	Luzern SR	U	A	Unknown	Collision w/Person	Unknown				
36	7/12/2013	Scan-Eagle	FW	C	UofAK	Research & Development	Poker Flat	M	I	Landing	Recovery System Fail	Collision w/Obstacle				
37	7/31/2013	SR-30	RW	C	NLRPD	Law Enforcement	N Little Rock, AR	S	I	Initial climb	Crash on Runway	LTRE		LC		
38	8/16/2013	Ultra-Stick	FW	A	NASA	Training	Smithfield VA	S	I	Landing	Collision w/Terrain	Misjudged Flight Path		LC		
39	8/24/2013	DJI-Phantom	MR	A	Hansen	Photography	Dinwiddie VA	U	I	Maneuvering	Uncontrolled Descent	Propulsion Failure		LC		
40	8/26/2013	Scan-Eagle	FW	C	Unkn	Unknown	Watts Bridge ON	U	U	Unknown	Unknown	Propulsion Failure				
41	9/3/2013	T-Rex-700L	RW	B	NASA	Test & Evaluation	JSC NASA	S	I	Maneuvering	Uncontrolled Descent	Uncommanded Pitch		LC		
42	9/4/2013	T-Rex-700N	RW	B		Personal Use	New York NY	S	A	Maneuvering	Collision w/Person	Pilot Lost Control		LC		
43	9/13/2013	Scan-Eagle	FW	C	Conoco	Aerial Survey	Chuchki Sea	S	I	Unknown	Ditching	Propulsion Failure				
44	9/15/2013	RQ-20A	FW	B	NOAA	Research & Development	Lignum-vitae Key	S	I	Unknown	Uncontrolled Descent	Flt Control System		LC		
45	11/5/2013	Vireo	FW	A	NCSU	Research & Development	Moycock NC	S	I	Initial climb	Collision w/Building	Wind Shear		LC		
46	11/18/2013	RQ-20A	FW	B	NOAA	Law Enforcement	San Miguel Isl	D	I	Maneuvering	CFIT	Unknown				
47	2/27/2014	QAV500	MR	A	NASA	Research & Development	JSC NASA	S	I	Maneuvering	Collision w/Obstacle	Software				

No	Date	Aircraft	Arr	Cl	Oper	Mission	Location	Dam	A/I	Phase	Outcome	Occurrence	FA	LC	LL	AT
48	4/12/2014	Avenger	RW	B	APD	Training	Lake Arlington	D	I	Maneu-vering	Collision w/Terrain	Flt Control System		LC		
49	4/21/2014	Unknown	U	A	Unkn	Illegal Activity	Bishop-ville SC	S	U	Unknown	Collision w/Terrain	Unknown				
50	4/25/2014	Shadow-Hawk	RW	C	MCSher	Training	Lake Conroe	S	I	Unknown	Uncontrolled Descent	Blade Separation		LC		
51	5/5/2014	DJI-Phantom	MR	A		Personal Use	St Louis MO	S	U	Unknown	Collision w/Building	Unknown	??			
52	5/22/2014	KSU-CROW	FW	A	KSU	Research & Development	6.5 SW KSLN	S	I	Aborted landing	Crash in Rwy Safety Area	Misjudged Flight Path				
53	6/8/2014	RQ-20A	FW	B	NOAA	Aerial Survey		M	I	Unknown	Collision w/Terrain	Unknown				
54	6/10/2014	DJI-Phantom	MR	A		Personal Use	Arlington TX	S	U	Unknown	Collision w/Building	Unknown				
55	6/10/2014	MD-4-1000	MR	B	NOAA	Aerial Survey		N	I	Maneu-vering	Return to Base	Lost Link			LL	
56	6/19/2014	RQ-20A	FW	B	NOAA	Aerial Survey		N	I	Initial climb	Return to Base	Lost Link			LL	
57	7/3/2014	KSU-Zephyr	FW	B	KSU	Research & Development		M	I	Initial climb	Uncontrolled Descent	EMI				
58	7/4/2014	Unknown	MR	B		Photography	Key West FL	U	I	Unknown	Collision w/Person	Unknown				
59	7/7/2014	Dragan-fly-X-4	MR	B	ILSP	Training		M	I	Maneu-vering	Crash on Runway	Uncommanded Pitch		LC		
60	7/14/2014	Penguin-B	FW	C	KSU	Research & Development		S	I	Initial climb	Collision w/Terrain	Flt Control System		LC		
61	7/18/2014	DJI-Phantom	MR	A		Photography	Yellow-stone WY	U	U	Maneu-vering	Collision w/Terrain	Power Loss				
62	7/30/2014	Lancas-ter-III	FW	B	NCSU	Research & Development		N	I	Unknown	Landed w/o Incident	Lost Link			LL	
63	8/2/2014	Unknown	U	A		Personal Use	Yellow-stone WY	U	I	Unknown	Collision w/Terrain	Unknown				
64	8/5/2014	AR-100	MR	A	GTRI	Research & Development		S	I	Unknown	Uncontrolled Descent	Propulsion Failure		LC		
65	8/21/2014	Dragan-fly-X-4	MR	B	ILSP	Training	Pawnee	S	I	Hover OGE	Uncontrolled Descent	Autopilot		LC		
66	10/7/2014	Unknown	FW	A		Personal Use	W Dallas. TX	U	U	Unknown	Collision w/Terrain	Unknown				
67	10/8/2014	Unknown	MR	A		Personal Use	Cambridge MA	U	I	Unknown	Uncontrolled Descent	Birdstrike		LC		
68	11/15/2014	Unknown	U	A		Personal Use	Tusca-loosa AL	U	I	Unknown	Collision w/Person	Unknown		LC		
69	12/17/2014	DJI-Phantom	MR	A	Unkn	Unknown	Van Nuys CA	U	U	Unknown	Collision w/Terrain	Unknown				
70	4/7/2015	Unknown	MR	B		Photography	Australia	U	U	Maneu-vering	Uncontrolled Descent	Collision w/Person		LC		
71	5/9/2015	HL-48	MR	B	Unkn	Unknown	Los Angeles	U	U	Unknown	Collision w/Structure	Flight Controls				

No	Date	Aircraft	Arr	Cl	Oper	Mission	Location	Dam	A/I	Phase	Outcome	Occurrence	FA	LC	LL	AT
72	5/25/2015	Unknown	U	A		Photography	Marble-head MA	S	I	Unknown	Collision w/Building	Collision w/Person		LC		
73	6/6/2015	Unknown	MR	A		Personal Use	Tampa FL	U	I	Unknown	Collision w/Vehicle	Unknown				
74	6/6/2015	DJI-Phantom	MR	A		Personal Use	Folsom Lake CA	U	I	Unknown	Collision w/Terrain	Unknown	??			
75	6/28/2015	Unknown	MR	A		Personal Use	Seattle WA	S	A	Unknown	Collision w/Building	Pilot Lost Control		LC		
76	7/24/2015	Phoenix 60	MR	B	Unkn	Unknown	Deer Lakes PA	S	U	Initial climb	Collision w/Obstacle	Unknown		LC		
77	8/2/2015	Unknown	U	A		Personal Use	Glens Falls NY	U	I	Unknown	Collision w/Terrain	Unknown				
78	8/2/2015	Unknown	U	A		Personal Use	Cincin-nati OH	U	I	Unknown	Collision w/Building	Unknown				
79	8/2/2015	Unknown	MR	A	Unkn	Unknown	Vancouver BC	N	I	Unknown	Airspace Conflict	NMAC				AT
80	8/22/2015	Unknown	U	A		Personal Use	Lexington KY	U	I	Unknown	Collision w/Building	Unknown				
81	9/4/2015	Unknown	U	A		Personal Use	Queens NY	U	I	Unknown	Collision w/Building	Unknown				
82	9/5/2015	Unknown	U	A		Personal Use	Lexington KY	U	I	Unknown	Collision w/Building	Unknown				
83	9/12/2015	DJI-Inspire	MR	B		Personal Use	Pasadena CA	U	I	Maneu-vering	Collision w/Terrain	Lost Link		LC	LL	
84	9/17/2015	DJI-Phantom	MR	A		Personal Use	Linden NJ	U	I	Unknown	Collision w/Building	Unknown				
85	9/17/2015	DJI-Phantom	MR	A		Personal Use	Albany NY	U	I	Unknown	Collision w/Building	Reckless Operation				
86	9/30/2015	Unknown	MR	A	Unkn	Unknown	London Heathrow	N	I	Unknown	Near Midair Collision	Airspace Conflict	??			AT
87	10/2/2015	Unknown	U	A	Unkn	Unknown	Manches-ter UK	N	I	Unknown	Near Midair Collision	Airspace Conflict	??			AT
88	10/6/2015	Unknown	U	A		Photography	Sag Harbor NY	S	I	Unknown	Collision w/Person	Blade/Person Accident				
89	10/7/2015	Unknown	U	A		Photography	Sunnyvale CA	U	I	Maneu-vering	Collision w/Terrain	Unknown				
90	10/9/2015	JJRC-F182-6	MR	A		Personal Use	Washing-ton DC	U	I	Unknown	Collision w/Terrain	Unknown				
91	10/10/2015	Unknown	MR	A		Personal Use	Port St Lucie FL	U	I	Unknown	Collision w/Building	Pilot Lost Control		LC		
92	10/11/2015	CX-20	MR	B		Personal Use	Batten Intl AP	U	I	Unknown	Collision w/Terrain	Pilot Lost Control		LC		
93	10/26/2015	Unknown	U	A		Personal Use	Waxahat-chie TX	U	I	Unknown	Collision w/Terrain	Unknown				
94	10/26/2015	Unknown	U	A	Unkn	Illegal Activity	McAlester OK	U	I	Unknown	Collision w/Terrain	Unknown				
95	10/26/2015	Unknown	U	A		Personal Use	West Hollywood	U	I	Unknown	Collision w/Structure	Unknown				

No	Date	Aircraft	Arr	Cl	Oper	Mission	Location	Dam	A/I	Phase	Outcome	Occurrence	FA	LC	LL	AT
96	11/11/2015	DJI-Phantom	MR	A		Photography	Seattle WA	M	I	Maneu-vering	Collision w/Obstacle	Lost Link			LL	
97	11/18/2015	Unknown	U	A		Personal Use	Linden NJ	U	I	Unknown	Collision w/Vehicle	Unknown				
98	11/26/2015	DJI-Phantom	MR	A		Photography	Andover MA	M	I	Maneu-vering	Collision w/Obstacle	Misjudged Clearance				
99	11/26/2015	Unknown	MR	A		Personal Use	Stourport -on-Sever	U	A	Maneu-vering	Collision w/Terrain	Pilot Lost Control		LC		
100	12/28/2015	Drone	U	A		Personal Use	Belle-ville ON	S	U	Unknown	Collision w/Vehicle	Unknown				

Key to Listing
Arrangement: FW: Fixed-Wing; RW: Rotary Wing; MR; Multirotor; H: Hybrid; VT: Vectored Thrust; U: Unknown
Weight Class: A: $W \leq 4.4$ lb; B: $4.4 < W \leq 20$ lb; C: $20 < W \leq 55$ lb
Damage: N: None; M: Minor; S: Substantial; D: Destroyed; U: Unknown
Severity A/I I: Incident; A: Accident; U: Unknown Severity
Other Flags: FA: Flyaway; ??: Possible Flyaway; LC: Loss-of-control; LL: Lost Link; AT Airspace or Air Traffic Issue

Appendix B. Precursor Sequence Analysis for Mishap 39 from the Mishaps Analysis Spreadsheet

Precursor Sequence Identification:

Mishap Basics				Mishap Details									
Accident No.	Date	Aircraft	Vehicle Class	Weight Class - MTOW (lbs)	Speed Class - Vmax (kts/mph)	Location	Phase of Flight	Mission	Operator	UAV Crashed into Public Area	Ground Infrastructure / Vehicle / Object was Struck / Damaged by UAV or sUAV Crash Debris	Person was Struck / Injured by sUAV or sUAV Crash Debris	Fatalities
39	8/24/2013	DJI-Phantom	Multi-Rotor (4)	3	22	Dinwiddie, VA	Maneuvering	Filming of Event	Hansen	1	0	5	0

Adverse Off-Board Infrastructure / Ground Support Conditions																			
	Ground Support		Ground Control Station					Remote Pilot / Flight Crew Action / Inaction											
None / Unknown	Ground Support Crew Error or Improper / Incorrect Procedure	Ground Recovery System Failure	Lost Communications / Control Link from GCS	GCS Power / Electrical System	System Operational Error / Inadequacy (Unexpected Design Characteristic / Validation Inadequacy / Response to Erroneous Sensor Input)	Ground Control Station (GCS) Inadequacy in Providing Sensory Input and Aural Cueing to Remote Crew	Ground Control Station (GCS) Instrumentation Failure / Malfunction / Inadequacy (Includes Lack of Notification, False Warnings, Interface Issues, and Conflicting Information)	Poor Operational / Test Planning	Pilot / Crew Decision-Making Error / Poor Judgement	Operation In / Near Restricted Airspace	Loss of Attitude State Awareness / Spatial Disorientation	Loss of Energy State Awareness / Inadequate Energy Management	Lack of Aircraft / System State Awareness / Mode Confusion	Aggressive Maneuver	Abnormal / Inadvertent Control Input / Maneuver	Improper / Ineffective / Unsuccessful Recovery	Inadequate Crew Resource Monitoring / Management (PF, PNF, & Systems)	Improper / Incorrect / Inappropriate Procedure and/or Action	Fatigue / Impairment / Incapacitation
	2									1									

Belcastro, Christine M. (LARC-D316):
A process should have been in place to check the charge on the battery and to ensure against losing the charge during flight (e.g., monitoring remaining battery charge during flight or setting a conservative time constraint on flight duration).

Belcastro, Christine M. (LARC-D316):
The UAS was being operated above the stands of a public event.

Adverse Aircraft Onboard Conditions																			
	Vehicle Impairment								System & Component Failures / Malfunctions / Inadequacy										
None / Unknown	Improper / Maintenance or Manufacturing Action / Inaction and/or Inadequate Maintenance Procedure	Inappropriate / Non-Standard Vehicle Configuration	Contaminated Airfoil	Smoke / Fire / Explosion	Improper Loading: Weight / Balance / CG Issues	Improper Loading: Cargo Problems / Hazards	Airframe Structural Damage	Engine Damage (FOD)	Lost Control / Comm Link	Control System Design / Validation Inadequacy (Includes Unexpected Design Characteristics)	Control System Operational Error (Includes Response to Erroneous Sensor Input)	System Operational Error (Software / Verification Error)	Control Component Failure / Malfunction	Propulsion System Failure / Malfunction	Navigation System Failure / Malfunction / Impairment	Sensor / Sensor System Failure / Malfunction / Inadequacy	System / Subsystem Failure / Malfunction (Non-control component)	System Failure / Malfunction / Error (Undetermined - Includes Intermittent Problems)
														4 **Belcastro, Christine M. (LARC-D316):** Loss of power to propulsion / control system			3 **Belcastro, Christine M. (LARC-D316):** Battery exhaustion - could have resulted from unhealthy batteries and/or environmental conditions	

Abnormal Dynamics & Vehicle Upset Conditions													
	Abnormal Vehicle Dynamics				Vehicle Upset Conditions								
None / Unknown	Uncommanded Motions	Oscillatory Vehicle Response (Includes PIO)	Abnormal Control for Trim / Flight and/or Control Asymmetry	Abnormal / Counterintuitive Control Responses	Abnormal Attitude	Abnormal Airspeed (Includes Low Energy)	Abnormal Angular Rates	Undesired Abrupt Dynamic Response	Unsuccessful Launch / Liftoff / Takeoff of UAV	Abnormal Flight Trajectory	Uncontrolled Descent (Includes Spiral Dive)	Vmc / Departure	Stall / Departure (Includes Falling Leaf, Spin)
											5 **Belcastro, Christine M. (LARC-D316):** Drone appeared to lurch sideways and crash into the crowd.		

UAS Autonomous System Actions		Remote Pilot Actions		Collisions								
					Aircraft	Terrain / Ground Obstacles / Vehicles / Person						
Return to Base (RTB)	Modified Mission - Non-Return to Base	Return to Base (RTB)	Modified Mission - Non-Return to Base	None / Unknown	Mid-Air Collision (MAC) / Near Mid-Air Collision (NMAC)	Collision with Terrain	Collision with Ground Obstacle / Vehicle	Collision with Person on the Ground	Controlled Flight into Terrain (CFIT)	Unpowered Descent into Terrain / Water	Intentional Grounding of UAS (by Remote Pilot)	Intentional Grounding of UAS (Pre-Programmed)
								6 **Belcastro, Christine M. (LARC-D316):** The drone crashed into the grandstand at Virginia Motorsports Park during the Great Bull Run. Four or five people suffered very minor injuries. They were treated by EMS personnel at the event, and none was taken to a hospital.				

Comments and Flags:

Comments	Lost Link Flag (Includes lost link from either UAS or GCS)		Fly-Away Flag		LOC Flag (Applies to LOC cases based on dynamics and control definition combining Wilborn & Foster and Lambregts et al, but excluding lost link)		System Failure Flag (Applies to UA and GCS and Includes Single Point System Failures, Lack of Redundancy, and Design Inadequacies)		Airspace Intrusion / ATC Impact Flag (Includes Entry into Non-Allocated Airspace with Potential for Traffic Conflicts, Action being Required by ATC, or other Safety Concerns)	
	Yes / No / Not Enough Information (NEI)	Comment	Yes / No / Not Enough Information (NEI)	Comment	Yes / No / Not Enough Information (NEI)	Comment	Yes / No / Not Enough Information (NEI)	Comment	Yes / No / Not Enough Information (NEI)	Comment
	No		No		Yes	Loss of propulsion / control system (due to battery exhaustion) caused an uncontrolled descent	No		No	

Comments and Flags

Remote Pilot Distraction / Preoccupation / Mis-aligned Focus Flag		Potential Human-Machine Interface Issue Flag (Includes Displays, Controls, Flight Management, Envelope Protection, Warning Systems, & Transport Delays that Influence Flight Control)		Potential to Mitigate through Research (Technologies, Training, Procedures, etc.)		
Yes / No / Not Enough Information (NEI)	Comment	Yes / No / Not Enough Information (NEI)	Comment	Yes / No / Not Enough Information (NEI)	Mitigation Description	References
Yes	Pilot was preoccupied with flying the UAV and did not properly monitor battery state or flight time	Yes	Notification of battery charge may not have been evident	Yes	Health monitoring of batteries and notification and/or automatic RTB upon detetcion of low batteries	

Appendix C: Individual Precursor Contributions to sUAS Mishaps

This appendix provides a full listing of the individual precursor contributions to the sUAS mishaps, including precursor outcomes and mishap consequences, resulting from adverse onboard conditions, adverse ground support conditions, environmental / external conditions, and abnormal vehicle dynamics and vehicle upset conditions.

Table C.1. Individual Precursors, Outcomes, and Mishap Consequences Resulting from Adverse Onboard Conditions

Adverse Aircraft Onboard Conditions	Precursors	Precursor Outcome	Mishap Class	Mishap Consequences
System Failures / Malfunctions / Inadequacy (49)	Flight Control Component Failure / Malfunction (4)	• Aircraft Loss of Control (LOC) (3) • Other / Unknown (1)	Incident (4)	• Uncontrolled Descent / Landing (2) • Landed Successfully (1) • Unknown (1)
	Control System Design / Validation Inadequacy (4)	• Aircraft Loss of Control (LOC) (4)	Incident (4)	• Uncontrolled Descent / Landing (4)
	Control System Operational Error (includes response to erroneous sensor inputs) (4)	• Aircraft Loss of Control (LOC) (2) • Loss of Navigation Capability (2)	Incident (4)	• Collision with Ground Obstacle / Infrastructure / Vehicle (2) • Intentional Grounding (1) • Unsuccessful Launch / Liftoff / Takeoff (1)
	System Operational Error (Software Verification Error) (4)	• Aircraft Loss of Control (LOC) (1) • Lost Link (1) • Abnormal Runway Contact (2)	Incident (4)	• Landed Successfully (1) • Uncontrolled Descent / Landing (2) • Unsuccessful Launch / Liftoff / Takeoff (1)
	Propulsion System Failure / Malfunction (8)	• Aircraft Loss of Control (LOC) (5) • Unpowered Descent into Terrain / Water (1) • Other / Unknown (2)	• Incident (7) • Serious Incident (1)	• Uncontrolled Descent / Landing (5) • Landed Successfully (1) • Unknown (2)
	Navigation System Failure / Malfunction / Impairment (6)	• Loss of Navigation Capability (5) • Aircraft Loss of Control (LOC) (1)	Incident (6)	• Intentional Grounding (2) • Landed Successfully (3) • Collision with Ground Obstacle / Infrastructure / Vehicle (1)
	Sensor / Sensor System Failure / Malfunction / Inadequacy (4)	• Aircraft Loss of Control (LOC) (3) • Loss of Navigation Capability (1)	Incident (4)	• Collision with Ground Obstacle / Infrastructure / Vehicle (2) • Unsuccessful Launch / Liftoff / Takeoff (1) • Landed Successfully (1)
	System / Subsystem Failure / Malfunction (Non-Control Component) (3)	• Aircraft Loss of Control (LOC) (1) • Lost Link (1) • Loss of Navigation Capability (1)	• Incident (2) • Serious Incident (1)	• Collision with Ground Obstacle / Infrastructure / Vehicle (1) • Uncontrolled Descent / Landing (1) • Landed Successfully (1)
	System Failure / Malfunction / Error (Undetermined – Includes Intermittent Problems) (6)	• Aircraft Loss of Control (LOC) (5) • Lost Link (1)	• Incident (5) • Accident (1)	• Collision with Ground Obstacle / Infrastructure / Vehicle (1) • Uncontrolled Descent / Landing (2) • Unsuccessful Landing – Controlled (1) • Landed Successfully (1) • Fly-Away / Intentional Grounding of sUAS (1)
	Lost Control / Communications Link (6)	• Loss of Control / Comm Link (6)	• Incident (5) • Serious Incident (1)	• Landed Successfully (4) • Uncontrolled Descent / Landing (1) • Collision with Ground Obstacle / Infrastructure / Vehicle (1)
Vehicle Impairment (3)	Improper Maintenance / Manufacturing (1)	• Aircraft Loss of Control (LOC) (1)	Incident (1)	• Landed Successfully
	Airframe Structural Damage (2)	• Abnormal Runway Contact (2)	Incident (2)	• Uncontrolled Descent / Landing (2)

Table C.2. Individual Precursors, Outcomes, and Mishap Consequences Resulting from Adverse Ground Support Conditions

Adverse Ground Support Conditions	Precursors	Precursor Outcome	Mishaps	Mishap Consequences
Remote Pilot / Flight Crew Error (25)	Pilot / Flight Crew Decision Error / Poor Judgment (4)	• CFIT / Collision with Terrain / Infrastructure (4)	• Incident (4)	• Collision with Ground Onstacle / Infrastructure / Vehicle (2) • Unsuccessful Landing – Controlled (1) • Uncontrolled Descent / Landing (1)
	Operation In / Near Restricted Airspace (9)	• Airspace Intrusion (5) • Aircraft Loss of Control (LOC) (3) • Other / Unknown (1)	• Incident (5) • Serious Incident (4)	• Uncontrolled Descent / Landing (6) • MAC / NMAC (3)
	Loss of Attitude State Awareness (1)	• Aircraft Loss of Control (1)	• Incident (1)	• Uncontrolled Descent / Landing (1)
	Aggressive Maneuver (1)	• Aircraft Loss of Control (1)	• Accident (1)	• Collision with Ground Onstacle / Infrastructure / Vehicle (1)
	Abnormal / Inadvertent Control Input / Maneuver (1)	• Aircraft Loss of Control (1)	• Incident (1)	• Unsuccessful Launch / Liftoff / Takeoff (1)
	Improper / Ineffective / Unsuccessful Recovery (1)	• Loss of Navigation Capability (1)	• Incident (1)	• Intentional Grounding of sUAS (1)
	Inadequate Crew Resource Monitoring / Management (1)	• Abnormal Runway Contact (1)	• Incident (1)	• Uncontrolled Descent / Landing (1)
	Improper / Incorrect / Inappropriate Procedure / Action (7)	• Aircraft Loss of Control (LOC) (3) • CFIT / Collision with Terrain / Infrastructure (2) • Loss of Navigation Capability (1) • Other / Unknown (1)	• Incident (4) • Serious Incident (2) • Accident (1)	• Uncontrolled Descent / Landing (4) • Collision with Ground Obstacle / Infrastructure / Vehicle (2) • Intentional Grounding of sUAS (1)
Ground Control Station Failure / Inadequacy (5)	Lost Communications / Control Link from GCS (4)	• Lost Communication / Control Link (4)	• Incident (4)	• Landed Successfully (4)
	GCS Power / Electrical System (1)	• Lost Communication / Control Link (1)	• Incident (1)	• Landed Successfully (1)
Ground Support (3)	Ground Support Crew Error or Improper / Incorrect Procedure (2)	• Aircraft Loss of Control (LOC) (1) • Other / Unknown (1)	• Incident (1) • Serious Incident (1)	• Landed Successfully (1) • Uncontrolled Descent / Landing (1)
	Ground Recovery System Failure (1)	• Other / Unknown	• Incident (1)	• Unsuccessful Landing – Controlled (1)

Table C.3. Individual Precursors, Outcomes, and Mishap Consequences Resulting from Adverse Environmental / External Conditions

Environmental / External Conditions	Precursors	Precursor Outcome	Mishaps	Mishap Consequences
Adverse Navigational Environment (5)	Flight Beyond Visual / Radio Line of Sight (2)	• Lost Control / Communication Link (2) • Aircraft Loss of Control (LOC (1)	• Incident (1) • Serious Incident (1)	• Uncontrolled Descent / Landing (1) • Collision with Ground Obstacle / Infrastructure / Vehicle (1)
	Loss of GPS Signal (2)	• Aircraft Loss of Control (LOC) (1) • Loss of Navigation Capability (1)	• Incident (2)	• Intentional Grounding of sUAS (2)
	Erroneous GPS Signal (1)	• Aircraft Loss of Control (LOC) (1) • Loss of Navigation Capability (1)	• Incident (1)	• Collision with Ground Obstacle / Infrastructure / Vehicle (1)
Weather & Atmospheric Conditions (3)	Wind (2)	• Aircraft Loss of Control (LOC) (1) • Abnormal Runway Contact (1)	• Incident (2)	• Uncontrolled Descent / Landing (2)
	Wind Shear (1)	• Aircraft Loss of Control (LOC) (1)	• Incident (1)	• Collision with Ground Obstacle / Infrastructure / Vehicle (1)
External Threat (4)	Fixed Obstacle (2)	• Other / Unknown (2)	• Incident (2)	• Unsuccessful Landing – Controlled (1) • Collision with Ground Obstacle / Infrastructure / Vehicle (1)
	Another Aircraft in Close Proximity to sUAS (1)	• Other / Unknown (1)	• Incident (1)	• Collision with Ground Obstacle / Infrastructure / Vehicle (1)
	Conflict with a Bird (1)	• Aircraft Loss of Control (LOC) (1)	• Incident (1)	• Uncontrolled Descent / Landing (1)

Table C.4. Individual Precursors, Outcomes, and Mishap Consequences Resulting from Adverse Environmental / External Conditions

Abnormal Vehicle Dynamics / Vehicle Upset Conditions	Precursors	Precursor Outcome	Mishaps	Mishap Consequences
Abnormal Vehicle Dynamics (14)	Uncommanded Motions (6)	• Aircraft Loss of Control (LOC (5) • Uncommanded Descent (1)	• Incident (6)	• Uncontrolled Descent / Landing (4) • Unsuccessful Landing – Controlled (1)
	Oscillatory Vehicle Response (6)	• Aircraft Loss of Control (LOC) (6)	• Incident (6)	• Uncontrolled Descent / Landing (5) • Collision with Terrain / Ground Infrastructure or Vehicle (1) • Unknown (1)
	Abnormal Control for Trim / Flight and/or Control Asymmetry (1)	• Aircraft Loss of Control (LOC) (1)	• Incident (1)	• Intentional Grounding of sUAS (1)
	Abnormal / Counterintuitive Control Response (1)	• Aircraft Loss of Control (LOC) (1)	• Incident (1)	• Uncontrolled Descent / Landing (1)
Vehicle Upset Condition (38)	Abnormal Attitude (2)	• Aircraft Loss of Control (LOC) (2)	• Incident (2)	• Uncontrolled Descent / Landing (2)
	Abnormal Airspeed (Includes Low Energy) (1)	• Aircraft Loss of Control (LOC) (1)	• Incident (1)	• Unsuccessful Launch / Liftoff / Takeoff (1)
	Undesired Abrupt Dynamic Response (2)	• Aircraft Loss of Control (LOC) (2) • Loss of Navigation Capability (1)	• Incident (2)	• Collision with Ground Obstacle / Infrastructure / Vehicle (1) • Intentional Grounding of sUAS (1)
	Unsuccessful Launch of sUAV (5)	• Aircraft Loss of Control (LOC) (5) • Abnormal Runway Contact (1)	• Incident (5)	• Unsuccessful Launch / Liftoff / Takeoff (5)
	Abnormal Flight Trajectory (11)	• Aircraft Loss of Control (LOC) (8) • Airspace Intrusion (3) • Abnormal Runway Contact (3)	• Incident (10) • Serious Incident (1)	• Unsuccessful Landing – Controlled (2) • Uncontrolled Descent / Landing (7) • Unsuccessful Launch / Liftoff / Takeoff (1) • Intentional Grounding of sUAS (1)
	Uncontrolled Descent (16)	• Aircraft Loss of Control (LOC) (15) • Lost Control / Communication Link (1)	• Incident (12) • Serious Incident (3) • Accident (1)	• Uncontrolled Descent / Landing (15) • Collision with Ground Obstacle / Infrastructure / Vehicle (1)
	Stall / Departure (1)	• Aircraft Loss of Control (LOC) (1)	• Incident (1)	• Collision with Ground Obstacle / Infrastructure / Vehicle (1)

Appendix D: sUAS Mishap Precursor Sequences

This appendix provides a full listing of the precursor sequences resulting from the sUAS mishaps analysis relative to initiating event.

Precursor 1	Precursor 2	Precursor 3	Precursor 4	Precursor 5	Precursor 6	Precursor 7	Precursor 8	Precursor 9	Intentional Grounding	Successful Landing	Unsuccessful Landing	Unkown	Total
AAOC: SCFMI: Control Component Failure / Malfunction	Remote Pilot Action: Return to Base								0	1	0	0	1
	Unknown								0	0	0	1	1
AAOC: SCFMI: Control System Design / Validation Inadequacy	ADVUC: AVD: Oscillatory Vehicle Response (Includes PIO)	ADVUC: VUC: Uncontrolled Descent (Includes Spiral Dive)							0	0	1	0	1
									0	0	1	0	1
	Uncommanded Motions	ADVUC: VUC: Abnormal Attitude							0	0	1	0	1
	ADVUC: VUC: Abnormal Flight Trajectory								0	0	1	0	1
AAOC: SCFMI: Lost Control / Comm Link	UAS Autonomous Action: Return to Base								0	2	0	0	2
AAOC: SCFMI: Navigation System Failure / Malfunction / Impairment	Collisions: Intentional Grounding of UAS (by Remote Pilot)								1	0	0	0	1
	Remote Pilot Action: Return to Base								0	2	0	0	2

Figure D.1-a. sUAS Mishaps Initiated by Adverse Aircraft Onboard Conditions

Precursor 1	Precursor 2	Precursor 3	Precursor 4	Precursor 5	Precursor 6	Precursor 7	Precursor 8	Precursor 9	Intentional Grounding	Successful Landing	Unsuccessful Landing	Unkown	Total
AAOC: SCFMI: Propulsion System Failure / Malfunction	Control Component Failure / Malfunction	Uncontrolled Descent (Includes Spiral Dive)							0	0	2	0	2
	Uncontrolled Descent (Includes Spiral Dive)								0	0	1	0	1
	Unpowered Descent into Terrain / Water								0	0	1	0	1
	Action: Return to Base								0	1	0	0	1
	Unknown								0	0	0	2	2
AAOC: SCFMI: Sensor / Sensor System Failure / Malfunction / Inadequacy	AAOC: SCFMI: Control System Operational Error	ADVUC: VUC: Abnormal Airspeed (Includes Low Energy)	ADVUC: VUC: Unsuccessful Launch / Liftoff / Takeoff of UAV						0	0	1	0	1
	Control System Operational Error	with Ground Obstacle / Vehicle							0	0	1	0	1
	AAOC: SCFMI: System / Subsystem Failure / Malfunction (Non-control component)	EHEHD: ANE: Erroneous GPS Signal	AAOC: SCFMI: Navigation System Failure / Malfunction / Impairment	UAS Autonomous Action: Return to Base	ADVUC: VUC: Undesired Abrupt Dynamic Response	AAOC: SCFMI: Control System Operational Error	Collisions: Collision with Ground Obstacle / Vehicle	Collisions: Collision with Terrain	0	0	1	0	1
AAOC: SCFMI: System / Subsystem Failure / Malfunction (Non-control component)	Remote Pilot Action: Return to Base								0	1	0	0	1

Figure D.1-b. sUAS Mishaps Initiated by Adverse Aircraft Onboard Conditions

Precursor 1	Precursor 2	Precursor 3	Precursor 4	Precursor 5	Precursor 6	Precursor 7	Precursor 8	Precursor 9	Intentional Grounding	Successful Landing	Unsuccessful Landing	Unkown	Total
AAOC: SCFMI: System Failure / Malfunction / Error (Undetermined)	Control / Comm Link	Action: Return to Base							0	1	0	0	1
	Oscillatory Vehicle Response (Includes PIO)	Collisions: Collision with Terrain							0	0	1	0	1
	Uncommanded Motions	Collisions: Collision with Terrain							0	0	1	0	1
	ADVUC: VUC: Abnormal Flight Trajectory	Uncontrolled Descent (Includes Spiral Dive)							0	0	1	0	1
		Intentional Grounding of UAS (Pre-Programmed)							1	0	0	0	1
AAOC: SCFMI: System Operational Error (Software / Verification Error)	Control / Comm Link	Action: Return to Base							0	1	0	0	1
	Abnormal Flight Trajectory	AAOC: VI: Airframe Structural Damage							0	0	1	0	1
	Unsuccessful Launch / Liftoff / Takeoff of UAV								0	0	1	0	1
	AOBI/GSC: RPFCAI: Inadequate Crew Resource Monitoring / Management (PF, PNF, & Systems)								0	0	1	0	1
AAOC: VI: Improper Maint or Manufact Action/Inaction and/or Inad Maint Proced	AAOC: SCFMI: Sensor / Sensor System Failure / Malfunction / Inadequacy	ADVUC: AVD: Uncommanded Motions	Remote Pilot Action: Return to Base						0	1	0	0	1

Figure D.1-c. sUAS Mishaps Initiated by Adverse Aircraft Onboard Conditions

Note: The red shading in the above sequence indicates a fly-away

Precursor 1	Precursor 2	Precursor 3	Precursor 4	Precursor 5	Precursor 6	Precursor 7	Precursor 8	Precursor 9	Intentional Grounding	Successful Landing	Unsuccessful Landing	Unkown	Total
AOBI/GSC: GCS: GCS Power / Electrical System	→ AOBI/GSC: GCS: Lost Communications / Control Link from GCS	→ UAS Autonomous Action: Return to Base							0	1	0	0	1
AOBI/GSC: GCS: Lost Communications / Control Link from GCS	→ Remote Pilot Action: Return to Base								0	1	0	0	1
	→ UAS Autonomous Action: Return to Base								0	2	0	0	2
AOBI/GSC: GS: Ground Support Crew Error or Improper/Incorrect Proc	→ AAOC: SCFMI: Navigation System Failure / Malfunction / Impairment	→ Remote Pilot Action: Return to Base							0	1	0	0	1
AOBI/GSC: RPFCAI: Abnormal / Inadvertent Control Input / Maneuver	→ ADVUC: VUC: Unsuccessful Launch / Liftoff / Takeoff of UAV								0	0	1	0	1
AOBI/GSC: RPFCAI: Aggressive Maneuver	→ AAOC: SCFMI: System Failure / Malfunction / Error (Undetermined)	→ Collisions: Collision with Person on the Ground							0	0	1	0	1

Figure D.2-a. sUAS Mishaps Initiated by Adverse Off-Board Infrastructure / Ground Support Conditions

Precursor 1	Precursor 2	Precursor 3	Precursor 4	Precursor 5	Precursor 6	Precursor 7	Precursor 8	Precursor 9	Intentional Grounding	Successful Landing	Unsuccessful Landing	Unkown	Total
AOBI/GSC: RPFCAI: Improper / Incorrect / Inappropriate Procedure and/or Action	AAOC: SCFMI: Navigation System Failure / Malfunction / Impairment	Collisions: Intentional Grounding of UAS (by Remote Pilot)							1	0	0	0	1
	ADVUC: VUC: Uncontrolled Descent (Includes Spiral Dive)	Collisions: Collision with Person on the Ground							0	0	1	0	1
	AOBI/GSC: RPFCAI: Operation In / Near Restricted Airspace	Collisions: Collision with Person on the Ground							0	0	1	0	1
	Collisions: Collision with Ground Obstacle / Vehicle								0	0	2	0	2
	Collisions: Collision with Terrain	ADVUC: VUC: Uncontrolled Descent (Includes Spiral Dive)	Collisions: Collision with Person on the Ground						0	0	1	0	1

Figure D.2-b. sUAS Mishaps Initiated by Adverse Off-Board Infrastructure / Ground Support Conditions

Precursor 1	Precursor 2	Precursor 3	Precursor 4	Precursor 5	Precursor 6	Precursor 7	Precursor 8	Precursor 9	Intentional Grounding	Successful Landing	Unsuccessful Landing	Unkown	Total
AOBI/GSC: RPFCAI: Operation In / Near Restricted Airspace	ADVUC: VUC: Abnormal Flight Trajectory	Collisions: Collision with Terrain							0	0	1	0	1
	AOBI/GSC: GS: Ground Support Crew Error or Improper/Incorrect Proc	AAOC: SCFMI: System / Subsystem Failure / Malfunction (Non-control component)	AAOC: SCFMI: Propulsion System Failure / Malfunction	ADVUC: VUC: Uncontrolled Descent (Includes Spiral Dive)	Collisions: Collision with Person on the Ground				0	0	1	0	1
	AOBI/GSC: RPFCAI: Improper / Incorrect / Inappropriate Procedure and/or Action	Collisions: Collision with Terrain	ADVUC: VUC: Uncontrolled Descent (Includes Spiral Dive)	Collisions: Collision with Person on the Ground					0	0	1	0	1
	Collisions: Collision with Terrain								0	0	1	0	1
	Collisions: Mid-Air Collision (MAC) / Near Mid-Air Collision (NMAC)								0	0	1	2	3
	EHEHD: ANE: Flight Beyond Visual / Radio Line of Sight	AAOC: SCFMI: Lost Control / Comm Link	ADVUC: VUC: Uncontrolled Descent (Includes Spiral Dive)	Collisions: Collision with Terrain	Collisions: Collision with Person on the Ground				0	0	1	0	1

Figure D.2-c. sUAS Mishaps Initiated by Adverse Off-Board Infrastructure / Ground Support Conditions

Precursor 1	Precursor 2	Precursor 3	Precursor 4	Precursor 5	Precursor 6	Precursor 7	Precursor 8	Precursor 9	Intentional Grounding	Successful Landing	Unsuccessful Landing	Unkown	Total
AOBI/GSC: RPFCAI: Pilot / Crew Decision-Making Error / Poor Judgement	Collisions: Collision with Ground Obstacle / Vehicle								0	0	2	0	2
	Collisions: Collision with Terrain								0	0	2	0	2
Collisions: Collision with Ground Obstacle / Vehicle	ADVUC: VUC: Uncontrolled Descent (Includes Spiral Dive)	Collisions: Collision with Person on the Ground							0	0	1	0	1
	Collisions: Collision with Person on the Ground								0	0	1	0	1
	Unsuccessful Landing								0	0	9	0	9

Figure D.2-d. sUAS Mishaps Initiated by Adverse Off-Board Infrastructure / Ground Support Conditions

Precursor 1	Precursor 2	Precursor 3	Precursor 4	Precursor 5	Precursor 6	Precursor 7	Precursor 8	Precursor 9	Intentional Grounding	Successful Landing	Unsuccessful Landing	Unkown	Total
EHEHD: ANE: Flight Beyond Visual / Radio Line of Sight	AAOC: SCFMI: Lost Control / Comm Link	UAS Autonomous Action: Return to Base	Collisions: Collision with Ground Obstacle / Vehicle						0	0	1	0	1
EHEHD: ANE: Loss of GPS Signal	AAOC: SCFMI: Control System Operational Error	AOBI/GSC: RPFCAI: Improper / Ineffective / Unsuccessful Recovery	Collisions: Intentional Grounding of UAS (by Remote Pilot)						1	0	0	0	1
	ADVUC: AVD: Uncommanded Motions	Collisions: Intentional Grounding of UAS (by Remote Pilot)							1	0	0	0	1
EHEHD: Obstacle: Another Aircraft in Close Proximity to UAS	Remote Pilot Action: Return to Base	EHEHD: Obstacle: Fixed							0	0	1	0	1
EHEHD: Obstacle: Conflict with a Bird	ADVUC: VUC: Uncontrolled Descent (Includes Spiral Dive)								0	0	1	0	1
EHEHD: WAC: Wind	ADVUC: AVD: Oscillatory Vehicle Response (Includes PIO)	AAOC: VI: Airframe Structural Damage							0	0	1	0	1
	ADVUC: VUC: Abnormal Flight Trajectory	Collisions: Collision with Ground Obstacle / Vehicle							0	0	1	0	1
EHEHD: WAC: Wind Shear	ADVUC: VUC: Stall / Departure (Includes Falling Leaf, Spin)	Collisions: Collision with Ground Obstacle / Vehicle							0	0	1	0	1

Figure D.3. sUAS Mishaps Initiated by Adverse Environmental / External Conditions

<u>Note</u>: In most sUAS mishap reports very little information was provided about ambient wind conditions. The sequences of Figure D.3 may therefore be under-represented.

Precursor 1	Precursor 2	Precursor 3	Precursor 4	Precursor 5	Precursor 6	Precursor 7	Precursor 8	Precursor 9	Intentional Grounding	Successful Landing	Unsuccessful Landing	Unkown	Total
ADVUC: AVD: Abnormal / Counterintuitive Control Responses	Loss of Attitude State Awareness / Spatial Disorientation	ADVUC: VUC: Uncontrolled Descent (Includes Spiral Dive)							0	0	1	0	1
ADVUC: AVD: Abnormal Control for Trim / Flight and/or Control Asymmetry	ADVUC: VUC: Undesired Abrupt Dynamic Response	Collisions: Intentional Grounding of UAS (by Remote Pilot)							1	0	0	0	1
ADVUC: AVD: Oscillatory Vehicle Response (Includes PIO)	ADVUC: VUC: Uncontrolled Descent (Includes Spiral Dive)								0	0	1	0	1
ADVUC: AVD: Uncommanded Motions	ADVUC: AVD: Oscillatory Vehicle Response (Includes PIO)	ADVUC: VUC: Uncontrolled Descent (Includes Spiral Dive)							0	0	1	0	1
	Collisions: Collision with Terrain								0	0	1	0	1
ADVUC: VUC: Abnormal Attitude	ADVUC: VUC: Uncontrolled Descent (Includes Spiral Dive)								0	0	1	0	1
ADVUC: VUC: Abnormal Flight Trajectory	Collisions: Collision with Person on the Ground								0	0	1	0	1
	Collisions: Collision with Terrain								0	0	1	0	1
	EHEHD: Obstacle: Fixed	AOBI/GSC: GS: Ground Recovery System Failure	Collisions: Collision with Terrain						0	0	1	0	1
	Unsuccessful Landing								0	0	1	0	1
ADVUC: VUC: Unsuccessful Launch / Liftoff / Takeoff of UAV	ADVUC: VUC: Abnormal Flight Trajectory								0	0	1	0	1
	Unsuccessful Landing								0	0	1	0	1

Figure D.4. sUAS Mishaps Initiated by Abnormal Dynamics and Vehicle Upset Conditions

Precursor 1	Precursor 2	Precursor 3	Precursor 4	Precursor 5	Precursor 6	Precursor 7	Precursor 8	Precursor 9	Intentional Grounding	Successful Landing	Unsuccessful Landing	Unkown	Total
Collisions: Collision with Ground Obstacle / Vehicle	ADVUC: VUC: Uncontrolled Descent (Includes Spiral Dive)	Collisions: Collision with Person on the Ground							0	0	1	0	1
	Collisions: Collision with Person on the Ground								0	0	1	0	1
	Unsuccessful Landing								0	0	9	0	9
Collisions: Collision with Person on the Ground	Unsuccessful Landing								0	0	1	0	1
Collisions: Collision with Terrain	Collisions: Collision with Person on the Ground								0	0	1	0	1
	Unsuccessful Landing								0	0	10	0	10

Figure D.5. sUAS Mishaps Initiated by Collisions

Notes:

1. “Abnormal Vehicle Dynamics” and “Vehicle Upset Conditions” typically are not initiating events in mishap sequences but result from other adverse conditions that are identified in the mishap report based on an accident / incident investigation. The sequences in Figure D.5 were catalogued as initiating with these events due to a lack of information in the associated sUAS mishap reports that could be used in identifying the actual initiating condition(s). These sequences are therefore an artifact of limited information in sUAS mishap investigation and reporting.

2. “Collision” is typically an “Outcome” of mishap sequences. The mishaps of Figure D.5 were catalogued as initiating with a collision because insufficient information was provided in the mishap report. These sequences are therefore an artifact of limited information in sUAS mishap investigation and reporting.

Appendix E: Future Hazards Identification

This appendix provides two example listings from the future hazards identification spreadsheet.

Example 1. Cross-Cutting Operational Paradigm Shift to Multi-UAS Operations with Identified Hazards and Impacts / Outcomes

Future Use Case / Application	Paradigm Shifts from Current Operations		Future Potential Hazards				Future Potential Impacts / Outcomes					
	New Operational Paradigms	New Vehicle Systems	Vehicle-Level Hazards	Ground Control Station (GCS) / Infrastructure	Operational	UTM / USS System	Related to UAV	Related to Other UAVs	Related to Other Vehicles (Air & Ground)	Related to People	Related to Infrastructure	Environmental
All / Many	Multiple UAS Operations			Poor Interfaces / Displays for Multiple Vehicle Operations (Situational Awareness, Safety Monitoring, Surveillance Information Processing, Detection Notification, etc.)				MACs	MAC with GA / Transport Aircraft; UAV Crashes into Ground Vehicle	UAV or UAV Debris Falls on & Injures People on the Ground	Collision with Terrain and/or Infrastructure	Collision with Terrain Starts a Fire
All / Many	Multiple UAS Operations			Poor Interface for Switching Between Manual and Autonmous UAV Control for Selected UAV (e.g., under Vehicle Impairment) Leading to Unanticipated Mode Changes and/or Transient Control Input Signals			LOC	MAC with Other UAVs	MAC with GA / Transport Aircraft; UAV Crashes on Highway and/or Hits an Automobile Causing Car Accidents	UAV Crashes into Public Area or Neighborhood	UAV Crashes into Building, Bridge, Power Lines / Sub-Station, or Other Infrastructure	UAV Crashes into Public Park and Causes a Fire
All / Many	Multiple UAS Operations			Inability / Ineffective Means to Manually Take Control Of UAV with Issues while Continuing to Monitor the Remaining UAS in Operation			LOC	MAC with Other UAVs	MAC with GA / Transport Aircraft; UAV Crashes on Highway and/or Hits an Automobile Causing Car Accidents	UAV Crashes into Public Area or Neighborhood	UAV Crashes into Building, Bridge, Power Lines / Sub-Station, or Other Infrastructure	UAV Crashes into Public Park and Causes a Fire
All / Many	Multiple UAS Operations				Poor Management and/or Multi-Sector Coordination of Multiple UAVs			MAC with Other UAVs	MAC with GA / Transport Aircraft			
All / Many	Multiple UAS Operations				Pilot Overload & Loss of Situational Awareness under Multiple UAV Operations			MAC with Other UAVs	MAC with GA / Transport Aircraft			
All / Many	Multiple UAS Operations				Poor Safety Monitoring of Multiple UAVs			MAC with Other UAVs	MAC with GA / Transport Aircraft			
All / Many	Multiple UAS Operations					UTM System Allows Entry into Restricted Airspace			MAC with GA / Transport Aircraft; UAV Crashes on Highway and/or Hits an Automobile Causing Car Accidents	UAV Crashes into Public Area or Neighborhood	UAV Crashes into Building, Bridge, Power Lines / Sub-Station, or Other Infrastructure	UAV Crashes into Public Park and Causes a Fire
All / Many	Multiple UAS Operations					UTM System Allows Entry into Secured Airspace by Unauthenticated (Rogue) UAS		MAC with Other UAVs	MAC with GA / Transport Aircraft; UAV Crashes on Highway and/or Hits an Automobile Causing Car Accidents	UAV Crashes into Public Area or Neighborhood	UAV Crashes into Building, Bridge, Power Lines / Sub-Station, or Other Infrastructure	UAV Crashes into Public Park and Causes a Fire
All / Many	Multiple UAS Operations		Loss of Navigation Capability by One or More UAVs				UAV Exits Assigned Geofence	MAC with Other UAVs	MAC with GA / Transport Aircraft			
All / Many	Multiple UAS Operations				GPS Outage During Operation		UAV Exits Assigned Geofence	MAC with Other UAVs	MAC with GA / Transport Aircraft			
All / Many	Multiple UAS Operations					Inadequate / Faulty Multiple UAS Coordination for Cooperative Missions and/or Across Multiple Independent Missions		MAC with Other UAVs	MAC with Large UAS or Manned Aircraft (if part of a coordinated mission)	Pilot in Manned Aircraft is Injured / Killed; Injury / Fatality to People on Ground	Crash Debris Damages Infrastructure	Crash Debris Causes a Fire
All / Many	Multiple UAS Operations				Communication Interference Among Multi-UAS Operators (e.g., EMI and/or Using Same Frequency for Communication)		LOC of Multiple UAS	MAC with Other UAVs	MAC with GA / Transport Aircraft	Pilot in Manned Aircraft is Injured / Killed; Injury / Fatality to People on Ground	Crash Debris Damages Infrastructure	Crash Debris Causes a Fire

Example 2. Cross-Cutting Operational Paradigm Shift to Multi-UAS Operations with Identified Hazards and Impacts / Outcomes

Future Use Case / Category	Paradigm Shifts from Current Operations		Future Potential Hazards				Future Potential Impacts / Outcomes					
	New Operational Paradigms	New Vehicle Systems	Vehicle-Level Hazards	Ground Control Station (GCS) / Infrastructure	Operational	UTM / USS System	Related to UAV	Related to Other UAVs	Related to Other Vehicles (Air & Ground)	Related to People	Related to Infrastructure	Environmental
Monitoring & Patrol (e.g., Border Patrol, Individual / Group / Vehicle Identification and Tracking, Maritime Patrol along Coastal Border Regions, Intelligence, Surveillance, and Reconnaissance of an Area or Building of Interest, etc.)		Use of Weaponized Vehicles	Payload Failure (e.g., Weapons) resulting in CG Shift / Incomplete Release / Vehicle Instability				LOC	MAC with UAV Operating within the UTM System	UAV Crashes onto Automobile or Highway & Causes Accident	UAV Crashes onto and Injures People on the Ground	UAV Gets Hung Up on Building, Bridge, Power Lines / Sub-Station, or Other Infrastructure	Gets Hung Up in Trees or Lands in Waterway & Negatively Impacts Wildlife
Monitoring & Patrol (e.g., Border Patrol, Individual / Group / Vehicle Identification and Tracking, Maritime Patrol along Coastal Border Regions, Intelligence, Surveillance, and Reconnaissance of an Area or Building of Interest, etc.)		Use of Weaponized Vehicles	Erroneous / Inadvertent Discharge of Weapons				Damage Resulting in LOC or In-Air Destruction	Loss of Other UAV (e.g., nearby UAV impacted by shock wave or shrapnel)	Weapon Damages or Destroys Unintended Target	Weapon Damages or Destroys Unintended Target	Weapon Injures or Kills Unintended Human Target	Weapon Discharge Results in Damage or Destruction to Local Environment
Monitoring & Patrol (e.g., Border Patrol, Individual / Group / Vehicle Identification and Tracking, Maritime Patrol along Coastal Border Regions, Intelligence, Surveillance, and Reconnaissance of an Area or Building of Interest, etc.)	Launch and Recovery of UAS from a Moving Vehicle Ground Control Station (GCS)			Lost Link with Mobile GCS			LOC or CFIT	MAC with UAV Operating within the UTM System	UAV Crashes onto Automobile or Highway & Causes Accident	UAV Crashes onto and Injures People on the Ground	UAV Gets Hung Up on Building, Bridge, Power Lines / Sub-Station, or Other Infrastructure	Gets Hung Up in Trees or Lands in Waterway & Negatively Impacts Wildlife
Monitoring & Patrol (e.g., Border Patrol, Individual / Group / Vehicle Identification and Tracking, Maritime Patrol along Coastal Border Regions, Intelligence, Surveillance, and Reconnaissance of an Area or Building of Interest, etc.)	Operation under Uncertain Conditions				Weather Conditions (e.g., Fog, Rain, Dust, Snow, etc.) Compromise Sensors Used in Monitoring and Patrol		MAC or CFIT	MAC with UAV Operating within the UTM System	MAC with Manned Aircraft Flying a Coordinated Mission (e.g., Monitoring and Patrol) or Operating within same Air Space	UAV Crashes onto and Injures People on the Ground	UAV Gets Hung Up on Building, Bridge, Power Lines / Sub-Station, or Other Infrastructure	Gets Hung Up in Trees or Lands in Waterway & Negatively Impacts Wildlife
Monitoring & Patrol (e.g., Border Patrol, Individual / Group / Vehicle Identification and Tracking, Maritime Patrol along Coastal Border Regions, Intelligence, Surveillance, and Reconnaissance of an Area or Building of Interest, etc.)	Coordination Across Multiple Municipalities and/or Jurisdictions					Ineffective Coordination by UTM System Among Multiple Operators In the Same Vicinity (DHS, Police, News Media, etc.)	MAC	MAC with UAV Operating within the UTM System	MAC with Manned Aircraft Flying a Coordinated Mission (e.g., Monitoring and Patrol) or Operating within same Air Space	People on Ground Are Endangered by Crash Debris	Infrastructure is Damaged by Crash Debris	Environment is Impacted by Crash Debris

Appendix F: Hazards Sets

This appendix provides a listing of the current, future, and combined hazards sets.

Table F.1-a. Current Hazards Set (1)

Category	Hazard	Causal / Contributing Factors	Use Case / Operational State	Result	Impacts	Hazardous Outcomes
Single UAS Manually Controlled by Remote Pilot under VLOS Operations	Aircraft Loss of Control (LOC)	• Vehicle Failures / Impairment • Control System Failures / Malfunctions / Inadequacy (Includes Design / Validation Errors) • Propulsion System Failure / Malfunction • Weather • Wind / Turbulence • Vehicle Upset Condition • Pilot Error • Power Loss / Fuel Exhaustion • Electromagnetic Interference (EMI) • Unsuccessful Launch • Bird Strike • Software Verification Error • Others	• Any / All Use Cases • Remote / Rural Location • Low-Density Operations	• Undesired Flight Trajectory that is Difficult to Predict • Unpredictable / Unstable Control Response • Uncontrolled / Unsuccessful Landing	• Vehicle Exits Assigned Geofence	• Mid-Air Collision with UAS • Mid-Air Collision with Manned Aircraft • Crash into Building / Obstacle Injures People • Crash Debris Injures People on Ground
			• Any / All Use Cases • Suburban / Urban / Congested • Low-Density Operations		• Uncontrolled Descent / Landing • Uncontrolled Descent into Terrain / Water • Vehicle Damage / Break-Up	• Injury to People on the Ground • Damage to Ground Asset Results in Fire
	Aircraft Fly-Away / Geofence Non-Conformance	• Loss of Communication / Control Link • Erroneous Way Points • GPS Failure / Errors • Autopilot Error / Malfunction • Pilot Error	• Any / All Use Cases • Remote / Rural Location • Low-Density Operations • Suburban / Urban • Low-Density Operations	• Inability to Control Aircraft from Ground • Inability to Monitor Aircraft Position • Inability to Initiate Flight Termination from Ground	• Vehicle Exits Assigned Geofence • Aircraft LOC	• Mid-Air Collision with UAS • Mid-Air Collision with Manned Aircraft • Crash into Building / Obstacle Injures People • Crash Debris Injures People on Ground
	Lost Communication / Control Link	• EMI at Vehicle • Signal Obscurence • Frequency / BW Overlap • Failure in GCS (e.g., Power Failure, etc.) • Software Verification Error	• Any / All Use Cases • Remote / Rural Location • Low-Density Operations • Suburban / Urban • Low-Density Operations	• Inability to Control Aircraft from Ground • Inability to Monitor Aircraft Position • Inability to Initiate Flight Termination from Ground • Return to Base	• Vehicle Exits Assigned Geofence • Aircraft Loss of Control (LOC) • Controlled Flight into Terrain (CFIT)	• Mid-Air Collision with UAS • Mid-Air Collision with Manned Aircraft • Crash into Building / Obstacle Injures People • Crash Debris Injures People on Ground

Table F.1-b. Current Hazards Set (2)

Category	Hazard	Causal / Contributing Factors	Use Case / Operational State	Result	Impacts	Hazardous Outcomes
Single UAS Manually Controlled by Remote Pilot under VLOS Operations	Loss of Navigation Capability	• Onboard Navigation System Failure / Malfunction • Loss of / Erroneous GPS Signal • Ground Station Set-Up Error	• Any / All Use Cases • Remote / Rural Location • Low-Density Operations • Suburban / Urban • Low-Density Operations	• Inability to Fly Desired Trajectory • Intentional Grounding	• Vehicle Exits Assigned Geofence	• Mid-Air Collision with UAS • Mid-Air Collision with Manned Aircraft • Crash into Building / Obstacle Injures People • Crash Debris Injures People on Ground
	Failure / Inability to Avoid Collision with Terrain and/or Fixed / Moving Obstacles	• Inadequate / Lack of Sense/Detect and Avoid (SAA/DAA) Capability • Erroneous Way Points that Create Conflict with Obstacle • Inaccurate GPS Signal • Inadequate Navigation / Tracking • Pilot Error / Poor Judgement • Wind / Weather that Results in Abnormal Flight Trajectory	• Any / All Use Cases • Remote / Rural Location • Low-Density Operations • Suburban / Urban • Low-Density Operations	• Collision with Building • Collision with Power Lines • Collision with Ground Vehicle	• Vehicle Break-Up	• Crash Debris Injures People on Ground • UAS / Crash Debris Causes Ground Vehicle Accident on Highway • Post-Crash Fire that Damages Building and/or Injures People Inside the Building • Post-Crash Fire that Damages Environment
	Unsuccessful Landing	• Unstable Approach • Remote Pilot Error	Within Runway Safety Area	• Abnormal Runway Contact • Crash on Landing	• Vehicle Damage / Break-Up	• Post-Crash Fire that Injures Ground Crew
			Outside Runway Safety Area	• Abnormal Runway Contact • Crash on Landing	• Vehicle Damage / Break-Up	• Crash Debris Injures People on Ground

Table F.2-a. Future Hazards Set (1)

Category	Hazard	Causal / Contributing Factors	Use Case / Operational State	Result	Impacts	Hazardous Outcomes
Single UAS Controlled Semi-Autonomously under BVLOS Operations	Aircraft Loss of Control (LOC)	• Inadequate Resilience in Flight Control System to Key LOC Hazards (Including Failures, Wind / Weather, etc.) • Sensor / System / Component Failure / Malfunction • System Validation Inadequacy • Software Coding Error / Verification Inadequacy • Unexpected Wind / Turbulence (Not Forecasted and At / Near Boundary Condition) • Unexpected Weather Conditions • Payload / CG Shift / Instability • Vehicle Damage (e.g., Lightning strike during long-duration missions, Damage from Explosion / Fire during Emergency Response, Radiation Exposure from HALE operations over urban areas, etc.) • Battery Failure / Fuel Exhaustion (e.g., under Long-Duration Missions) • EMI Across Multiple UAS • Harsh Environmental Conditions (Smoke, Ash, Extreme Temperatures, etc.) for Specialized Missions (Wildfire Monitoring / Control, Search & Rescue, Maritime, etc.) • Vehicle Instability Resulting from Attempted Retrieval of Objects of Unknown size/weight • Vehicle Instability Resulting from Failure/Malfunction of Object Retrieval System • Launch/Landing Instability on Water-Based Platform • Propulsion or Vision Systems Failure / Inadequacy under Harsh Conditions (Fire, Smoke, Ash, Smog, Salty Sea Air, etc.)	• Any / All Use Cases • Suburban / Urban • Moderate- / High-Density Operations	• Undesired Flight Trajectory that is Difficult to Predict • Unpredictable / Unstable Control Response • Uncontrolled Descent • Potential for LOC Involving Multiple UAS under Common Causal Conditions (e.g., Unexpected Wind / Weather)	• One or More UAS Exit Assigned Geofence • One or More UAS on Uncontrolled Trajectory	• MACs with One or More UAS • MAC with Manned Aircraft by One or More UAS • One or More UAS Crash into Buildings / Obstacles and Injures People • Crash Debris Injures People on Ground • Damage to ground asset causes fire
	Failure / Inability to Avoid Collision with Fixed / Moving Obstacle	• Inadequate Design / Validation or Failure of SAA / DAA System • Vision System Failure / Inadequacy in Low Visibility Conditions • Missed Detection of Obstacle • Inadequate / Erroneous / Incomplete Terrain Database • Inadequate / Ineffective Sensor System for Detection of Small / Thin Obstacles (e.g., Power Lines) • Inadequate Resilience to Key Hazards (e.g., component failures, external disturbances) • Launch/Landing Instability on Water-Based Platform • Propulsion or Vision Systems Failure / Inadequacy under Harsh Conditions (Fire, Smoke, Ash, Smog, Salty Sea Air, etc.)	• Any / All Use Cases • Suburban / Urban • Moderate- / High-Density Operations	• Collisions Between Once or More UAS • Collision with Manned Aircraft • Collision with Infrastructure (Building, Bridge, Power Lines / Sub-Station, etc.) or Terrain Features • Collision with Ground Vehicle • Potential for Widespread Collisions under Common Causal Conditions (e.g., Poor Visibility)	• Vehicle Break-Up	• MACs with One or More UAS • MAC with Manned Aircraft by One or More UAS • One or More UAS Crash into Buildings / Obstacles and Injures People • Crash Debris Injures People on Ground • Damage to ground asset (e.g., High-Voltage Power Lines) causes fire

Table F.2-b. Future Hazards Set (2)

Category	Hazard	Causal / Contributing Factors	Use Case / Operational State	Result	Impacts	Hazardous Outcome
Single UAS Controlled Semi-Autonomously under BVLOS Operations	Geofence Nonconformance / Fly-Away	• GPS Signal Loss / Error • Network Unavailability • Onboard GPS System Failure / Malfunction • Lack of Navigational Redundancy • Jamming / Spoofing of GPS and/or ADS-B Signals • Erroneous Way Points • Error in Autonomous Mission Planner • Software / Verification Error in Autonomous Mission Planner	• Any / All Use Cases • Suburban / Urban • Moderate- / High-Density Operations	• Inability to Control Aircraft from Ground • Inability to Monitor Aircraft Position • Inability to Initiate Flight Termination from Ground • Potential for Widespread Collisions under Common Causal Conditions (e.g., Network Loss)	• One or More UAS Exit Assigned Geofence	• Mid-Air Collision with UAS(s) • Mid-Air Collision(s) with Manned Aircraft • Crash into Building / Obstacle Injures People • Crash Debris Injures People on Ground
	Lost Communication / Control Link	• GPS Drop-Outs in Urban Environments • EMI Weapon Targeting One or More UAS • Signal Jamming / Spoofing • Frequency / BW Block • Network Unavailability	• Any / All Use Cases • Suburban / Urban • Moderate- / High-Density Operations	• Inability to Fly Desired Trajectory • Inability to Remotely Initiate Flight Termination • Potential for Widespread Collisions under Common Causal Conditions (e.g., Network Loss, Widespread Jamming)	• One or More UAS Exit Assigned Geofence • Aircraft Loss of Control (LOC) Involving One or More UAS • Controlled Flight into Terrain / Obstacle by One or More UAS	• Mid-Air Collision with One or More UAS • MAC with Manned Aircraft by One or More UAS • One or More UAS Collisions with One or More Buildings • Crash Debris Injures People on Ground
	Loss of Navigation Capability	• Hostile Takeover and Control of UAS • GPS / ADS-B Signal Inaccuracy / Jamming / Spoofing • Network Unavailability • Vision System Inadequacy under Low-Visibility Conditions • Inadequate Perception of Visual Scene by Vision System	• Any / All Use Cases • Suburban / Urban • Moderate- / High-Density Operations	• Above Results • UAS Location is Inaccurate or Cannot be Determined • Potential for Widespread Collisions under Common Causal Conditions (e.g., GPS Signal or Network Loss)	• UAS Leaves Assigned Geofence • Safe Separation Cannot be Maintained	• MAC(s) Among One or More UAS • MAC(s) with Manned Aircraft • Collision(s) with Terrain, Obstacle(s), Building(s) • Crash Debris Injures People on Ground
	Unintentional / Unsuccessful Flight Termination	• Failure / Inadequacy of the Onboard Flight Termination System • Inadequate Database for or RT Identification of Safe Landing Zone(s) • Vision System Inadequacy under Low-Visibility Conditions • Inadequate Perception of Visual Scene by Vision System • Failure of Command Link from Operator to Initiate Flight Termination	• Any / All Use Cases • Suburban / Urban • Moderate- / High-Density Operations	• Vehicle lands or has a forced crash in an unsafe location	• Vehicle Damage / Break-Up	• UAS injures people on ground • UAS crashes into ground vehicle • UAS causes accident involving ground vehicles

Table F.2-c. Future Hazards Set (3)

Category	Hazard	Causal / Contributing Factors	Use Case / Operational State	Result	Impacts	Hazardous Outcome
Single UAS Controlled Semi-Autonomously under BVLOS Operations	Hostile Remote Takeover and Control of UAS	• Lack of Data / Cyber Security by Operator or within UTM System • Increasing Level of Sophistication of Terrorist Threat	• Any / All Use Cases • Suburban / Urban • Moderate- / High-Density Operations	• UAS is no longer under operator control • Potential for Simultaneous Takeover of Multiple UAS	• One or More UAS Leaves Assigned Geofence	• One or More UAS is Intentionally Crashed into Manned Aircraft • One or More UAS is Intentionally Crashed into Vital Infrastructure
	Rogue / Noncompliant UAS	• Inability by UTM System to Stop Rogue / Noncompliant Operation(s) of UAS • Inability to Detect / Contain Rogue UAS • Ineffective Methods for Detecting / Containing Rogue UAS • Unsuccessful Detection / Containment of Rogue UAS	• Any / All Use Cases • Suburban / Urban • Moderate- / High-Density Operations	• One or More UAS is Not Operating within UTM System • One or More UAS Does Not Operate within an Assigned Geofence • One or More UAS Flight Plan is Unknown to Other UAS Operating with UTM System • Potential for Large-Scale Implications Involving Multiple Rogue UAS	• One or More UAS is Used to Interfere with Other UAS Missions (e.g., Search & Rescue) • One or More UAS is Used to Terrorize / Injure / Kill People on the Ground or to Gather Intelligence for Future Use in Terrorist Activities • One or More UAS is Used to Deliver Chemical / Biological Toxins • Aircraft loss of control • Destruction of Rogue UAS • Destruction of Innocent UAS in the same area	• People on the Ground are Poisoned, Injured, or Killed in Potentially Large Region or Multiple Regions • People in One or More Manned Aircraft are Injured / Killed • UAS causes accident involving ground vehicles • Negative Impact to Wildlife and Environment from UAS crash or Rogue UAS mission
	Rogue / Noncompliant UAS (Weaponized)				• One or More UAS is Used as a Sniper • One or More UAS is Used as a Weapon of Mass Destruction (WMD)	• People on the Ground are Injured / Killed in Potentially Large Region or Multiple Regions • People in One or More Manned Aircraft are Injured / Killed • One or More Critical Infrastructure is Destroyed
	Hostile Ground-Based Attack of UAS (e.g., Using High-Powered Rifle, UAS Counter Measure Devices, etc.)	• Inability to Prevent Such Attacks by FAA, UTM System, Law Enforcement	• Any / All Use Cases • Suburban / Urban • Moderate- / High-Density Operations	• Aircraft LOC Resulting from Vehicle Damage • Inflight UAS Breakup • Potential for Large-Scale Implications Involving Multiple UAS In Single or Multiple Regions	• Inability to Fly Desired Trajectory • UAS Exits Assigned Geofence	• Mid-Air Collision with One or More UAS • MAC with Manned Aircraft by One or More UAS • One or More UAS Collisions with One or More Buildings • Crash Debris Injures People on Ground

Table F.2-d. Future Hazards Set (4)

Category	Hazard	Causal / Contributing Factors	Use Case / Operational State	Result	Impacts	Hazardous Outcome
Single UAS Controlled Semi-Autonomously under BVLOS Operations	Unintentional / Erroneous Discharge of Weapons, Explosives, Chemicals, etc.	• Destruction of Vehicle Carrying Dangerous Cargo / Weapons (e.g., Toxic Substances / Chemicals, Explosives, etc.) • Failure of Delivery / Discharge System • Leak in Chemical Containment System • Unsuccessful Containment / Capture of Rogue UAS	• Any / All Use Cases • Suburban / Urban • Moderate- / High-Density Operations	• Stray Bullets • Explosion On / Near UAS • Release of Chemical Toxins	• UAS Damage / Break-Up • Damage to Other UAS • Damage to Nearby Manned Aircraft • Damage to Nearby Infrastructure	• Stray Bullets Injure / Kill People on Ground • Crash Debris Injures / Kills People on Ground • People on Manned Aircraft are Inured / Killed • Cascading Effects of Damaged Vehicles or Injured Persons on Roadways Leading to More Injury or Damage • People / Wildlife / Plant Life Harmed by Release of Toxic Chemicals
	Erroneous Autonomous Decisions / Actions by UAS Compromise Vehicle / Operational Safety	• Failure in Autonomous System Component • Inadequate Sensor Integrity Management for Critical Decision-Making by the System • Error Propagation Across Vehicle Autonomous Systems and Systems of Systems • Inadequate Resilience under Off-Nominal Conditions • Inadequate System Validation and/or Software Verification • Error Propagation Across Multiple UAS in Collaborative Missions	• Any / All Use Cases • Suburban / Urban • Moderate- / High-Density Operations	• Unreliable / Unexpected Actions by One or More UAS under Nominal or Off-Nominal Conditions • UAV Makes Faulty Decision that Results in Unsafe Flight / Mission	• UAS Exits Assigned Geofence • Aircraft Loss of Control (LOC) • Collision with Infrastructure (Building, Bridge, Power Lines / Sub-Station, etc.) or Terrain Features • Potential Impacts to Multiple UAS in Collaborative Mission	• Mid-Air Collision with One or More UAS • MAC with Manned Aircraft by One or More UAS • One or More UAS Collisions with One or More Buildings • Crash Debris Injures People on Ground • People in One or More Manned Aircraft are Injured / Killed
Multi-UAS & Collaborative UAS Controlled Autonomously under BVLOS Operations	Cascading Failures in Multi-UAS and Collaborative Missions	• Lack of Resilience in One or More UAS under Off-Nominal Conditions • Failure of Single Vehicle System that Affects Multiple UAS • Communication Interference / EMI Across Multi-UAS Operations • Error / Failure of Collaborative Control & Decision-Making • Inadequate Real-Time Safety Monitoring (Includes Autonomous & Human Operator and Inadequate Interfaces for Human-Automation Teaming) • Inadequate System Validation and/or Software Verification with or Across Multiple Interconnected Systems • Loss of Navigation Capability by One or More UAS	• Any / All Use Cases • Suburban / Urban • Moderate- / High-Density Operations	• Aircraft LOC Involving Multiple (Potentially Many) UAS • Loss of Separation Involving Multiple (Potentially Many) UAS • One or More UAS Exit(s) Assigned Geofence	• In-Flight UAS Damage / Breakup Involving Multiple (Potentially Many) UAS • MAC with One or More Manned Aircraft • One or More Collisions with Critical Infrastructure • MAC between potentially multiple UAS	• People on the Ground are Injured / Killed in Potentially Large Region or Multiple Regions • People in One or More Manned Aircraft are Injured / Killed • One or More Critical Infrastructure is Damage / Destroyed • Environment is Compromised by Crash Debris (e.g., Fuel Spill)

Table F.3-a. Combined Hazards Set (1)

Hazard No.	Hazard	Use Case / Category	Operational State	Causal / Contributing Factors	Result	Impacts	Hazardous Outcomes
VH-1	Aircraft Loss of Control (LOC)	Any / All Use Cases Associated with: Remote / Rural Location (Includes Precision Agriculture, Border Patrol, Wildfire Monitoring & Control, Package Delivery, etc.)	• Single UAS Manually Controlled by Remote Pilot under VLOS • Low-Density Airspace	• Vehicle Failures / Impairment • Control System Failures / Malfunctions / Inadequacy • Propulsion System Failure / Malfunction • Weather (Includes Rain, Snow / Icing, Thunderstorms, etc.) • Wind / Wind Shear / Turbulence (Includes Boundary Layer Effects) • Vehicle Upset Condition / Damage • Pilot Error • Power Loss / Fuel Exhaustion • Electromagnetic Interference (EMI) • Unsuccessful Launch • Flight Control System Design / Validation Errors / Inadequacy • Flight Control System Software Implementation / Verification Error / Inadequacy • Unexpected Obstacle Encounter Results in Unstable / Aggressive Avoidance Maneuver • Bird Strike • Others	• Undesired Flight Trajectory that is Difficult to Predict • Unpredictable / Unstable Control Response • Uncontrolled Descent	• Vehicle Exits Assigned Geofence • Uncontrolled Descent / Landing • Uncontrolled Descent into Terrain / Water • Vehicle Damage / Break-Up	• Mid-Air Collision with UAS • Mid-Air Collision with Manned Aircraft • Crash into Building / Obstacle Injures People • Crash Debris Injures People on Ground • Damage to Ground Asset Causes Fire
		Any / All Use Cases Associated with: Suburban / Urban / Congested (Includes Package Delivery, Traffic Monitoring, Infrastructure Inspection, etc.)	• Single UAS, Semi-Autonomous Control, BVLOS • Moderate- / High-Density Airspace	• All Hazards Listed Above • Payload / CG Shift / Instability • Inadequate Resilience in Flight Control System to Key LOC Hazards (Including Failures, Wind / Weather, etc.) • Vehicle Instability Resulting from Attempted Retrieval of Objects of Unknown size/weight • Vehicle Instability Resulting from Failure/Malfunction of Object Retrieval System • Launch/Landing Instability on Water-Based Platform • Propulsion or Vision Systems Failure / Inadequacy under Harsh Conditions (Fire, Smoke, Ash, Smog, Salty Sea Air, etc.)	• Above Results • Potential for LOC Involving Multiple UAS under Common Causal Conditions (e.g., Unexpected Wind / Weather)	• Above Impacts Involving Multiple (Potentially Many) UAS • Mid-Air Collision with One or More Manned Aircraft • One or More Collisions with Critical Infrastructure	• Above Outcomes on Potentially Large Scale • People on the Ground are Injured / Killed in Potentially Large Region or Multiple Regions • People in One or More Manned Aircraft are Injured / Killed • One or More Critical Infrastructure(s) are Damaged / Destroyed
		Any / All Use Cases Associated with: Suburban / Urban / Congested (Includes Videography / Security at Public Events, Environmental Monitoring, etc.)	• Single / Multiple Semi- / Fully-Autonomous Control under BVLOS • Moderate- / High-Density Airspace	• All Hazards Listed Above • Vehicle Damage (e.g., Lightning strike during long-duration missions, Damage from Explosion / Fire during Emergency Response, Radiation Exposure from HALE operations over urban areas, etc.) • Harsh Environmental Conditions (e.g., Extreme Temperatures, etc.) • Cascading Factors Involving Multi-UAS Operations • Unexpected Battery Depletion	• Above Results • Potential for LOC Involving Many UAS (Particularly from Design / Validation Inadequacy that Affects Multiple UAS and Multi-UAS Operations)		

Table F.3-b. Combined Hazards Set (2)

Hazard No.	Hazard	Use Case / Category	Operational State	Causal / Contributing Factors	Result	Impacts	Hazardous Outcomes
VH-2	Aircraft Fly-Away / Geofence Non-Conformance	Any / All Use Cases Associated with: Remote / Rural Location (Includes Precision Agriculture, Border Patrol, Wildfire Monitoring & Control, Package Delivery, etc.)	• Single UAS Manually Controlled by Remote Pilot under VLOS • Low-Density Airspace	• Loss of Communication / Control Link • Erroneous Way Points • GPS Failure / Errors • Autopilot Error / Malfunction • Pilot Error	• Inability to Control Aircraft from Ground • Inability to Monitor Aircraft Position • Inability to Initiate Flight Termination from Ground	• UAS Exits Assigned Geofence • Aircraft LOC	• Mid-Air Collision with UAS • Mid-Air Collision with Manned Aircraft • Crash into Building / Obstacle Injures People • Crash Debris Injures People on Ground
		Any / All Use Cases Associated with: Suburban / Urban / Congested (Includes Package Delivery, Traffic Monitoring, Infrastructure Inspection, etc.)	• Single UAS, Semi-Autonomous Control, BVLOS • Moderate- / High-Density Airspace	• GPS Signal Loss / Error • Network Unavailability • Onboard GPS System Failure / Malfunction • Lack of Navigational Redundancy • Jamming / Spoofing of GPS and/or V-V Signals • Erroneous Way Points • Error in Autonomous Mission Planner (Includes V&V Inadequacy)	• Above Results • Potential for Widespread Collisions under Common Causal Conditions (e.g., Network Loss)	• One or More UAS Exit Assigned Geofence • One or More UAS Enter Aircraft LOC Condition	• Potential for Above Outcomes on Larger Scale Involving Multiple UAS
		Any / All Use Cases Associated with: Suburban / Urban / Congested (Includes Videography / Security at Public Events, Environmental Monitoring, etc.)	• Single / Multiple Semi- / Fully- Autonomous Control under BVLOS • Moderate- / High-Density Airspace	• All of the Above • Loss of Navigation Capability by One or More UAS • Inadequate Design / Validation and/or Implementation / Verification of Coordinated Multi-UAS Operations • Communication Interference Among Multi-UAS Operators (e.g., EMI and/or Lack of Frequency Separation) • Inadequate Contingency Management	• Above Results • Potential for Widespread Results Involving Many UAS (Particularly from Design / Validation Inadequacy that Affects Multiple UAS and Multi-UAS Operations)	• Potentially Many UAS Exit Assigned Geofence • Potentially Many UAS Enter Aircraft LOC Condition	• Potential for Above Widespread Outcomes on Large Scale Involving Multiple UAS

Table F.3-c. Combined Hazards Set (3)

Hazard No.	Hazard	Use Case / Category	Operational State	Causal / Contributing Factors	Result	Impacts	Hazardous Outcomes
VH-3	Lost Communication / Control Link	Any / All Use Cases Associated with: Remote / Rural Location (Includes Precision Agriculture, Border Patrol, Wildfire Monitoring & Control, Package Delivery, etc.)	• Single UAS Manually Controlled by Remote Pilot under VLOS • Low-Density Airspace	• EMI at Vehicle • Signal Obscurence • Frequency / BW Overlap • Failure in GCS (e.g., Power Failure, etc.)	• Inability to Control Aircraft from Ground • Inability to Monitor Aircraft Position • Inability to Initiate Flight Termination from Ground • Automated Return to Base	• UAS Exits Assigned Geofence • Aircraft Loss of Control (LOC) • Controlled Flight into Terrain / Obstacle	• Mid-Air Collision with UAS • Mid-Air Collision with Manned Aircraft • Crash into Building / Obstacle Injures People • Crash Debris Injures People on Ground
		Any / All Use Cases Associated with: Suburban / Urban / Congested (Includes Package Delivery, Traffic Monitoring, Infrastructure Inspection, etc.)	• Single UAS, Semi-Autonomous Control, BVLOS • Moderate- / High-Density Airspace	• All of the Above • GPS Drop-Outs in Urban Environments • EMI Weapon Targeting One or More UAS • Signal Jamming / Spoofing • Frequency / BW Block • Network Unavailability	• Inability to Fly Desired Trajectory • Inability to Remotely Initiate Flight Termination • Potential for Widespread Collisions under Common Causal Conditions (e.g., Network Loss, Widespread Jamming)	• One or More UAS Exit Assigned Geofence • Aircraft Loss of Control (LOC) Involving One or More UAS • Controlled Flight into Terrain / Obstacle by One or More UAS	• Mid-Air Collision with One or More UAS • MAC with Manned Aircraft by One or More UAS • One or More UAS Collisions with One or More Buildings • Crash Debris Injures People on Ground
		Any / All Use Cases Associated with: Suburban / Urban / Congested (Includes Videography / Security at Public Events, Environmental Monitoring, etc.)	• Single / Multiple Semi- / Fully-Autonomous Control under BVLOS • Moderate- / High-Density Airspace	• All of the Above • Communication Interference Among Multi-UAS Operators (e.g., EMI and/or Lack of Frequency Separation) • Others	• Above Results • Potential for Widespread Results Involving Many UAS (Particularly from Design / Validation Inadequacy that Affects Multiple UAS and Multi-UAS Operations)	• Potentially Many UAS Exit Assigned Geofence • Aircraft Loss of Control (LOC) Involving Potentially Many UAS • Controlled Flight into Terrain / Obstacle by Potentially ManyUAS	• Potential for Above Widespread Outcomes on Large Scale Involving Multiple UAS

Table F.3-d. Combined Hazards Set (4)

Hazard No.	Hazard	Use Case / Category	Operational State	Causal / Contributing Factors	Result	Impacts	Hazardous Outcomes
VH-4	Loss of Navigation Capability	Any / All Use Cases Associated with: Remote / Rural Location (Includes Precision Agriculture, Border Patrol, Wildfire Monitoring & Control, Package Delivery, etc.)	• Single UAS Manually Controlled by Remote Pilot under VLOS • Low-Density Airspace	• Onboard Navigation System Failure / Malfunction • Loss of / Erroneous GPS Signal • Ground Station Set-Up Error	• Inability to Fly Desired Trajectory • Intentional Grounding	• UAS Exits Assigned Geofence	• Mid-Air Collision with UAS • Mid-Air Collision with Manned Aircraft • Crash into Building / Obstacle Injures People • Crash Debris Injures People on Ground
		Any / All Use Cases Associated with: Suburban / Urban / Congested (Includes Package Delivery, Traffic Monitoring, Infrastructure Inspection, etc.)	• Single UAS, Semi-Autonomous Control, BVLOS • Moderate- / High-Density Airspace	• All of the Above • Hostile Takeover and Control of UAS • GPS / ADS-B Signal Inaccuracy / Jamming / Spoofing • Network Unavailability • Vision System Inadequacy under Low-Visibility Conditions • Inadequate Perception of Visual Scene by Vision System	• Above Results • UAS Location is Inaccurate or Cannot be Determined • Potential for Widespread Collisions under Common Causal Conditions (e.g., GPS Signal or Network Loss)	• One or More UAS Exit Assigned Geofence • Safe Separation Cannot be Maintained	• MAC(s) Among One or More UAS • MAC(s) with Manned Aircraft • Collision(s) with Terrain, Obstacle(s), Building(s) • Crash Debris Injures People on Ground
		Any / All Use Cases Associated with: Suburban / Urban / Congested (Includes Videography / Security at Public Events, Environmental Monitoring, etc.)	• Single / Multiple Semi- / Fully-Autonomous Control under BVLOS • Moderate- / High-Density Airspace	• All of the Above • Autonomous Navigation System Error / Failure / Inadequacy • Lack of Resilience under Off-Nominal Conditions • Error Propagation Across Multi-UAS Autonomous Systems • Others	• Above Results • Potential for Widespread Collisions under Common Causal Conditions & Error Propagation Associated with Multi-UAS Operations	• Potentially Many UAS Exit Assigned Geofence • Potential for Widespread Collisions	• Potential for Above Widespread Outcomes on Large Scale Involving Multiple UAS
VH-5	Unsuccessful Landing	Any / All Use Cases Associated with: Single UAS Manually Controlled by Remote Pilot under VLOS Operations	Within Runway Safety Area	• Unstable Approach • Remote Pilot Error	• Abnormal Runway Contact • Crash on Landing	• Vehicle Damage / Break-Up	• Post-Crash Fire that Injures Ground Crew
			Outside Runway Safety Area				• Crash Debris Injures People on Ground

Table F.3-e. Combined Hazards Set (5)

Hazard No.	Hazard	Use Case / Category	Operational State	Causal / Contributing Factors	Result	Impacts	Hazardous Outcomes
VH-6	Unintentional / Unsuccessful Flight Termination	Any / All Use Cases Associated with: Remote / Rural Location (Includes Precision Agriculture, Border Patrol, Wildfire Monitoring & Control, Package Delivery, etc.)	• Single UAS Manually Controlled by Remote Pilot under VLOS • Low-Density Airspace	• Pilot Error in Either Initiating or Executing Flight Termination • Flight Termination System Error / Failure / Malfunction • Unexpected Wind / Weather Negatively Impacts Flight Termination • Failure of Command Link from Operator to Initiate Flight Termination	• UAS lands or has a forced crash in an unsafe location	• UAS Damage / Break-Up	• Post-Crash Fire that Threatens Wildlife & Environment
		Any / All Use Cases Associated with: Suburban / Urban / Congested (Includes Package Delivery, Traffic Monitoring, Infrastructure Inspection, etc.)	• Single UAS, Semi-Autonomous Control, BVLOS • Moderate- / High-Density Airspace	• Inadequate Database for or RT Identification of Safe Landing Zone • Vision System Inadequacy under Low-Visibility Conditions • Inadequate Perception of Visual Scene by Vision System • Failure of Command Link from Operator or Network to Initiate Flight Termination • Failure / Inadequacy of the Onboard Flight Termination System	• One or more UAS land or have a forced crash in one or more unsafe locations	• Damage / Break-Up of One or More UAS	• UAS injures people on ground • UAS crashes into ground vehicle • UAS causes accident involving ground vehicles • UAS Collides with Infrastructure (Building, Bridge, Power Lines / Sub-Station, etc.)
		Any / All Use Cases Associated with: Suburban / Urban / Congested (Includes Videography / Security at Public Events, Environmental Monitoring, etc.)	• Single / Multiple Semi- / Fully- Autonomous Control under BVLOS • Moderate- / High-Density Airspace	• All of the Above • Failure / Error / Inadequacy of Flight Termination System for Multi-UAS and Coordinated Multi-UAS Operations	• Potentially many UAS land or have a forced crash in multiple unsafe locations	• Damage / Break-Up of Potentially Many UAS	• Multiple UAS injure people on ground • One or more UAS crash into ground vehicle • One or more UAS cause accident involving ground vehicles • Multiple UAS Collide with Infrastructure (Building, Bridge, Power Lines / Sub-Station, etc.)

Table F.3-f. Combined Hazards Set (6)

Hazard No.	Hazard	Use Case / Category	Operational State	Causal / Contributing Factors	Result	Impacts	Hazardous Outcomes
VH-7	Failure / Inability to Avoid Collision with Terrain and/or Fixed / Moving Obstacle	Any / All Use Cases Associated with: Remote / Rural Location (Includes Precision Agriculture, Border Patrol, Wildfire Monitoring & Control, Package Delivery, etc.)	• Single UAS Manually Controlled by Remote Pilot under VLOS • Low-Density Airspace	• Pilot Error / Poor Judgment • Wind / Weather that Results in Abnormal Flight Trajectory • Erroneous Way Points that Create Conflict with Obstacle • Inaccurate GPS Signal • Inadequate Navigation / Tracking	• Collision with Building / Bridge • Collision with Power Lines / Sub-Station • Collision with Ground Vehicle	• UAS Break-Up	• Crash Debris Injures People on Ground • UAS / Crash Debris Causes Ground Vehicle Accident on Highway • Post-Crash Fire that Damages Building and/or Injures People Inside the Building • Post-Crash Fire that Damages Power System & Environment
		Any / All Use Cases Associated with: Suburban / Urban / Congested (Includes Package Delivery, Traffic Monitoring, Infrastructure Inspection, etc.)	• Single UAS, Semi-Autonomous Control, BVLOS • Moderate- / High-Density Airspace	• All of Above • Inadequate / Lack of Sense/Detect and Avoid (SAA/DAA) Capability • Inadequate Design / Validation or Failure of SAA / DAA System • Vision System Failure / Inadequacy in Low Visibility Conditions • Missed Detection of Obstacle • Inadequate / Erroneous / Incomplete Terrain Database • Inadequate / Ineffective Sensor System for Detection of Small / Thin Obstacles (e.g., Power Lines) • Inadequate Resilience to Key Hazards (e.g., component failures, external disturbances) • Launch/Landing Instability on Water-Based Platform • Propulsion or Vision Systems Failure / Inadequacy under Harsh Conditions (Fire, Smoke, Ash, Smog, Salty Sea Air, etc.)	• Above Results • Mid-Air Collision with UAS • Mid-Air Collision with Manned Aircraft • Potential for Widespread Collisions under Common Causal Conditions (e.g., Poor Visibility)	• Break-Up of One or More UAS • Damage to Air / Ground Vehicle	• Above Outcomes • UAV Collides with High-Voltage Power Lines and Causes a Fire / Explosion • MACs with One or More UAS • Crash by One or More UAS into Building / Obstacle and Injures People • MAC with Manned Aircraft by One or More UAS
		Any / All Use Cases Associated with: Suburban / Urban / Congested (Includes Videography / Security at Public Events, Environmental Monitoring, etc.)	• Single / Multiple Semi- / Fully-Autonomous Control under BVLOS • Moderate- / High-Density Airspace		• Above Results • Potential for Widespread Collisions under Common Causal Conditions & Error Propagation Associated with Multi-UAS Operations	• Break-Up of Multiple UAS • Damage to One of More Air / Ground Vehicles	• Above Outcomes • Potential for Widespread Collisions involving Multiple UAS

Table F.3-g. Combined Hazards Set (7)

Hazard No.	Hazard	Use Case / Category	Operational State	Causal / Contributing Factors	Result	Impacts	Hazardous Outcomes
VH-8	Hostile Remote Takeover and Control of UAS	Any / All Use Cases Associated with: Suburban / Urban / Congested (Includes Videography / Security at Public Events, Environmental Monitoring, etc.)	• Single / Multiple Semi- / Fully-Autonomous Control under BVLOS • Moderate- / High-Density Airspace	• Lack of Data / Cyber Security by Operator or within UTM System • Increasing Level of Sophistication of Terrorist Threat	• UAS is no longer under operator control • Potential for Simultaneous Takeover of Multiple UAS	• One or More UAS Exit Assigned Geofence	• One or More UAS is Intentionally Crashed into Manned Aircraft • One or More UAS is Intentionally Crashed into Vital Infrastructure
VH-9	Rogue / Noncompliant UAS	Any / All Use Cases Associated with: Suburban / Urban / Congested (Includes Videography / Security at Public Events, Environmental Monitoring, etc.)	• Single / Multiple Semi- / Fully-Autonomous Control under BVLOS • Moderate- / High-Density Airspace	• Inability by UTM System to Stop Rogue / Noncompliant Operation(s) of UAS • Inability to Detect / Contain Rogue UAS • Ineffective Methods for Detecting / Containing Rogue UAS • Unsuccessful Detection / Containment of Rogue UAS	• One or More UAS is Not Operating within UTM System • One or More UAS Does Not Operate within an Assigned Geofence • One or More UAS Flight Plan is Unknown to Other UAS Operating with UTM System • Potential for Large-Scale Implications Involving Multiple Rogue UAS	• One or More UAS is Used to Interfere with Other UAS Missions (e.g., Search & Rescue) • One or More UAS is Used to Terrorize / Injure / Kill People on the Ground or to Gather Intelligence for Future Use in Terrorist Activities • One or More UAS is Used to Deliver Chemical / Biological Toxins • Aircraft loss of control • Destruction of Rogue UAS • Destruction of Innocent UAS in the same area	• People on the Ground are Poisoned, Injured, or Killed in Potentially Large Region or Multiple Regions • People in One or More Manned Aircraft are Injured / Killed • UAS causes accident involving ground vehicles • Negative Impact to Wildlife and Environment from UAS crash or Rogue UAS mission
VH-10	Rogue / Noncompliant UAS (Weaponized)		• Single / Multiple Semi- / Fully-Autonomous Control under BVLOS • Moderate- / High-Density Airspace			• One or More UAS is Used as a Sniper • One or More UAS is Used as a Weapon of Mass Destruction (WMD)	• People on the Ground are Injured / Killed in Potentially Large Region or Multiple Regions • People in One or More Manned Aircraft are Injured / Killed • One or More Critical Infrastructures are Destroyed

Table F.3-h. Combined Hazards Set (8)

Hazard No.	Hazard	Use Case / Category	Operational State	Causal / Contributing Factors	Result	Impacts	Hazardous Outcomes
VH-11	Hostile Ground-Based Attack of UAS (e.g., Using High-Powered Rifle, UAS Counter Measure Devices, etc.)	Any / All Use Cases Associated with: Suburban / Urban / Congested (Includes Videography / Security at Public Events, Environmental Monitoring, etc.)	• Single / Multiple Semi- / Fully- Autonomous Control under BVLOS • Moderate- / High-Density Airspace	• Inability to Prevent Such Attacks by FAA, UTM System, Law Enforcement	• Aircraft LOC Resulting from Vehicle Damage • Inflight UAS Breakup • Potential for Large-Scale Implications Involving Multiple UAS In Single or Multiple Regions	• Inability to Fly Desired Trajectory • UAS Exits Assigned Geofence	• Mid-Air Collision with One or More UAS • Mid-Air Collision with Manned Aircraft by One or More UAS • One or More UAS Collide with One or More Buildings • Crash Debris Injures People on Ground
VH-12	Unintentional / Erroneous Discharge of Weapons, Explosives, Chemicals, etc.	Any / All Use Cases Associated with: Suburban / Urban / Congested (Includes Videography / Security at Public Events, Environmental Monitoring, etc.)	• Single / Multiple Semi- / Fully- Autonomous Control under BVLOS • Moderate- / High-Density Airspace	• Destruction of Vehicle Carrying Dangerous Cargo / Weapons (e.g., Toxic Substances / Chemicals, Explosives, etc.) • Failure of Delivery / Discharge System • Leak in Chemical Containment System • Unsuccessful Containment / Capture of Rogue UAS	• Stray Bullets • Explosion On / Near UAS • Release of Chemical Toxins	• UAS Damage / Break-Up • Damage to Other UAS • Damage to Nearby Manned Aircraft • Damage to Nearby Infrastructure	• Stray Bullets Injure / Kill People on Ground • Crash Debris Injures / Kills People on Ground • People on Manned Aircraft are Inured / Killed • Cascading Effects of Damaged Vehicles or Injured Persons on Roadways Leading to More Injury or Damage • People / Wildlife / Plant Life Harmed by Release of Toxic Chemicals

Table F.3-i. Combined Hazards Set (9)

Hazard No.	Hazard	Use Case / Category	Operational State	Causal / Contributing Factors	Result	Impacts	Hazardous Outcomes
VH-13	Erroneous Autonomous Decisions / Actions by UAS Compromise Vehicle / Operational Safety	Any / All Use Cases Associated with: Suburban / Urban / Congested (Includes Videography / Security at Public Events, Environmental Monitoring, etc.)	• Single / Multiple Semi- / Fully-Autonomous Control under BVLOS • Moderate- / High-Density Airspace	• Inadequate Sensor Integrity Management for Critical Decision-Making by the System • Error Propagation Across Vehicle Autonomous Systems and Systems of Systems • Inadequate Resilience under Off-Nominal Conditions • Inadequate System Validation & Software Verification	• Unreliable / Unexpected Actions by One or More UAS under Nominal or Off-Nominal Conditions • UAV Makes Faulty Decision that Results in Unsafe Flight / Mission	• UAS Exits Assigned Geofence • Aircraft Loss of Control (LOC) • Collision with Infrastructure (Building, Bridge, Power Lines / Sub-Station, etc.) or Terrain Features • Potential Impacts to Multiple UAS in Collaborative Mission	• Mid-Air Collision with One or More UAS • Mid-Air Collision with Manned Aircraft by One or More UAS • One or More UAS Collide with One or More Buildings • Crash Debris Injures People on Ground • People in One or More Manned Aircraft are Injured / Killed
VH-14	Cascading Failures in Multi-UAS and Collaborative Missions	Any / All Use Cases Associated with: Suburban / Urban / Congested (Includes Videography / Security at Public Events, Environmental Monitoring, etc.)	• Single / Multiple Semi- / Fully-Autonomous Control under BVLOS • Moderate- / High-Density Airspace	• Lack of Resilience in One or More UAS under Off-Nominal Conditions • Failure of Single Vehicle System that Affects Multiple UAS • Communication Interference / EMI Across Multi-UAS Operations • Error / Failure of Collaborative Control & Decision-Making • Inadequate Real-Time Safety Monitoring (Includes Autonomous & Human Operator and Inadequate Interfaces for Human-Automation Teaming) • Inadequate System Validation and/or Software Verification with or Across Multiple Interconnected Systems • Loss of Navigation Capability by One or More UAS	• Aircraft LOC Involving Multiple (Potentially Many) UAS • Loss of Separation Involving Multiple (Potentially Many) UAS • One or More UAS Exit(s) Assigned Geofence	• Mid-Air Collision with One or More Manned Aircraft • In-Flight UAS Damage / Breakup Involving Multiple (Potentially Many) UAS • One or More Collisions with Critical Infrastructure • Mid-Air Collision between potentially many UAS	• People on the Ground are Injured / Killed in Potentially Large Region or Multiple Regions • People in One or More Manned Aircraft are Injured / Killed • One or More Critical Infrastructure is Damage / Destroyed • Environment is Compromised by Crash Debris (e.g., Fuel Spill)

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