Unmanned Aircraft Systems in the National Airspace System: Establishing Equivalency in Safety and Training Through a Fault Tree Analysis Approach

A thesis presented to
the faculty of
the Russ College of Engineering and Technology of Ohio University

In partial fulfillment
of the requirements for the degree
Master of Science

Jessica A. Belzer
April 2017
© 2017 Jessica A. Belzer. All Rights Reserved.
This thesis titled
Unmanned Aircraft Systems in the National Airspace System: Establishing Equivalency in Safety and Training Through a Fault Tree Analysis Approach

by
JESSICA A. BELZER

has been approved for
the Department of Electrical Engineering and Computer Science
and the Russ College of Engineering and Technology by

Frank van Graas
Fritz J. and Delores H. Russ Professor of Electrical Engineering and Computer Science

Dennis Irwin
Dean, Russ College of Engineering and Technology
ABSTRACT

BELZER, JESSICA A., M.S., April 2017, Electrical Engineering

Unmanned Aircraft Systems in the National Airspace System: Establishing Equivalency in Safety and Training Through a Fault Tree Analysis Approach (325 pp.)

Director of Thesis: Frank van Graas

With approval of UAS for civilian use in the National Airspace System, comes the need for formal integration. Manned and unmanned aircraft will share the same volumes of airspace, for which the safety standards must be upheld. Under manned aircraft operations, certain implicit assumptions exist that must be made explicit and translatable to the unmanned aircraft context. A formal system safety assessment approach through a fault tree analysis was used to identify assumptions contingent on a pilot's presence inside the fuselage and areas of weakness in operational equivalency of UAS.

The UAS fault tree framework developed is applicable to unmanned aircraft systems of different sizes and complexity, while maintaining a semblance to the framework accepted within the manned aircraft community. In addition, a database of UAS incidents and accidents occurring internationally 2001-2016 was developed from published materials and databases of various sources. Database events were categorized according to the UAS Fault Tree Framework Level 1 Subsystems, the International Civil Aviation Organization (ICAO) Aviation Occurrence Categories, and the Human Factors Analysis and Classification System (HFACS). ICAO Aviation Occurrence Category specific fault trees were constructed for the three most commonly occurring categories in the database results.

Significant sources of risk for UAS operations lie in Aircraft/System and Flight Crew/Human Factors failures. Commonly occurring Occurrence Categories in the results of the UAS database were different than those identified for fatal accidents occurring in manned commercial aviation operations. Increased system reliability and
standardization is needed to ensure equivalent levels of safety for UAS operations in the NAS. Additionally, needs of UAS pilots are different than those for manned and model aircraft. Training requirements must be approached independently and formally evaluated for their effectiveness in risk mitigation.
DEDICATION

To my friends, colleagues, and family
ACKNOWLEDGMENTS

Thank you to the committee members and my advisor, Dr. Frank van Graas, for serving on my committee and making my thesis possible. Additionally, I would like to thank the Joint University Program for their contribution to making this research possible. This research was funded in part through the JUP sponsored by the Federal Aviation Administration. Funding was received Fall 2014- Spring 2015 and quarterly presentations on this research were performed during November 2013, February 2014, and January 2015 at the Massachusetts Institute of Technology, and the Federal Aviation Administration Technical Center respectively.
# Table of Contents

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Abstract</td>
<td>3</td>
</tr>
<tr>
<td>Dedication</td>
<td>5</td>
</tr>
<tr>
<td>Acknowledgments</td>
<td>6</td>
</tr>
<tr>
<td>List of Tables</td>
<td>11</td>
</tr>
<tr>
<td>List of Figures</td>
<td>12</td>
</tr>
<tr>
<td>List of Terms and Abbreviations</td>
<td>13</td>
</tr>
<tr>
<td>1 Introduction</td>
<td>15</td>
</tr>
<tr>
<td>1.1 The Origins of UAS</td>
<td>15</td>
</tr>
<tr>
<td>1.2 UAS and the NAS</td>
<td>16</td>
</tr>
<tr>
<td>2 Background</td>
<td>20</td>
</tr>
<tr>
<td>2.1 The National Airspace System and Operations within It</td>
<td>20</td>
</tr>
<tr>
<td>2.1.1 UAS Operations in the NAS</td>
<td>22</td>
</tr>
<tr>
<td>2.2 Problems Presented by the Introduction of Civil Small Unmanned Aircraft System Use</td>
<td>24</td>
</tr>
<tr>
<td>2.2.1 Accidents and Incidents</td>
<td>24</td>
</tr>
<tr>
<td>2.2.2 Privacy Concerns and the Expectation of Privacy</td>
<td>26</td>
</tr>
<tr>
<td>2.2.3 Liability Concerns for UAS Operations in the NAS and Responsibility of the UAS Operator</td>
<td>29</td>
</tr>
<tr>
<td>2.3 UAS and Model Aircraft</td>
<td>32</td>
</tr>
<tr>
<td>2.4 Concerns for Civil Unmanned Aircraft System Integration into the National Airspace System</td>
<td>35</td>
</tr>
<tr>
<td>2.4.1 Avoiding Other Aircraft</td>
<td>35</td>
</tr>
<tr>
<td>2.4.2 Environmental Concerns</td>
<td>37</td>
</tr>
<tr>
<td>2.5 System Safety Assessments and Fault Tree Analyses</td>
<td>38</td>
</tr>
<tr>
<td>2.5.1 The System Safety Assessment</td>
<td>38</td>
</tr>
<tr>
<td>2.5.2 The Fault Tree Analysis</td>
<td>39</td>
</tr>
<tr>
<td>2.5.3 System Safety Assessments, Fault Tree Analyses, and Unmanned Aircraft Systems</td>
<td>41</td>
</tr>
<tr>
<td>2.6 The Path Toward Integration of Unmanned Aircraft Systems into the National Airspace System Through a System Safety Assessment</td>
<td>43</td>
</tr>
<tr>
<td>2.6.1 Achieving an Equivalent Level of Safety in UAS Operations and The UAS System-Level Fault Tree Analysis</td>
<td>43</td>
</tr>
<tr>
<td>Section</td>
<td>Title</td>
</tr>
<tr>
<td>---------</td>
<td>----------------------------------------------------------------------</td>
</tr>
<tr>
<td>2.6.2</td>
<td>Additional ICAO Aviation Occurrence-Specific Fault Tree Analyses</td>
</tr>
<tr>
<td>2.6.3</td>
<td>Introduction to Scope and Assumptions</td>
</tr>
<tr>
<td>2.7</td>
<td>Recent UAS Integration Developments and Operational Requirements for</td>
</tr>
<tr>
<td></td>
<td>Flight in the National Airspace System</td>
</tr>
<tr>
<td>2.7.1</td>
<td>UAS Developments and Flight</td>
</tr>
<tr>
<td>2.7.2</td>
<td>Manned Aircraft Flight Requirements and Airmen Qualification</td>
</tr>
<tr>
<td>2.7.2.1</td>
<td>Equipage Requirements</td>
</tr>
<tr>
<td>2.7.2.2</td>
<td>Pilot Qualification and Training</td>
</tr>
<tr>
<td>3</td>
<td>Literature Review</td>
</tr>
<tr>
<td>3.1</td>
<td>Target Levels of Safety for Operations in the NAS: System Safety</td>
</tr>
<tr>
<td></td>
<td>Assessments and Certifying Part 23 Airplanes</td>
</tr>
<tr>
<td>3.2</td>
<td>On Integrating Unmanned Aircraft Systems into the National Airspace</td>
</tr>
<tr>
<td></td>
<td>System: Dalamakisid et al.</td>
</tr>
<tr>
<td>3.3</td>
<td>Safety Considerations for Operation of Unmanned Aerial Vehicles in the</td>
</tr>
<tr>
<td></td>
<td>National Airspace System</td>
</tr>
<tr>
<td>3.4</td>
<td>An Evidence Theoretic Approach to Design of Reliable-Low Cost UAVs</td>
</tr>
<tr>
<td>4</td>
<td>Methods</td>
</tr>
<tr>
<td>4.1</td>
<td>Fault Tree Analysis</td>
</tr>
<tr>
<td>4.1.1</td>
<td>Scope of the Fault Tree Analyses</td>
</tr>
<tr>
<td>4.1.2</td>
<td>Assumptions for the Fault Tree Analyses</td>
</tr>
<tr>
<td>4.1.3</td>
<td>Fault Tree Development Procedure, References, and Objective</td>
</tr>
<tr>
<td>4.1.4</td>
<td>Introduction to the Fault Tree Analysis Results</td>
</tr>
<tr>
<td>4.1.5</td>
<td>ICAO Aviation Occurrence Category-Specific Fault Tree Analyses:</td>
</tr>
<tr>
<td></td>
<td>Selection and Objectives</td>
</tr>
<tr>
<td>4.1.6</td>
<td>General Resolution Objectives for the Fault Tree Analyses</td>
</tr>
<tr>
<td>4.2</td>
<td>Database Creation and Categorization</td>
</tr>
<tr>
<td>4.2.1</td>
<td>Database Categorization Taxonomy 1: UAS Fault Tree Framework</td>
</tr>
<tr>
<td></td>
<td>Subsystem Level 1 Category, and the UAS Fault Tree Framework</td>
</tr>
<tr>
<td>4.2.2</td>
<td>Database Categorization Taxonomy 2: ICAO Aviation Occurrence Categories</td>
</tr>
<tr>
<td>4.2.3</td>
<td>Database Categorization Taxonomy 3: Human Factors Analysis</td>
</tr>
<tr>
<td></td>
<td>and Classification System (HFACS) Unsafe Acts</td>
</tr>
<tr>
<td>4.2.4</td>
<td>Definition of Accident and Incident Terms in the Context of the</td>
</tr>
<tr>
<td></td>
<td>Database</td>
</tr>
<tr>
<td>4.2.5</td>
<td>Data Sources, Collection Procedure, and Data Boundaries</td>
</tr>
<tr>
<td>5</td>
<td>Results</td>
</tr>
<tr>
<td>5.1</td>
<td>Database Results</td>
</tr>
<tr>
<td>5.1.1</td>
<td>The Database at a Glance</td>
</tr>
<tr>
<td>5.1.1.1</td>
<td>Results by Year</td>
</tr>
<tr>
<td>5.1.1.2</td>
<td>Results by Criticality</td>
</tr>
</tbody>
</table>
5.1.2 Accidents and Incidents by UAS Type ........................................ 103
5.1.3 Accidents and Incidents by Human Error Involvement ............... 105
5.1.4 Database Categorization Results ............................................. 105
  5.1.4.1 Taxonomy 1: The UAS Fault Tree Framework Level 1
    Subsystems ........................................................................... 105
5.1.5 Taxonomy 2: ICAO Aviation Occurrence Categories ................... 107
5.1.6 Taxonomy 3: HFACS Unsafe Acts ........................................... 110
    5.1.6.1 Categorized by Entity at Fault: Definitions of Formal
    and Other UAS Operators ..................................................... 111
5.2 Fault Tree Analyses ................................................................. 113
  5.2.1 FT1: System Wide Fault Tree ............................................... 113
    5.2.1.1 Aircraft/System Level 1 Subsystem ................................. 114
    5.2.1.2 Flight Crew/Human Factors Level 1 Subsystem ............... 115
    5.2.1.3 Maintenance Level 1 Subsystem ..................................... 117
    5.2.1.4 Weather/Environmental Factors Level 1 Subsystem .......... 117
    5.2.1.5 Air Traffic Control and Miscellaneous Level 1 Subsystems 118
  5.2.2 FT2: ICAO Occurrence Category 1: System/Component Failure or
    Malfunction (Non-Powerplant) ............................................... 119
  5.2.3 FT3: ICAO Occurrence Category 2: AIRPROX/TCAS Alert/Loss
    of Separation/Near Midair Collisions/Midair Collisions (MAC) ..... 121
  5.2.4 FT4: ICAO Occurrence Category 3: Navigation Errors (NAV) .... 124

6 Discussion ................................................................. 128
  6.1 Interpreting the Results ....................................................... 128
    6.1.1 Accidents and Incidents by UAS Type ................................. 128
    6.1.2 Accidents and Incidents by Human Error Involvement .......... 129
    6.1.3 Taxonomy 1: The UAS Fault Tree Framework Level 1 Subsystems 129
    6.1.4 Taxonomy 2: ICAO Aviation Occurrence Categories ................ 131
    6.1.5 Taxonomy 3: HFACS Unsafe Acts ..................................... 132
  6.2 Challenges and Areas of Need in UAS Integration ...................... 133
    6.2.1 UAS Aircraft System Needs .............................................. 134
    6.2.2 UAS Flight Crew/Operator Needs ...................................... 135
    6.2.3 Aircraft Development and Certification Needs ...................... 137
    6.2.4 UAS Hobbyist Community Development .............................. 138

7 Summary and Conclusions ................................................... 139

8 Recommendations ............................................................. 143

References ................................................................. 145

Appendix A: Fault Tree Analysis Results at a Glance .................... 153
LIST OF TABLES

<table>
<thead>
<tr>
<th>Table</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1</td>
<td>23</td>
</tr>
<tr>
<td>5.1</td>
<td>109</td>
</tr>
</tbody>
</table>

2.1 Summary of Current Requirements for Operation of Unmanned Aircraft Systems in the National Airspace System, Based on Application. This table is a reproduction from the Federal Aviation Administration ‘Getting Started’ webpage [23].

5.1 Glossary of ICAO Aviation Occurrence Category Abbreviations Which Occur in the UAS Accidents/Incidents Database.
# List of Figures

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1</td>
<td>Official Federal Aviation Distributed Diagram of the Characteristics of Different Classes of Airspace Within the National Airspace System. This diagram has been reproduced from a promotional educational bookmark issued by the FAA [11].</td>
<td>20</td>
</tr>
<tr>
<td>4.1</td>
<td>Example of General Fault Tree Framework for Manned Aircraft. This diagram has been reproduced from a Federal Aviation Administration educational promotional item.</td>
<td>85</td>
</tr>
<tr>
<td>4.2</td>
<td>Example of Proposed General Fault Tree Framework for Unmanned Aircraft</td>
<td>85</td>
</tr>
<tr>
<td>5.1</td>
<td>Unmanned Aircraft System Accidents and Incidents by Year (Database Derived)</td>
<td>101</td>
</tr>
<tr>
<td>5.2</td>
<td>Unmanned Aircraft System Criticality of Reported Event as Database Proportion. A critical event is defined as Class A mishap.</td>
<td>102</td>
</tr>
<tr>
<td>5.3</td>
<td>Unmanned Aircraft System Models Involved in Accidents and Incidents by Proportion (Database Derived). The “Other” identifier encompasses all identified models with 5 events or fewer.</td>
<td>104</td>
</tr>
<tr>
<td>5.4</td>
<td>Unmanned Aircraft System Models Involved in Accidents and Incidents by Number of Reported Events (Database Derived).</td>
<td>104</td>
</tr>
<tr>
<td>5.5</td>
<td>Unmanned Aircraft System Accidents and Incidents Involving Human Error by Proportion (Database Derived). Human Error was not necessarily the primary cause in these events.</td>
<td>105</td>
</tr>
<tr>
<td>5.6</td>
<td>Unmanned Aircraft System Accidents and Incidents Categorized by UAS Fault Tree Level 1 Subsystem Events (Database Derived). For the purposes of this categorization, the top level event was each occurrence.</td>
<td>106</td>
</tr>
<tr>
<td>5.7</td>
<td>Unmanned Aircraft System Accidents and Incidents Categorized by ICAO Aviation Occurrence.</td>
<td>108</td>
</tr>
<tr>
<td>5.8</td>
<td>Unmanned Aircraft System Accidents and Incidents Involving Human Error Classified by HFACS Unsafe Acts (Database Derived). This is a subset of the database data.</td>
<td>111</td>
</tr>
<tr>
<td>5.9</td>
<td>Unmanned Aircraft System Accidents and Incidents Involving Human Error Classified by Entity at Fault (Database Derived). These are the entities which committed the errors and violations which progressed to HFACS Unsafe Acts. This is a subset of the database data.</td>
<td>113</td>
</tr>
</tbody>
</table>
LIST OF TERMS AND ABBREVIATIONS

ICAO  International Civil Aviation Organization
HFACS  Human Factors Analysis Classification System
UAS  Unmanned Aircraft System
NAS  National Airspace System
FAA  Federal Aviation Administration
SSA  System Safety Assessment
FTA  Fault Tree Analysis
AMA  Academy of Model Aeronautics
sUAS  Small Unmanned Aircraft System
AUVSI  Association for Unmanned Vehicle Systems International
FAR  Federal Aviation Regulation
NTSB  National Transportation Safety Board
AGL  Above Ground Level
NMAC  Near Midair Collision
FHA  Functional Hazard Assessment
PSSA  Preliminary System Safety Assessment
SAE  Society of Automotive Engineers
DD  Dependence Diagram
MA  Markov Analysis
FMEA  Failure Modes and Effects Analysis
FMES  Failure Modes and Effects Summary
CCA  Common Cause Analysis
ZSA  Zonal Safety Analysis
PRA  Particular Risks Analysis
CMA  Common Mode Analysis
GA  General Aviation
CAST  Commercial Aviation Safety Team
ATSB  Australian Transport Safety Bureau
AIDS  FAA Accident and Incident Data System
ASRS  NASA Aviation Safety Reporting System
RWS  Runway Safety Office Runway Incursion Database
NMACS  FAA Near Midair Collision System Database
COA  Certificate of Authorization
1 Introduction

1.1 The Origins of UAS

The concept of an unmanned aircraft is not new. In fact, it can be traced in its modern form to the first “drones” implemented for use in artillery training during World War II. Manned aircraft were converted for remote flight for use in artillery training of anti-aircraft military forces. Notably, the first aircraft converted and successfully used in target training was the Queen Bee target drone implemented by the British Royal Navy in 1933 [1]. Today’s use of the word “drone” in unmanned aircraft conversation stems from this original implementation. As increasingly advanced electrical and radio technologies became available, hobby kites turned into hobby aircraft, and model boats turned into model planes. Today, there is a large body of hobbyists who identify as “drone” or Unmanned Aircraft System (UAS) users. The hobby aircraft market was taken by storm with the release of the Parrot AR. Drone in 2010 [2]. This aircraft was the first model to kick-start a massive quadcopter trend on a hobbyist level. With captivating technical features such as easy interfacing with common user-electronics (running iOS or Android), an on-board camera for a “bird’s-eye” view, and a certain level of preprogrammed autonomy [2], the aircraft quickly became a great entry-level machine for interested hobbyists lacking formal pilot (manned or radio control) training. These aircraft quickly caught on for applications in research such as autonomous navigation in indoor environments, for which algorithms were previously tested on much heavier, and more expensive platforms. However, it was only a matter of time before videos began to surface on the internet of crashes. Fortunately, these were resilient hobby aircraft encased in a Styrofoam bumper [2]. As time has passed, and “drone technologies” have evolved since 2010, these small aircraft have become increasingly sophisticated, while remaining widely available to consumers. Companies have met widespread interest by producing a large array of machines with
varying performance characteristics, sizes, and payload capacities. In fact, these systems which started as toys, have evolved into an aircraft type of their own.

In addition to their growing use on a personal hobby front, remotely piloted aircraft have an established history in the military context. Beginning with the use of target drones such as the Queen Bee, the aircraft grew into use for more difficult longer-range applications such as reconnaissance during the Cold War, an application which they are still used extensively for today. Originally these aircraft were often retrieved by parachute before they became truly remotely piloted [3]. These points and a larger history of the development of UAS for both civil and military applications are discussed in Chapter 2 of the book On Integrating Unmanned Aircraft Systems into the National Airspace System by Dalamagkidis, et al. In the military, a wide range of UAS are currently implemented, including small aircraft similar in size and payload to their consumer-electronic counterparts. However, there is a distinct difference between the two types of operations. Military operations involve formal procedure, training, aircraft maintenance, and strategic oversight in order to ensure that the use of these aircraft is as seamless and low-risk as possible. Much of this stems from the fact that a Reaper is estimated by Time Magazine to cost roughly 15.1 million dollars for a single aircraft and its associated sensors. This figure does not include the associated ground station [4]. This aircraft has a large wingspan to match its high price point, measuring at 66 feet [5].

1.2 UAS and the NAS

As Unmanned Aerial Systems become integrated in to the National Airspace System (NAS), these remotely piloted and unmanned aircraft will be functioning on a wide base of applications and as such will feature a wide spectrum of size and performance characteristics. Overall, the aircraft projected to be fully integrated in the future may vary in wingspan from 10 to 250 feet and in weight from 30 to 900,000 pounds [6] (with
room for larger and smaller yet, such as the smaller Parrot “drones”). The integration of these systems into the NAS, therefore, is a multi-faceted problem. The Federal Aviation Administration Concept of Operations for Integration of Unmanned Aircraft Systems into the National Airspace System, released in 2012, outlines UAS integrated NAS operations for a chosen seven aircraft. These aircraft are projected to create a reasonable and sufficient spectrum of size and performance characteristics from which cases of integration may be regarded [6]. In order to ensure a thoroughly safe and cohesive integration of these aircraft which are fundamentally different from their manned counterparts, the inherent differences in their functionality and resulting implications must be formally accounted for.

The United States currently hosts a large amount of aircraft operations each day, and that number is projected to grow. For example, the Federal Aviation Administration (FAA) reported in March of 2016 that paid passenger miles flown by mainline and regional airlines are projected to increase at about 2.6% per year [7]. Alongside these operations, with increased integration of UAS, the number of total operations will increase drastically. The total projected sales of UAS for commercial and hobbyist operations is expected to almost triple from the current 2016 sum to 7 million units in 2020 [8]. In order to accommodate the increased volume of operations, the workload has increased for aircraft and pilot certification, traffic management, and airport management operations. This projected increase is a large motivation for the adoption of the NextGen Airspace system—a performance based approach to streamlining the airspace for increased efficiency in operations [9].

The FAA is motivated to provide a highly safe environment for airspace operations of all kinds through implementation of advanced technology and formal UAS integration through legislation, certification, licensing, and registration efforts. Training of manned operators, remotely piloted aircraft operators, and air traffic controllers is an essential part of the safety equation. The measured introduction of unmanned aircraft systems into the
NAS will introduce a new host of unique training concerns which must be addressed. In order to achieve equivalency in safety and training, these differences which have not been previously identified must be formally examined.

In the thesis, training needs necessary to mitigate the risks posed by introduction of unmanned aircraft systems will be examined for manned, unmanned aircraft, and air traffic control operations. These areas of concern will be identified through the use of a Fault Tree Analysis, a statistical modeling tool, formed upon the basis of Boolean logic of related event occurrences, used as a routine component of a System Safety Assessment. System Safety Assessments (SSA) and Fault Tree Analyses (FTA) are cornerstones for use in proving the reliability of manned aircraft for operation in the National Airspace System. Through the use of these tools to formally prove adherence to safety standards, the aircraft are certified for operations.

Once areas of concern are identified, and a framework within which to view them created, statistical analysis and the use of safety modeling tools will drive the increased research, development, and system requirements in order to ensure that a given unmanned aircraft system operation is proven to be as safe as its manned counterpart. The development of a formal Fault Tree framework tailored to Unmanned Aircraft Operations will be modeled upon the existing industry-accepted model applied as a high level framework for current manned aircraft operations. Additionally, a database of 529 accidents and incidents involving Unmanned Aircraft Systems of various operating entities and aircraft characteristics was created for this research. The database covers adverse events taking place internationally from 2001 through July 2016. Information on the failures, faults, and errors which caused these events was instrumental in building the Fault Tree Analysis framework not only from the top down, but also from low-level events up. This is parallel to the way in which the National Transportation Safety Board frequently uses Fault Tree Analyses to accurately model the path of a failure or failures.
in a complex aircraft accident by taking a look at manufacturer-developed fault trees and comparing them with the accident or incident which occurred [10]. Through this formal statistical and system modeling process, the stringent safety requirements which current NAS operations adhere to will be upheld. As a result, unmanned aircraft systems will eventually become wholly integrated into the National Airspace System as opposed to merely being accommodated.

Additionally, in order for true integration of UAS into the NAS to be achieved, additional risk mitigation and/or training is needed on all sides of the operations. For example, UAS training knowledge for manned aircraft pilots should be considered a fundamental and taught to student pilots. At the time of this writing, no formal characterization of risk and safety analysis for civil operations of UAS in the NAS exists in the public domain.
2 BACKGROUND

2.1 The National Airspace System and Operations within It

When small quadcopter drones first began to enter the mainstream market, there were no formal operator restrictions. They were typically regarded as an extension of model aircraft. Operators could fly in their backyards, and at open areas so long as they did not engage in any dangerous or law breaking activity. Local law enforcement would respond to operations where law breaking activity took place, such as if someone was using their aircraft to spy on their neighbor, or was flying recklessly around people. Generally, users were expected to operate according to the guidelines practiced by the Academy of Model Aeronautics (AMA) or local self-taught and self-regulating hobbyist groups. Operations for hire in the civil airspace, however, did not fall into this realm or under these guidelines and were illegal. In order to understand the context for the formation of UAS legislation, it is important to examine the classification of the National Airspace System. Figure 2.1 is the formal government issued airspace diagram describing the characteristics of each of the different volumes of airspace in the NAS.

Figure 2.1: Official Federal Aviation Distributed Diagram of the Characteristics of Different Classes of Airspace Within the National Airspace System. This diagram has been reproduced from a promotional educational bookmark issued by the FAA [11].
The current National Airspace System is divided into six categories: Airspace A, B, C, D, E, and G. Within these airspaces, additional areas, sites, or routes with exceptional rules are found, but are non-standard. The general definitions of the classes follow: Class A pertains to the airspace above the United States and over the surrounding waters from within 12 nautical miles of the coast from 18,000 feet MSL up to and including Flight Level (FL)600 (60,000 ft.)[12]. Class B is centered on a primary airport. These airports are listed in subpart B of FAA Order 7400.9W [13]. Class C is again centered on a primary airport listed in subpart C of the aforementioned Order [14]. Class D is centered around a primary airport listed in subpart D of the Order, and Class E pertains to the airspace above the United states and over the surrounding waters from the surface (for a non-towered airport) up to, but not including 18,000 feet MSL [15, 16]. In addition, Class E includes the airspace higher than FL600 with some exclusions [16]. Finally, Class G airspace is uncontrolled and covers all airspace not otherwise covered or designated as controlled. Class G airspace is located in the area from the ground up to 1200 feet AGL or when otherwise noted, from the ground up to 700 feet AGL. In an uncontrolled area, Class G airspace may extend from the surface up to but not including 14,500 feet MSL [16, 17]. The equipment and operational requirements for operation in each of these airspace classes are different. Alphabetically earlier Classes have more stringent requirements than Class G airspace, and are typically associated with larger and more complex aircraft with higher certified levels of safety. Flights by RC model airplane hobbyists have historically been limited to Class G airspace, with exceptional cases involving formal coordination with, and approval from Air Traffic Control in order to ensure seamless continuity in airspace safety. Until recently, these events requiring coordination and ATC accommodation were relatively few and far between.
2.1.1 UAS Operations in the NAS

The first legal small UAS (sUAS) operation for hire was approved by the FAA in September 2013 when Conoco Phillips was approved to conduct aerial surveillance in remote waters off of the coast of Alaska. In order to do so, the Insitu ScanEagle X200 and the AeroVironment Puma AE (both sUAS) were granted Restricted Category Type Certificates by the FAA [18] which outlined the specific operations for which the aircraft was approved for flight and the conditions on which those operations were contingent [19]. Previously, flights were allowed to be conducted by organizations for experimental purposes with an Experimental Airworthiness Certificate [20].

The website http://knowbeforeyoufly.org/ was launched as an educational source for new small UAS operators by the FAA. The campaign was launched in December 2014 in an effort to intercept inexperienced users who likely received the model aircraft as holiday gifts before they took them outside for flying practice. This project is maintained through a partnership between the Association for Unmanned Vehicle Systems International (AUVSI), the FAA, and the Academy of Model Aeronautics (AMA) and has evolved as a resource as the guidelines and regulations for small unmanned aircraft systems (sUAS) [21]. Over the last decade, the rules for operating sUAS in the NAS have fluctuated greatly. The current operating rules are reflected in the recently instated Federal Aviation Regulation (FAR) Part 107 [22] and summarized in Table 2.1, a table reproduced from [23]. Operations which do not lie fully under Part 107 can be approached through a waiver of certain operating rules by way of a Section 333 exemption, or a Certificate of Waiver or Authorization [24]. More information on exemption types and how they may be acquired can be found on the FAA website, cited.
Table 2.1: Summary of Current Requirements for Operation of Unmanned Aircraft Systems in the National Airspace System, Based on Application. This table is a reproduction from the Federal Aviation Administration ‘Getting Started’ webpage [23].

<table>
<thead>
<tr>
<th></th>
<th><strong>Fly for Fun</strong></th>
<th><strong>Fly for Work</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Pilot Requirements</strong></td>
<td>No pilot requirements</td>
<td>- Must have Remote Pilot Airman Certificate</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Must be 16 years old</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Must pass TSA vetting</td>
</tr>
<tr>
<td><strong>Aircraft Requirements</strong></td>
<td>Must be registered if over 0.55 lbs.</td>
<td>- Must be less than 55 lbs.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Must be registered if over 0.55 lbs (online)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Must undergo pre-flight check to ensure UAS is in condition for safe operation</td>
</tr>
<tr>
<td><strong>Location Requirements</strong></td>
<td>5 miles from airports without prior notification to airport and air traffic control</td>
<td>Class G airspace*</td>
</tr>
<tr>
<td><strong>Operating Rules</strong></td>
<td>- Must ALWAYS yield right of way to manned aircraft</td>
<td>- Must keep the aircraft in sight (visual line-of-sight)*</td>
</tr>
<tr>
<td></td>
<td>- Must keep the aircraft in sight (visual line-of-sight)</td>
<td>- Must fly under 400 feet*</td>
</tr>
<tr>
<td></td>
<td>- UAS must be under 55lbs.</td>
<td>- Must fly during the day*</td>
</tr>
<tr>
<td></td>
<td>- Must follow community-based safety guidelines</td>
<td>- Must fly at or below 100 mph*</td>
</tr>
<tr>
<td></td>
<td>- Must notify airport and air traffic control tower before flying within 5 miles of an airport</td>
<td>- Must yield right of way to manned aircraft*</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Must NOT fly over people*</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Must NOT fly from a moving vehicle*</td>
</tr>
<tr>
<td><strong>Example Applications</strong></td>
<td>Educational or recreational flying only</td>
<td>- Flying for commercial use (e.g. providing aerial surveying or photography services)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Flying incidental to a business (e.g. doing roof inspections or real estate photography)</td>
</tr>
<tr>
<td><strong>Legal or Regulatory Basis</strong></td>
<td>- Public Law 112-95, Section 336 - <em>Special Rule for Model Aircraft</em></td>
<td>Title 14 of the Code of Federal Regulation (14 CFR) Part 107</td>
</tr>
</tbody>
</table>
The road from guideline-only UAS management toward the FAR Part 107 rule has presented a slew of hurdles. As hobby use of UAS grew to be widespread, a complicated discussion began on airspace jurisdiction. Users, law enforcement, and legislators began to reconsider questions like: what is the altitude limit for which you can consider your back yard your own property? A critical moment in the path toward regulation took place when the National Transportation Safety Board (NTSB) ruled that for court purposes, sUAS are to be considered as aircraft, as opposed to hobby toys. This took place in the overturn of the Huerta v. Pirker case decision in December 2014 [25]. Raphael Pirker was taken to court for reckless operation of a sUAS on the University of Virginia campus in October 2011 while performing an operation for hire. At the time, the argument that a sUAS was in fact a small hobby toy was in full swing, and the court ruled that the FAA could not charge Pirker a penalty fine. The decision to overturn the ruling in 2014 solidified the status of sUAS officially as aircraft by definition, and paved the way toward legislation under the control of the FAA [25, 26].

2.2 Problems Presented by the Introduction of Civil Small Unmanned Aircraft System Use

2.2.1 Accidents and Incidents

With the introduction of new small unmanned aircraft systems into the United States Airspace, comes new concerns in a variety of categories that were not previously considered. This often goes for any new technology. For example, before aircraft were invented, people were able to consider their personal land as completely private from aerial viewing. However, that expectation of privacy of course changed with the arrival of aircraft technology, and it continues to shift with the introduction of UAS. Privacy is one concern which has been presented in a new light following the arrival of UAS technology. Other concerns span from injury to the operator or people in the vicinity, damage to property,
other privacy concerns including surveillance and spying, and environmental concerns. Many of these issues stem from the fact that these aircraft can carry a payload with a variety of sensors and cameras. Perhaps one of the most complicating factors to UAS use and integration is the fact that sUAS can be quiet from a distance, allowing them to perform activities without being noticed. This becomes an increasingly significant issue when they have a possibility of falling from midair and striking life or objects on the ground.

There is no shortage of stories voicing these concerns and reporting wild accidents in the news. They have become a hot topic of discussion, particularly in the years leading up to the FAA Part 107 legislation. In an article by The Verge, the author Ben Popper comes clean in his title “I almost killed someone with a drone” [27]. In the article he recounts his experience where a situation in his in-laws backyard quickly escalated out of his control. He was flying the aircraft across the backyard and back when the GPS lock signal was lost, the aircraft hovered, and was soon being blown by wind in the direction of the house at a quick speed. His efforts to correct the situation, quickly led to panic when he experienced control disorientation, sending the aircraft even closer to the house and above it. When it quickly escaped his line of sight, he attempted to stop the aircraft by killing the motors, allowing it to fall blindly out of the sky where it crash landed into pieces very close to a mother and her child on a bike in the street. [27].

Unintentional accidents are abound in inexperienced owners, but intentional issues are arising too. According to a Slate blog, in June 2015, a man was brought on trial for charges of spying through the windows of a medical campus in Ulster, New York, on the people inside. In the trial, however, he was found not guilty. While we can have faith that the jury likely decided this man was simply in the wrong place at the wrong time, and chose a poor place to practice flying, this presents an incredible concern for surveillance of sensitive activity, or even increased risk of onlookers into homes [28].
Accidental injuries through hobby UAS use are abound. Most operators or others injured get away with just a small scratch or two. Some even pride themselves on their “drone scars,” but there is a serious risk. November 2015 brought an article to BBC News where an 18 month old baby lost an eye from a sUAS accident that happened when his next door neighbor was attempting to land. During the landing, the operator lost control when the aircraft nicked a tree, and the loss of control resulted in the toddlers eye being cut by the propeller [29].

Another example of an incident was the injury of Stephanie Creignou who experienced a cervical sprain when a DJI Phantom lost power at a 5k event and fell from 33 feet, striking her atop the head. The man operating this aircraft in Quebec admitted to operating without a license, and had no explanation as to how the accident happened [30, 31]. It is interesting to note that in addition to this aircraft, the company VTOL X Drones were also operating at the event under hire and were filming safely, abiding laws, and experienced no complications to their operations[31]. While most of the hobby UAS injuries in the news are new “off the shelf” drone users, it is not unheard of for operators to be injured in hobby RC aircraft flights. In 2013, a 19 year old experienced model helicopter operator was practicing tricks at an Academy of Model Aeronautics (AMA) flying field when he was struck by the propeller blade in the head, and pronounced dead at the scene [32].

2.2.2 Privacy Concerns and the Expectation of Privacy

Additional issues include the general public’s new privacy concerns regarding sUAS use due to the fact that most of these aircraft carry cameras. While UAS hobbyists often use these cameras to take photographs, they are also used for navigation and if aircraft are at higher altitudes, they typically would not contain any footage at a high enough resolution that would make individuals in the photos identifiable. When hobbyist quadcopters first started rolling off the shelves, many people were unsure of what they were capable of in
terms of photography and spying. This is apparent in a 2014 example where a young quadcopter operator was taking higher altitude beach footage until he was physically assaulted by a woman who claimed that he had been taking privacy-intrusive photographs of women on the beach. The 23 year old woman attacked the operator (after he had landed the aircraft) knocking him on the ground, scratching his face and tearing his shirt. Haughwout, the sUAS operator, supplied the footage he recorded to the police, which was completely legal [33]. Another, more recent instance occurred in May 2016 when someone on the ground attempted to shoot a sUAS out of the sky.

A man was flying while his young son was looking on, watching the iPad controller. His son asked for a closer look of people on the ground, so the father descended and a neighbor attempted to shoot the aircraft. The shooter was probably worried about safeguarding their privacy, but what if the aircraft had fallen as a result? The incident could have escalated into injury to unparticipating people on the ground very quickly, but the sUAS operator was able to maintain flight and return the aircraft to home base [34]. This example presents the question “If I fly a UAV Over My Neighbors House, Is It Trespassing?,” a topic examined by Alexis Madrigal in The Atlantic in 2012.

In this piece the legal aspects are examined in a historical context of monumental court decisions. In the 1800s when balloons were experimented with, the Guile vs. Swan case was take to the Supreme Court of New York. The pilot of the balloon, Guile, lost control of the aircraft and descended into a crop garden owned by Swan. Through the balloon falling, and people coming to see the commotion, the garden was destroyed, and Guille was responsible for the damage. In a contrasting case, United States vs. Causby in 1946, it was ruled that the low flight of aircraft on approach to an airport which was disturbing a chicken farm, was not the fault of the pilots. The farmer experienced huge losses as a result of the chickens being frightened, but it was found that flights which were above safe altitudes were considered to be in public space. The question comes back to a central
argument for privacy cases: rather, what is the expectation of privacy of the subject, and is that expectation of privacy warranted, or able to be guaranteed under law [35]. Expectation of privacy is a difficult topic to come to a conclusion on, especially with the advent of modern technologies, and thus there is no overarching federal law specifically addressing technologies of the internet age and their surveillance uses in the United States at this time.

The Electronic Privacy Information Center, a D.C. based non-profit organization which researches and fights issues of civil liberties and privacy [36], has sued the FAA for not releasing or putting into effect a drone privacy law. EPIC sees that in order for full and safe integration to occur, privacy issues must be reflected in UAS law, and privacy issues have not been completely and specifically addressed in the commercial UAS laws adopted [37]. In contrast, the European Union has instated more direct laws on internet privacy and have issued a data protection directive for the member nations [38]. In this vein the EU Article 29 Data Protection Working Party has issued a formal opinion document outlining “Privacy and Data Protection Issues Relating to the Utilization of Drones” and the ways in which they fall under EU data protection law [39, 40].

Some privacy considerations for UAS use have been taken into consideration on the state-level, however. For example, the State of California in 2014 made it illegal for UAS to be used for surveillance purposes by the police without a search warrant. This is an interesting issue because police do not require a warrant for helicopter surveillance flights. In general, people do not have a reasonable expectation for privacy from manned aircraft, due to the fact that these aircraft will fly over private property inevitably in their travels. Therefore, police surveillance from a helicopter is legal, yet people can bank on the high cost of helicopter operations to ensure that surveillance levels to not reach excessive amounts. With UAS, the costs of operations are a great deal less, and thus there is a greater possibility for aerial surveillance to become a widespread phenomenon [41]. Through this discussion we see that while pilot qualification is a large issue in management of sUAS
flights, it is accompanied by a slew of additional factors that must be considered in formal integration of UAS into the NAS, creating a multi-faceted problem.

2.2.3 Liability Concerns for UAS Operations in the NAS and Responsibility of the UAS Operator

Target levels of safety and the definitions of accidents and catastrophic events bring us to the topic of insurance. Insurance for UAS operations is available and offered by companies such as AIG [42]. Given many of the accidents covered over and over in the news, it would make sense for UAS operators to pursue some sort of liability insurance. It is already required for manned aircraft operations. Additionally, in Canada, liability insurance of 100,000 dollars is required for commercial UAS operations [43, 44]. In the proposition of FAR Part 107 in the US and the subsequent period for commentary, there was no shortage of advocates that a similar rule for mandatory insurance be adopted for commercial UAS operations in the US, with the idea that aside from the protection to all parties, it would be particularly beneficial for encouraging safe UAS practices. However, the FAA announced that they do not have jurisdiction to enforce mandatory insurance requirements through this rule. The Office of the Secretary of Transportation was also a direct participant in the development of FAR Part 107, but they similarly cannot mandate such a requirement as the use of UAS for commercial purposes does not technically fall under the category of air transportation [22].

In the discussion between UAS enthusiasts and users some opt for the extra protection through either home insurance (which does not typically cover UAS liability) or through packages such as those offered by select insurance companies. The Academy of Model Aeronautics, the major organization for RC hobbyists offers significant liability insurance as part of its memberships ranging from 500,000 to 2.5 million dollars. Though operators may be quick to assume that this insurance covers them, it is clear that this is for personal
liability only, and does not apply to commercial operations [45]. Interestingly enough, due to the very historic nature of the AMA and its growth from traditional RC aircraft into encompassing modern off the shelf UAS users, the UAS users taking advantage of the insurance options at their disposal are more likely to be the more educated and self-aware users, who may operate with less risk to begin with.

Eventually with formal integration of UAS into the NAS, it is expected that UAS will inevitably require insurance comparable to the other aircraft which occupy the same airspaces which they are authorized to operate within. In order for insurance agencies to offer appropriate insurance policies and for the government to make decisions on what levels of insurance are required a formal study of risk of failures in Unmanned Aircraft Systems is needed especially with the end goal of a quantified model. However, the first step in assembling an accurate study and quantification of risk for UAS operations in the NAS is to begin with a qualitative study of the system. It is safe to assume that the risk mitigation measures in place for UAS operating within the NAS are not necessarily appropriate or complete given the limited current system operational requirements. In order to place UAS on the same levels of safety as comparable manned aircraft an intensive study and modeling of system safety on the same level as those manned aircraft is required.

The existing concerns about insurance required for UAS operations in the NAS indicate that there is a perceivable risk to allowing these aircraft to occupy the same airspace as manned aircraft, even at the low altitudes authorized by the FAR Part 107 rule. One of the main concerns for operation within this airspace is the helicopter operations which occur regularly, often performing tasks which UAS advocates are interested in using UAS to perform. Helicopters are a valid concern as helipads are less intrusive than traditional airports and are very common in urban areas in particular. Helicopter entry procedures and some helicopter operational knowledge may be a useful addition to pilot training for UAS operations in order to reduce risk of UAS strikes for helicopters. The database created in
this research only confirmed that due to their altitude of operations, UAS pose a significant threat to helicopters in flight. Couple the increased risk of impact with the reduced glide distance of helicopters compared to airplanes and the danger becomes a significant issue. Other aircraft operating within the airspace used for UAS operations are model aircraft pilots, general aviation aircraft near airports and experiencing emergencies, and ultralights and air balloons.

UAS pilots need to have a situational awareness on the ground of the airspace around them and how other aircraft may utilize it, similar to that expected of ultralight operators. In particular, a UAS operator should be able to identify aircraft which are at risk or locations which are unsuitable for UAS operations prior to creating a conflict or potential risk. For example, it would be relevant to UAS operators to have an understanding of the ditching operations of manned aircraft in order to identify an aircraft in distress and remain well clear. For example this would create additional incentive to remain well clear of airports. Additionally, UAS pilots should be able to utilize a multitude of informational resources to decide if a potential operation is safe or not, similar in some ways to the practices suggested through the AMA operational guidelines [46]. Informational resources of particular use include weather resources, knowledge of radio frequencies near airports, and additionally methods for self-reporting violations, such as through the NASA ASRS database. Ideally, UAS pilots should be able to use sectionals to their aid in identifying the heights of landmarks, locations of airports and heliports, and populated areas. Operators could use this information to gain an understanding of how manned aircraft are likely to be operating in the area, with respect to their utilization of checkpoints. Lastly, they could gain other important information such as where to expect glider activity or skydiving, or where the dimensions of an airspace volume begin and end that could assist them in remaining well clear from these areas.
2.3 UAS and Model Aircraft

With the increased popularity of “off the shelf UAS” came the influx of accidents and incidents as well as a greater need for regulation. One of the main forces driving the need for regulation is of course the potential that these aircraft have for use in commercial applications. However the more pressing need for formal law and pilot qualification standards which have culminated in the release of FAR Part 107 brings forth the question, why are UAS different from traditional model aircraft? And why have we not had to worry about RC aircraft all this time? By taking a look at pilot qualification standards to understand the path toward integration, we must also look toward the virtues of self-regulation of RC Aircraft Hobbyists and what this means for UAS. Additionally, the practices of RC aircraft hobbyists must be examined because they will occupy the same airspace volumes as those authorized for use through FAR Part 107.

The AMA has published a formal safety code, titled the Academy of Model Aeronautics National Model Aircraft Safety Code which outlines recommended practices for members of AMA while flying their model aircraft, which could be RC, non-RC, model rockets, airplanes, helicopters, cars, and boats [46, 47]. While these are only guidelines, the single page of rules is thorough and actively encourages safe practices both in regular flight and in competitions. There are indicated distances of clearance for takeoff and landing operations and a system for ensuring stunt operations are at a safe distance from onlookers. The safety code requires that pilots who operate their model aircraft within 3 miles of an airport must notify the airport operator of their intentions ahead of time.

At a quick glance, the guidelines look quite similar to the guidelines for hobbyists operating UAS under FAR Part 107. In fact, there is a large possibility that the AMA rules and guidelines for operating model aircraft in the NAS were in part an inspiration in the development of Part 107, likely because these guidelines and the self-regulating practices are effective. One example of this is the 55lb rule. FAA Part 107 authorizes operation of
small UAS aircraft under 55 lbs. without an airworthiness certificate. The AMA Rules outlined in the AMA Radio Control Large Model Airplane Program, a document which dates to 1993, classify Large Model Airplanes into 4 categories: LMA-1, LTMA-1, LMA-2, and LTMA-2. The difference between LMA and LTMA is that LTMA have turbines (jet) engines. LMA-1 airplanes weigh 55 to 77.2 lbs. and LMA-2 airplanes weigh 77.3 to 125 lbs. In order to fly LMA aircraft, pilots and model airplanes need to fulfill additional requirements and qualifications and must be formally approved. Model airplanes under 55 lbs. do not need a waiver [48]. Therefore it is likely this is the origin of the 55 lbs. figure presented in the FAR Part 107 legislation.

So why are the guidelines and rules employed by the AMA and RC practices in general so effective? Why is it we never had to worry about them before? Part of it is the long history of model aircraft. The Academy of Model Aeronautics (AMA) was founded in 1936 and is the worlds largest model aircraft organization with a membership of 195,000 people and is the worlds largest model aircraft organization with a membership of 195,000 people [48, 49]. The history and size of this organization has made it extremely well established and it provides extensive resources to its members. Additionally, the rules, etiquette, and guidelines set in place are very well respected by members, other hobbyists, and the aviation community.

The AMA encourages members to contact manned aviation airports within the area of AMA endorsed fields and notify them of their operations, and the extensive model aircraft community utilizes a plethora of online forums to communicate and assist one another in their operations. By creating relationships between AMA members and airport operators, historically aircraft operators have published NOTAMS and additional airport information on airport diagrams or the popular website AIRNAV [50] alerting manned aircraft to the fact that aircraft model operations occur within the vicinity. However, these are purely voluntary based upon the discretion of the airport operator.
Additionally, the AMA provides liability insurance to members as integrated into their membership, has more than 2,500 model airplane clubs in the U.S., holds more than 2,000 model aircraft competitions each year, and endorses sites for flying [49]. All members receive a regular publication from the Academy and the organization provides extensive guidance for getting started and the AMA website features detailed online training programs and documents to guide users through their model aircraft operations [49]. These publications include see and avoid practices [51].

Member to member communication as well as formal local organizations in local communities contribute to making sure operators are educated and aware. Many enthusiasts grew up building and operating models at a young age which can convey an increased importance and respect for the process and operations. Historically, model aircraft hobbyists are known to spend hours upon hours constructing, modifying, and perfecting their aircraft which can also become costly models very quickly. This traditionally creates large investments of hobbyists into their models which contributes to their interest in operating their aircraft safely. This results in a very low number of insurance claims filed through the AMA per year, coming up at around 35 annual claims in 2012, with only 15 of those involving injury [52].

With the huge rise in ready-made off the shelf drones, small UAS type aircraft have become accessible to anyone willing to spend the money. Additionally, off the shelf UAS are heavily marketed as technologically advanced toys. This presents a reality where many purchasers have no awareness of model aircraft organizations and likely decreases their personal interest in protecting their aircraft investment. As a result, model aircraft hobbyists are among the first to advocate increased educational and awareness for off the shelf UAS users. For example, if a UAS loses its GPS signal, disabling a “GPS lock” feature for the aircraft, a UAS hobbyist may have significant difficulty continuing to operate the aircraft
in a safe and reliable manner, while an aircraft hobbyist would be accustomed to operating the aircraft as they probably learned to operate models primarily using manual inputs.

While UAS are similar in nature to model aircraft, there are distinct differences. The widespread development of off the shelf UAS have created systems which have a wide range of performance capabilities and can carry increasingly large payloads. Additionally, there is a gap in oversight for hobbyist uses since UAS do not have the same established background and community of model aircraft. As the aircraft become increasingly popular, the desire to apply them for commercial purposes is often born out of their uses for hobby, and less from the side of viewing them as a sophisticated aircraft system or commercial aircraft.

Depending on the complexity of the UAS, many UAS are already as complex as existing aircraft or even more complex due to their remote piloting and autonomous properties. Therefore, it is necessary that they be viewed as true aircraft and approached for integration accordingly whether it is through pilot training or equipage requirements and formal system reliability standards. An ideal way to approach this problem is through the use of System Safety Assessment and Fault Tree Analyses, as these are tried and true in their applications to the manned aircraft industry and enforcing the safety levels we currently hold in the National Airspace System of the U.S.

2.4 Concerns for Civil Unmanned Aircraft System Integration into the National Airspace System

2.4.1 Avoiding Other Aircraft

The current regulations proposed by the introduction of FAR Part 107 allow sUAS to fly in Class G airspace under 400ft above ground level (AGL). Many consider this relatively intuitive due to the fact that Class G is “unregulated airspace.” However, the term “unregulated” here means something more like “self-regulated.” Aircraft still operate
in these volumes of airspace, however, there may not be radar services readily available due to terrain, or other geographical properties, and for workload purposes as many aircraft use Class G airspace as transitional airspace to more stringent classes.

Class G airspace is typically filled with helicopters, hobbyist RC aircraft, General Aviation aircraft experiencing emergencies, aircraft on approach and departure routes, sightseeing aircraft, ultralight aircraft, and air balloons. Helicopters operate extensively in Class G airspace for purposes such as providing air ambulance services, police surveillance, and news and traffic coverage. Additionally, helipads are quite common and due to their less obtrusive nature, they are often less visually identifiable than airports to those who are less familiar with them. Proposed uses of sUAS overlap with some of the applications of these aircraft already operating in the airspace. While sUAS are a cheaper alternative to get the job done for some applications, this means that both types of aircraft will be performing the same duties in the same airspace, most likely in relatively close proximity to one another. Therefore it is imperative to come up with solutions that ensure safe separation between manned and unmanned or remotely piloted aircraft.

Part of why “see and avoid” is such a challenging problem for the integration of UAS into the NAS is because UAS are stealthy in the air, for some of the same reasons they are stealthy to people they could be flying over on the ground. Manned aircraft pilots are taught to scan for traffic when operating in Class G airspace, but UAS are particularly difficult to sight, especially when they are small in size. Typically the strategy for scanning for aircraft used by manned aircraft pilots allows them to focus their eyes far in the distance, and not up close where UAS are likely to pop up due to the agile flight control properties of multi-copter UAS in particular. If a pilot is lucky enough to sight a UAS prior to a near midair collision (NMAC), they may become disoriented and think it is a large aircraft that is far in the distance, or a bird. If the pilot thinks the aircraft is large and in the distance they may think they have more time to perform an avoidance maneuver, or they could mistake the
UAS for other manned aircraft in a location where they are expecting traffic (i.e. aircraft maneuvering to enter a traffic pattern at an un-towered field). Additionally, a sUAS could be mistaken as a bird, which also present a large hazard, but are often likely to shift their flight according to disruptions in airflow created by the aircraft.

Larger aircraft may employ a traffic alerting system, such as a Traffic Collision Avoidance System or TCAS, as a last resort safety measure to avoid collisions. These systems alert the pilot to traffic in near conflict, and provide a formal resolution advisory by commanding a specific flight maneuver (climbing or descending) such that the traffic conflict will be avoided. These systems operate on the assumption that the traffic in conflict is transponder equipped, however, which is not the case for most UAS. This creates an issue where UAS are difficult to detect both by “see-and-avoid” methods and through the aircraft system for manned aircraft.

2.4.2 Environmental Concerns

One last concern to be considered in the integration of UAS into the NAS are the implications of not only increased aircraft use, but UAS use toward wildlife. UAS will cause increased hazard to birds in flight and noise disruption to other animals. A quadcopter operator made the news in 2014 when a hawk attacked his sUAS mid-flight, knocking it to the ground. Fortunately there was no apparent damage to the UAS, or injury to the hawk or other surrounding life, but this presents another case where an aircraft could end up in free fall unexpectedly, and given other accidents, it is surprising that the hawk was unscathed [53]. For these reasons, operations in Class G airspace cannot be considered trivial and a formal integration needs to be performed in order to allow UAS to fly alongside manned aircraft in the National Airspace System.
2.5 System Safety Assessments and Fault Tree Analyses

In order to take into account the concerns documented in Section 2.4, a systematic identification, study, and mitigation of risk must be performed. Many of these issues are common to those which are considered in the process of certifying manned aircraft operations in certain volumes of airspace. Additionally, many of these risks have new implications or are different all together for Unmanned Aircraft Systems. One large difference is encompassed by the use of the word “Systems” to describe these aircraft. In the transition from an in-fuselage cockpit to a remote cockpit control setup, there is a very different concept of operations for the system component of UAS versus manned aircraft. This must be specifically, and accurately reflected in a formal safety analysis in order for certification of these airframes to be performed, and in order for complete verification that UAS operations are able to perform at a given target level of safety. One very appropriate certification tool that may be used to fulfill this need is a formal System Safety Assessment.

2.5.1 The System Safety Assessment

A System Safety Assessment is a tool extensively used in industry for the certification of manned aircraft for operations in the National Airspace System. A formal and full safety assessment typically consists of three parts: a Functional Hazard Assessment (FHA), a Preliminary System Safety Assessment (PSSA), and a System Safety Assessment (SSA) [54] according to the official Aerospace Recommended Practice from the Society of Automotive Engineers (SAE ARP4761). A complete SSA is composed of the following tools for analysis: a “Fault Tree Analysis (FTA), Dependence Diagram (DD), Markov Analysis (MA), Failure Modes and Effects Analysis (FMEA), Failure Modes and Effects Summary (FMES) and Common Cause Analysis (CCA).” A Common Cause Analysis encompasses a “Zonal Safety Analysis (ZSA), Particular Risks Analysis (PRA), and Common Mode Analysis (CMA)” [54, p. 4]. Many of these tools for development and
risk analysis are applied at different stages in development, certification, or investigation as deemed necessary by the problem at hand.

In the case of aircraft development, FHAs are often performed as a beginning point for categorization and classification of the system and components for the aircraft and system separately. Functional Hazard Assessments include a categorization of “functions, hazards, effects, and classifications” [54, p.30]. As the system begins to develop in maturity, more specific tools may be applied, such as Fault Tree Analyses, and Failure Modes and Effects Analyses, or Failure Modes and Effects Summaries. As yet a higher level of maturity is attained in development, tools like the Common Cause Analysis may be performed in order to analyze the safety implications of system components or risk aspects which interact or could interfere with one another, and how the failure or fault of one, a few, or all, could affect the system on a larger scale [54].

For this research, it was deemed that the creation of a fault tree analysis framework for UAS in general is a beneficial starting contribution to the formally scientific and systematic integration of UAS into the National Airspace System. A partial System Safety Assessment was conducted consisting of the generation of a formal database of incidents and accidents categorized by three different categorization taxonomies, and three additional case/failure specific fault trees for UAS were created in addition to the tailorable FTA framework applicable to UAS of all characteristics, sizes, and complexities. The case-specific fault tree analyses top level events were driven by the categorization results of the database incidents and accidents. The top three most occurring ICAO Aviation Occurrences were chosen for closer analysis using the fault tree approach.

2.5.2 The Fault Tree Analysis

Fault trees have a long history and are an integral part of the aviation industry due to their relevance to the entire lifecycle of the aircraft which operate in our national airspace.
A fault tree is a visual representation logic diagram of small, low level adverse system events and their relationships to one another through Boolean logic. Each tree has many levels of failures or faults. The bottommost level consists of the tiniest (figuratively) subsystem failures which make up a large system. The topmost level consists of a single extreme adverse event which must be mitigated, such as a loss of life. The idea is that every occurrence of an adverse top level event, or occurrence, can be traced to a combination of lower level events which are ultimately caused by a failure or failures/faults on the lowest level of events. They are useful both for designing a system to prevent a top level event, or solving why a certain top level event occurred for a system already in operation. Fault trees are particularly insightful as tools due to their wide accessibility and the ease of modeling changes in small parts of a large system. In the design process, fault tree analyses are effectively used as a tool to allocate risk. Additionally, they are useful in examining specific paths of failures within a system and system sensitivity to certain failures.

A brief history of the development of the Fault Tree Analysis and its important role in the development and maintenance of safety critical systems is outlined in Clifton Ericson’s paper Fault Tree Analysis-A History. The Minuteman Missile System Launch Control System was a driving project for the creation of the fault tree analysis by Bell Laboratories in 1961. The tool was quickly taken up at Boeing for further application on the Minuteman Missile System project. This, in turn, evolved into wider application of fault trees at Boeing, namely for commercial aircraft. During the 1960s the fault tree analysis tool quickly spread to be an integral part of aircraft development. Other applications it was adopted for are nuclear power, train transport, automobile transport, and robotics. It has since been used for the analysis a multitude of other systems as its logical and statistical construct make it quite versatile [55]. With respect to aircraft, fault trees are extensively utilized in the creation of new aircraft and systems from scratch [56], the certification of aircraft and systems for operations in the National Airspace System, and for the close study
of aircraft accidents, in order to fully analyze a system for increased risk mitigation in the future.

2.5.3 System Safety Assessments, Fault Tree Analyses, and Unmanned Aircraft Systems

While System Safety Assessments and Fault Tree Analyses have been extensively applied to aircraft operating in the National Airspace System at all stages of lifecycle for 50+ years, such large scale qualitative and quantitative analyses have not been applied to Unmanned Aircraft Systems in the same ways, to the same extent, or on the same scale of the industry. One reason why there is so much room for development in this area is because the large volume of statistics needed to extensively quantitatively evaluate these analyses have not yet been recorded or aggregated. The need for integration of UAS into the NAS has become ever more pressing since the aircraft have hit the consumer market on a large scale in the early 2010s. As a result, the need for legislation has been unyielding since before the release of the Federal Aviation Administration Concept of Operations for Unmanned Aircraft Systems in the National Airspace System in 2012 [6]. In fact, the need for legislation has surpassed the ability to gather, assimilate, and analyze data extensively prior to introducing wide-scale airframe-based certification.

As a result, the current legislation dictating the operations of UAS in the NAS has been largely based upon the pre-existing guidelines for the operations of model RC and rocket aircraft in the NAS. In general, up until this point in history, the certification standards used to deem aircraft and pilots of the appropriate safety qualification to operate in the National Airspace System have been entirely based upon the assumption that the pilot is flying the aircraft from a control interface located inside the fuselage. This inherent assumption has also been included in fault trees used for accident investigations and aircraft design.
Additional need for this research is apparent from the fact that currently there is no formal educational requirement on strategies to mitigate the risk of UAS encounters in manned aircraft training for private pilot standards and less stringent licenses. While the primary responsibilities for mitigating risk proposed by UAS operations in the NAS should be shouldered by the UAS manufacturing and operating entities, there will always be possible failures in the system and manned aircraft should be educated and prepared to mitigate the risk from their side accordingly.

- In order for full and complete integration of UAS into the NAS to be achieved:
  - Additional risk mitigation and/or training is needed on all sides of the operations: the regulation side, the industry side, ATC, and operators of both manned and unmanned aircraft operating in the volumes of airspace affected.
  - UAS training knowledge for manned aircraft pilots should be considered a fundamental and taught to the lower certifications of airmen.

- Additionally, this study is important because there exists no formal characterization of risk and safety analysis for civil operations of UAS in the NAS.

Formal characterization here means thorough, systematic, and complete identification of risks for UAS operating in civil airspace and by extension these risks must be quantified, evaluated, and mitigated. This is a necessity in order to uphold the existing levels of safety in the NAS as all other risks are identified, quantified, evaluated, and mitigated formally in such a manner. The current state of UAS operations in the NAS have these aircraft generally operating below 400 feet AGL. One reason why this is considered a starting point is that this airspace volume is “segregated” from the airspace typically used by aircraft operating in the NAS. However, aircraft do operate below 400 feet and engage in self-separation of traffic. By adding UAS operations into the mix of aircraft operating within this volume of airspace, the issue of maintaining separation of traffic increases.
2.6 The Path Toward Integration of Unmanned Aircraft Systems into the National Airspace System Through a System Safety Assessment

Unmanned Aircraft Systems are intrinsically unique and different from manned aircraft aviation and so system safety models, or risk assessment models need to reflect these system differences. As a product, risk mitigation procedures and pilot checklists created for manned aircraft operations are not directly translatable and transferrable in a complete sense from manned aircraft operations to unmanned or remotely piloted aircraft operations. They may be an appropriate starting point, but they do not have the same level of effectiveness guaranteed for risk mitigation within the context of unmanned aircraft as they do for manned aircraft. Risk mitigation procedures should be approached from a ground-up evaluation of the needs of UAS operations in order to effectively account for the fundamental differences between the two aircraft categories and to build a solution along the most appropriate and effective path.

The fast development of sUAS technology and increased popularity due to low operating costs have accelerated the development of legislation. As a result, the standards of required training to conduct commercial UAS flights in the national airspace are relatively incomplete and do not necessarily completely encompass the needs of the aircraft system in terms of pilot capability. This may result in over-qualification, or under-qualification of the pilot. It could also be that there are additional needs encompassed by neither traditional aircraft flight nor traditional ground training that have not been taken into account.

2.6.1 Achieving an Equivalent Level of Safety in UAS Operations and The UAS System-Level Fault Tree Analysis

In order for full and true integration, not accommodation, of UAS operations in the NAS, there must be appropriately tailored training of UAS pilots and operators in order
to ensure that the safety of the airspace is upheld and the transition from manned-only to shared airspace is seamless. For the airspace safety levels to be preserved and unchanged through integration, UAS need to be held to an equivalent level of safety as their manned aircraft counterparts. An equivalent level of safety is only achieved through identification of the weak areas of the system and introducing targeted and effective risk mitigation in those areas where the equivalence is not yet confirmed.

The purpose of this research is to contribute a partial system safety assessment by way of a qualitative fault tree analysis which identifies risks and areas in need of further development to ensure an equivalent level of safety. Additionally, statistics and trend data are incorporated based upon a database consisting of 529 entries for events occurring internationally in the years 2001-2016. While it was deemed that these statistics were insufficient for producing accurate quantitative probabilities for the fault tree events, they are particularly insightful for proportional data and trends which identify the key areas in the most need of solution development. It is noted that the data collected pertains to UAS accidents and incidents occurring internationally. While UAS are not widely approved for use in airspace above the United States, aircraft are used in military operations around the world and some civil UAS activity has begun in other nations. Due to the fact that these systems are relatively new, data pertaining to civil use is limited. Therefore, it is appropriate and sufficient to assimilate data pertaining to military operations as accidents and incidents are frequently reported, systems are tested, and UAS operators are trained before beginning flight operations. This provides similar insight into UAS operations of varying aircraft type where the pilot has received a level of training with that aircraft.

The contribution of a qualitative fault tree framework for UAS operations in the NAS falls under the scope of a Preliminary System Safety Assessment (PSSA) and typically is conducted on the path toward quantitative FTAs and system Failure Modes and Effects Analyses and Failure Modes and Effects Summaries [54, p.13]. Once such a fault tree
is deemed to be sufficiently populated and contains appropriate and statistically certain quantitative probabilities of event occurrence insightful quantitative common mode, zonal safety, and particular risk analyses can be performed. In order for extensive analyses to be performed, the accepted fault tree framework must reflect a given aircraft in order to have full inclusion of system failure and fault events and therefore full analysis capability.

The results of this report will offer a qualitative Unmanned Aircraft System fault tree analysis framework suitable for tailoring to specific aircraft systems as desired. An analysis of the database has been performed with categorizations based upon three different taxonomies: the UAS FTA top level subsystem categorization, the ICAO Aviation Occurrences Categories [57], and the Human Factors Analysis and Classification System [58]. This will result in formal identification of areas of need both within the system and within the scope of pilot knowledge and preparation. The results of the trend data from categorization of the UAS accident and incident database is used for targeted broken-down modeling of commonly occurring failures. By taking a closer look at failures and faults from a logical breakdown perspective, an examination of the differences between manned and unmanned cases will be possible. The results lend for identification of areas of need which hold strong ties to the differences in both system structure and human factors interface introduced by the fundamental differences in UAS from manned aircraft.

2.6.2 Additional ICAO Aviation Occurrence-Specific Fault Tree Analyses

Three failure-specific fault tree analyses were conducted for UAS based upon the trend results from the accident and incident database. The top three most commonly occurring ICAO Aviation Occurrences were chosen for further evaluation. These occurrences were Navigation Errors (NAV), AIRPROX/TCAS alert/Loss of separation/Near Midair Collisions/Midair Collisions (MAC), and System/Component failure or malfunction (non-powerplant) (SCF-NP). Areas of specific concern to be examined in this study are:
• loss of communication with the aircraft

• loss of navigation

• and loss of control of the aircraft.

These are events which have significantly different implications when viewed within an unmanned aircraft system context as opposed to manned aircraft. After examining the UAS data assimilated in the database it was determined that these concerns are encompassed by these three aviation occurrences, which made up a significant portion of the database entries as expected. While Loss of Control-Inflight (LOC-I) was an additionally occurring ICAO Aviation Occurrence in the database, the majority of UAS accidents and incidents involving loss of control pertained to the loss of control by way of a loss of link occurrence, which falls under the scope of SCF-NP. There were fewer occurrences where the pilot lost physical control of the aircraft from a control input perspective.

The Navigation Errors occurrence involves all accidents and incidents for which the aircraft is navigated incorrectly. This error includes airspace incursions, incursions on the ground, and a failure to maintain course heading. Additionally the occurrence encompasses airspace incursions which are the result of an improperly programmed mission [57]. In some ways this error encompasses the loss of control of a UAS in flight due to an improperly programmed mission which the pilot may not notice immediately. This does not encompass a loss of control signal or loss of active control of the aircraft, as the pilot still has commanded this maneuver and has the ability to intercept the aircraft’s preprogrammed path.

Navigation errors were the third most common aviation occurrence in the accidents and incidents recorded. This error is particularly relevant due to the fact that the remotely piloted nature of UAS make navigation errors less likely to be discovered in an immediate manner. By remotely piloting the aircraft, pilots are less likely to be as spatially aware
of the airspace surrounding them as if they were piloting from within the aircraft fuselage. There is a decrease in traditional visual cues such as an excessive nose up attitude compared to the horizon as viewed from inside the cockpit. Additionally, the remotely piloted system introduces latencies which can make a small altitude or course deviation turn into a significant altitude or course deviation quickly. By taking a closer look at the failure for UAS, we can get a better idea of the implications of the differences in the system from manned aircraft operations, and where the largest differences are felt.

The second most common aviation occurrence in the database results was the AIRPROX/TCAS alert/Loss of separation/Near midair collisions/Midair collisions. This occurrence includes all losses of aircraft separation and collisions [57]. A loss of aircraft separation, is a technical term for which aircraft separation is an official separation distance which is a function of the airspace volume of operation. This error encompasses all losses of separation and collisions or near collisions which are a result of loss of navigation, loss of control, or loss of communications with the UAS. This occurrence is, relatively speaking, the most concerning as ultimately the goal of operating safety in the national airspace is for no collisions to occur.

The last, and most common ICAO aviation occurrence category for the events recorded in the database was the System/Component Failure or Malfunction-Non-Powerplant. This failure is particularly of interest for UAS because it encompasses all of the system hardware and software changes which allow the aircraft to be operated remotely and without a pilot controlling the aircraft from inside the fuselage. It is a significant concern in UAS operations due to the fact that the ability to pilot the aircraft lies directly in the system and hardware components and their functionality and reliability. Also, all aviation systems are designed to be highly reliable especially those which are deemed safety critical, and redundancy is typically introduced in aircraft in order to achieve highly improbable failure statistics. The issue of the aircrafts ability to withstand equipment
failures is further complicated in the context of UAS, and in specific sUAS, due to the light nature of the aircraft and the limited payload carrying capability. In some ways these aircraft are designed to carry a smaller payload due to the operational cost benefits a lighter takeoff weight can provide.

The issues of loss of navigation, loss of communication, and loss of control are heavily encompassed by this aviation occurrence as all of these systems are reliant on system functionality and hardware both in the ground station and on the aircraft, with a very strong need for redundancy either through training or equipment. In general, the pilot of a manned aircraft plays a huge role in reliability and redundancy in the event of equipment failure as he/she oversees all operations of the aircraft from the inside of the airframe. As a result, he/she is able to make decisions and control inputs accordingly as a situation progresses and diagnose the situation from the inside to attempt to restore lost functionalities.

Through modeling of this occurrence through a “closer look” FTA, an examination of system functionality will aid in identification of safety critical system components, and the proportional needs of component reliability. The development of a qualitative fault tree will lend to further development of a quantitative fault tree allowing for hardware and software reliability budgeting in order to ensure that systems are not only deemed safe enough for operations, but are actually designed to ensure a high level of safety. The unique development and path to popularity of consumer available UAS came from roots in the model aircraft and toy aircraft industries. These aircraft were likely born out of creative minds which may not have prioritized reliability in functionality from an airframe and system certification and international aviation regulatory perspective as it is outside the scope of these industries.
2.6.3 Introduction to Scope and Assumptions

The scope of this research is to provide a non-UAS specific Fault Tree framework which can be tailored to UAS of all sizes, complexities, different cockpit systems, and levels of autonomy. A universal framework will provide an industry standard type starting point for all fault tree analyses of UAS with additional details being available when tailored to a specific model. Therefore, when a specific operation is selected for modeling, events will take on different probabilities of occurrence based upon the system and environment of operation. For example, sUAS operations within an urban area near buildings will be associated with increased risk of injury to bystanders as a result of population density. Additionally, such an operation would have to worry about events which a rural operation may not have to, such as the risk of sudden airflow changes when approaching a skyscraper or navigating within an alleyway.

By taking a look at a general framework, there remains a focus on general pilot qualifications. When examining the role of the pilot within the system, areas of specific concern and training needs will present themselves. These roles will vary on a spectrum of logical importance based upon their placement within the fault trees. More statistically significant events which draw on risk mitigation from the pilot will require increased risk mitigation measures through additional pilot training, prioritized pilot knowledge requirements (as opposed to uniform importance), or increased aircraft/system automation in order to provide more fail-safe functions. Certain pilot roles will increase or decrease in statistical significance as a function of the operation and aircraft/system, and may require additional training or increased or decreased levels of autonomy. In ways, this is similar to the increased equipage requirements of manned aircraft and training of manned aircraft pilots needed to operate in more stringent volumes of airspace and areas of higher traffic volume.
For the purposes of this research, the current airspace model is employed and assumed in all analyses, with no changes. As the fault tree analyses are airspace of operation in-specific, the surrounding traffic to consider will be a function of the airspace of operation. A synopsis of the equipage requirements for operations in different classes of airspace is included in the literature review. The fault tree analyses will take into account occurrences in events within the collected database entries in order to create a model which most accurately represents currently available data and UAS operations, though these are not civil airspace specific. A review of literature and relevant previously conducted work is presented in the following section. Additional regulatory information will also be included.

Then a review of the methods used to conduct this research will be presented, and the results of the four fault tree analyses: the general framework, and the aviation occurrence specific trees will be shown. The results of the accident and incident database will also be included. These results will be discussed in the Discussion section, where differences between manned and unmanned aircraft system operation will be discussed, as well as significant events where the pilots role is of the utmost important. Implications caused by shifting from an in-fuselage pilot- to a remotely piloted system will be identified and examined. The discussion will be followed by conclusions and recommendations for further research and the path forward toward a fully integrated National Airspace where manned and unmanned aircraft systems can conduct safe operations in the same volumes of airspace.

2.7 Recent UAS Integration Developments and Operational Requirements for Flight in the National Airspace System

2.7.1 UAS Developments and Flight

While UAS have received a good deal of press ever since their widespread introduction as ready-made hobby aircraft around 2010, it is not only for the sensational accidents
and uses. Legislation measures and methods to address unlawful UAS activity and achievements in the path toward integration of UAS into the NAS have also been shared. Earlier in this Background section, one point which was discussed regarding current events was the potential dangers that UAS could present to wildlife. By putting small, nontraditional aircraft at lower altitudes, bird flights are susceptible to a greater threat either by injury or noise pollution when occupying these altitudes. One video was discussed where a hawk knocked a hobbyists UAS out of the sky. While this was a very unusual occurrence at the time, there is an inverse perspective to be had.

In the Netherlands, the Dutch National Police Corps are investigating the use of trained eagles for law enforcement pertaining to illegal UAS use. A company called Guard from Above has been training the animals to snatch UAS out of the sky the same way they would snatch their own prey, depositing them in another area as directed [59]. If birds are trained to do so in a way which does not harm them, this is an interesting and innovative perspective. However, this does not negate the issues presented to wild bird populations, and it does introduce a changed and potentially more dangerous task for such a bird of prey. As a bottom line, this strategy is still a wide departure from typical risks and patterns that the animal associates with hunting [60].

Additionally, one very successful achievement toward the goal of integration of UAS into the National Airspace (that of the US, or in this case, otherwise) was the first flight of a UAS in shared airspace with commercial aircraft in the UK in October 2015 [61, 62]. The flight was conducted with a Thales Watchkeeper UAS, typically used by the British Army. This aircraft features a 35 foot wingspan, comparable in wingspan to a Cessna 172 (which measures at 35’ 10”’) [63]. The three and a half hour flight was performed while maintaining constant communication with ATC, not unlike IFR flights for general aviation aircraft. It is important to note, however, that only one hour of the total flight time was through a shared volume of airspace [61].
Earlier in the Background section, it was discussed that for the purposes of this research, the fault tree analyses are designed to be operation in-specific. This is important in that the surrounding manned aircraft to be considered and accounted for in achieving integration is a function of the volume of airspace in which the operation occurs. Therefore, it is important to understand the different equipage requirements for different airspace classes as these requirements describe the complexity level of the aircraft which may operate within them.

2.7.2 Manned Aircraft Flight Requirements and Airmen Qualification

2.7.2.1 Equipage Requirements

For visual flight in the day, aircraft are required to be equipped with standard instruments including an airspeed indicator, magnetic direction indicator, altimeter, tachometer (for each engine), oil pressure gauge (for each engine), an oil temperature gauge (for air cooled engines), temperature gauge (for liquid cooled engines), a fuel gauge, a manifold pressure gauge, a landing gear position indicator, and anti-collision lights when applicable [64, 91.205A]. These are all very standard equipment and do not provide much to aid in see and avoid aside from the required lighting. For VFR operations at night, the aircraft must additionally be equipped with position lights and a landing light for commercial operations [64, 91.205C].

Standard IFR equipment requirements for powered civil aircraft with standard category U.S. airworthiness certificates require that aircraft operate using two way radio communication and navigation equipment are as follows: in addition to standard equipment for day and night operations as provided in FAR 91.205 (b)-Day, and (c)-Night, additional, two way radio communications are required. Transponder equipment is assumed mandatory as an extension of ADS-B equipment. However, prior to January 1, 2020, transponder equipment is mandated as follows: Class A, Class B, and Class C
airspace require that all aircraft operating within this volume are equipped [65, 91.215B]. The airspace surrounding airports listed in Appendix D, Section 1 of FAR Part 91 require transponder equipment within 30 NM of a primary airport from the surface to 10,000 feet MSL; however there is an exception for aircraft such as gliders and balloons, which are not certified as engine-driven aircraft.

For the non-engine driven aircraft, operations may be conducted within 30 NM of an airport specified in Appendix D, section 1, so long as the aircraft is outside of Class A, B, or C airspace, is lower than the ceiling of either a Class B or Class C ceiling for an airport, or below 10,000 feet MSL (the lower of the two altitude conditions). For non-glider or balloon aircraft, transponder equipment is required for all airspace at and above 10,000 feet MSL except that at and below 2,500 feet AGL, and for all airspace from the surface to 10,000 feet MSL inside a 10 NM radius of airports listed in Appendix D, section 2 of part 91 [65, 91.215B]. For all aircraft meeting these requirements, transponders must be operated in the on configuration within the airspaces listed. This includes adherence to all ATC squawk code standards and instructions [65, 91.215C].

These specifications for the use of transponders are somewhat difficult to envision, so alternatively, the aircraft traffic operating in different volumes of airspace can be looked at by general aircraft types. Most manned general aviation aircraft are equipped with transponders, but alternative aircraft such as ultralights, hot air balloons, and fabric aircraft usually are not. Most often these aircraft are not equipped with radios either, and rely on traditional see-and-avoid techniques to avoid other traffic. Aircraft which operate within the National Airspace System span from small ultralights, balloons, fabric airplanes, and model aircraft up through mainline air carrier transport planes, and even rockets. As aircraft complexity increases from hobby aircraft, to general aviation aircraft, to commercial aircraft, and mainliner cargo/transport planes, and other high power aircraft, the pilot qualifications become more stringent and in that, the pilots of these aircraft receive
additional training to prepare them for their flights ahead using aircraft with advanced features. Additionally, as aircraft increase in size, the payload is less of an issue, and heavier systems such as TCAS become more easily implemented.

### 2.7.2.2 Pilot Qualification and Training

For all of these aircraft which operate within the NAS, however, the fundamentals of manned aircraft flight are typically taught through the following elementary airman certifications: Sport Pilot, Private Pilot Airplane, and Private Pilot Rotorcraft. While other aircraft do not need these same airman certifications, that does not necessarily mean that they do not require any qualification. Thus pilot qualifications for small model aircraft up through private pilot rotorcraft will be discussed. It is important to note that by in large, hobbyist RC aircraft use is self-regulated by organized hobbyist groups around the country. While these aircraft operate very seriously under suggested guidelines, there is no formal legislation requirements which require the pilots to hold a certain level of certification, other than to have formally registered UAS according to the FAR Part 107 law [66] which requires that the aircraft owner be a US Citizen, or a foreign citizen which is permitted to live in the U.S. permanently. (They may also be operated by a company which meets the criteria or a government entity).

Basic (elementary) pilot qualification can be broken down into five categories: sport pilot, recreational pilot, private pilot aircraft, private pilot rotorcraft, and other. Note that these are very rudimentary licenses and are not meant to encompass the larger qualifications of additional ratings. The category of UAS operators would fall under the “other” category, as well as balloon operators and glider operators for example. These aircraft operators operate with requirements other than those covered by the formal training and testing methods of the other three categories. In fact, there is typically some registration and qualification required, but it does not result in a traditional airman certification. The aircraft
which are piloted by way of each of these five informal categorizations make up the aircraft which operate within the NAS.

To start, ultralight aircraft are defined such that they are to be operated by one person, they are for hobbyist use, and do not have an airworthiness certificate. If they are powered aircraft, they must weigh less than 254 lbs. and if they are unpowered, they must weigh less than 155 lbs. Additionally, ultralights have requirements for maximum airspeed and are only allowed to operate during daylight hours. Given that these aircraft are designed purely for hobbyist use, they are not required to be marked with an identification number and they do not require a medical certificate or any formal knowledge requirements in order to operate within the NAS. These aircraft are allowed in airspaces greater than Class G, but are typically expected to remain in the lower classes of airspace as they are lightweight and low powered, unless they are towed. For all ultralight and glider operations, they must remain clear from all other aircraft and densely populated areas [67]. The “other” category would also encompass UAS operations, for which pilot qualifications were discussed in Table 2.1 and summarized in the Introduction. Note that UAS similarly require no formal requirements for hobbyist use and are expected according to the Part 107 rules in place to be occupying low levels of airspace at low altitudes for the present time. One difference, however, is the need for markings and registration for UAS operations, and UAS operations for hire require a knowledge test (either previously as a manned aircraft pilot or for a first time UAS airman certificate) [22].

A Sport Pilot certification lets a pilot fly aircraft up to 1,320 lbs. (max gross weight) with either a medical certificate or a driver’s license in the United States. However, flights are limited to 50 NM from the home airport, and flights are restricted to Class E and G airspace unless more training and a formal exception is arranged by a flight instructor’s endorsement. Similar to ultralights pilots, these pilots are also not allowed to fly at night and have visibility limitations. A Recreational Pilot certification is a relatively
unpopular compromise between a sport pilot certificate and a private pilot certificate. A medical certificate is required for operations, but there is additionally a limit on the aircraft capability. Specifically recreational pilots can only operate aircraft with less than or equal to 180 horsepower and 4 seats. Like sport pilot certificates, airmen are restricted on the number of passengers they are allowed to take, but can receive their license with fewer flight hours than a private pilot airman. This license has the same airspace requirements as the sport pilot certification, where aircraft may only operate within airspace classes E and G. In some limited cases, operations are allowed after sunset with this license [68].

A Private Pilot certification is a step up from the Sport Pilot and Recreational Pilot certifications. Private Pilots are allowed to operate outside of the 50 NM range with significantly fewer restrictions (in altitude as well) but a medical is required, and more flight hours are required for certification. Operations may be conducted in airspace classes B-G, and possible aircraft permitted for operation technically has no limit, but more complex aircraft require further endorsement or ratings. A private pilot may take more than one passenger on flights and fly at night, outside the country, or with less ideal visibility, than what is necessary for the other two types previously discussed. Private Pilot rotorcraft certification is analogous to that for airplanes but with varying pilot knowledge and practical requirements based upon the difference between the aircraft systems [68]. In order for a pilot to operate in Class A airspace, they must have at least an Instrument Flight Rating on their private pilot certificate, as well as the associated equipage requirements. All of the ratings for non-hobbyist non-ultralight flight requires that the pilot pass a knowledge test of varying scope (based upon the complexity of the license).

From this information we can infer that at this point of UAS integration, low altitude flights in Class E and Class G are expected to be occupied by all aircraft, UAS through ultralights, and further through private pilot aircraft such as helicopters performing low altitude operations and approaches. Class D, C, and B are likely to be occupied primarily
by private pilot aircraft, but also sport pilot aircraft, and recreational pilot aircraft, and Class A airspace is to be occupied by only instrument rated private pilot aircraft. The higher levels of training required of the airmen operating in higher classes of airspace is one factor which contributes to the higher levels of safety achieved in more stringent classes of airspace.

The training requirements for all airmen certifications are published by the FAA. UAS airmen training requirements are published in Airmen Certification Standards and Practical Test Standards which formally outline the federal knowledge requirements tested. Airmen Certification Standards pertain to Instrument Rating Standards [69], Private Pilot Airplane Standards [70], and Remote Pilot sUAS Standards [71]. In contrast, Practical Test Standards are published for Sport Pilot [72], Recreational Pilot [73], and Private Pilot Rotorcraft airmen certifications [74]. Knowledge requirements are closely itemized within these references, and are insightful to the pilot knowledge expected of and held by the operators of the associated aircraft. A comparison helps to illuminate the differences between the pilots which operate each of these aircraft of varying complexities, but a formal and intensive exploration of these requirements is outside the scope of this research.
3 LITERATURE REVIEW

3.1 Target Levels of Safety for Operations in the NAS: System Safety Assessments and Certifying Part 23 Airplanes

Higher levels of airspace are associated with more stringent qualifications for flight and equipage requirements for the aircraft. Additionally, Class A airspace for example implies a more complex aircraft in order to have the higher operational ceiling necessary to perform flights. All of these factors contribute to higher levels of safety, and conversely, lower acceptable probabilities for catastrophic events. The FAA Advisory Circular, AC 23.1309-1E outlines the system safety modeling of aircraft operations for Part 23 Airplanes. These aircraft are able to be operated in all classes of airspace, but have less strict performance requirements than Part 25 Airplanes and less strict requirements for redundant systems for example.

The airworthiness circular identifies the acceptable probabilities of failure for hardware or software for four classes of aircraft. The acceptable probability of a catastrophic event occurrence is as follows, according to Figure 2 on page 23 of the Advisory Circular. For Class I airplanes it must be less than 1E-6 per flight hour, for Class II airplanes it must be less than 1E-7 per flight hour, for Class III airplanes it must be less than 1E-8 per flight hour, and for Class IV airplanes it must be less than 1E-9 per flight hour. Note, that this is only a subset of the statistical safety probabilities offered in the Advisory Circular text. In addition to a catastrophic event, the failure conditions of Minor, Major, Hazardous, and Catastrophic are defined in detail.

Each of these different failure condition classifications have different identified manifestations of the failure in its effects on the airplane, passengers, and flight crew. Within the different categorizations, events such as physical distress and injury of varying severity to flight crew or passengers are considered. These allowable probabilities of
occurrence have relevance in considering events such as injury to “non-participants” as well. As there is a level of risk which is accepted by members of a flight crew and passengers upon boarding a plane, generally speaking the permissible probability of an adverse event is higher for these individuals than for “non-participant” individuals who have not deliberately accepted that same risk.

Class I aircraft are usually single engine aircraft weighing at most 6,000 lbs., Class II aircraft are also under 6,000 lbs. and are either multi-engine (either reciprocating or turbine) or have a single reciprocating engine. Class III aircraft weigh more than 6,000 lbs. and can be any of the engine types listed previously, and Class IV aircraft are multi-engine aircraft which can carry a maximum of 19 passengers and are weigh a maximum of 19,000 lbs. [75, 76]. Therefore, a wide variety of aircraft of different levels of complexity are encompassed by these requirements. Additionally, these requirements can be used as a benchmark to evaluate acceptable levels of failure for different volumes of airspace based upon which aircraft types are expected to inhabit them.

The levels of safety to which these commercial aircraft operations are certified to must be considered within the context of commercial aviation. According to a Summary Report released by Boeing in 2015, the annual number of flight hours for worldwide commercial jet operations was 60 million flight hours conducted by 24,611 airplanes [77]. Note that these statistics are for jet airplanes with a max gross weight greater than 60,000 lbs. Also, some of these aircraft may be temporarily non-flying, but operational. There are additional commercial aircraft operations performed by non-jet aircraft annually across the globe. In contrast, as of May 12th, 2016, 39,462 UAS have been registered with the Federal Aviation Administration [78]. These numbers, along with the number of flight hours, are expected to continue to grow given the relatively low cost to purchase UAS. Since UAS are much easier to own and operate than commercial aircraft, with less stringent pilot requirements, low-
altitude UAS operations are becoming increasingly more common, and relatively speaking more common than commercial manned aircraft operations.

If a constant risk per flight hour to a person on the ground is assumed, this risk will increase proportional to the volume of UAS operations. In order to accurately model these risks, it will be important to accurately estimate the number of flight hours flown by UAS. For worldwide commercial manned jet aircraft operations (with a max gross weight greater than 60,000 lbs.) we may see around 6.68 flight hours per day per aircraft. This means a relatively low number of aircraft fly a large number of hours. If UAS operations grow as projected, we can estimate a relatively low number of flight hours to be flown by a huge fleet of aircraft. It is important to acknowledge the implications of per flight hour probabilities in assessing the risk posed by UAS and the differences from manned aviation modeling.

3.2 On Integrating Unmanned Aircraft Systems into the National Airspace System: Dalamakidis et al.

The target levels of safety listed in Section 3.1 are also presented by Dalamagkidis et al. as a starting point for developing safety requirements for UAS in their discussion of the safety analyses in Chapter 5 of On Integrating Unmanned Aircraft Systems into the National Airspace System [79, p. 94]. Dalamagkidis et al. note that while these accepted levels of safety are a great starting point, they do not necessarily transfer to the context of UAS due to the fact that the danger presented to lives does not pertain to lives on board the aircraft [79, p.94]. In addition to the levels of safety considered in certification of manned aircraft operations, the authors examine the context of other non-aviation related activities and the corresponding risks which people deem acceptable for a given operation. One example of this would be the risk which a person assumes in driving a car. This is a daily activity for most people, but it does involve the risk of dying in a motor accident.
Chapter 5 of this text goes on to discuss a variety of statistical models developed for modeling fatalities and catastrophic events resulting from failures in UAS as well as their virtues and shortcomings. This text offers a well-rounded discussion of all of the elements which must be considered in choosing a target level of safety for the certification of a device or operation. For the discussion within this textbook, UAS Accidents are divided into three categories for examination. These categories are: Unintended/Abnormal System Mobility Operations, Midair Collisions, and Early Flight Terminations. The first category, Unintended/Abnormal System Mobility Operations pertains to accidents which happen on the ground. Midair Collisions were regarded as an accident between either two UAS or a UAS and a manned aircraft, and were considered to have a secondary accident of impact to the ground. Lastly, Early Flight Termination accidents describe a ground or water crash either commanded intentionally or otherwise [79, p.97].

For the purposes of developing case studies in this text, the authors choose to use a target level of safety of 1E-7 fatalities per flight hour [79, p.126]. This target level of safety was chosen for use across the board of UAS aircraft types on the basis that for manned aircraft accidents, the probabilities of an accident for aircraft varies from 2.84E-5 for general aviation to 2.06E-7 for airlines. Therefore, if the target level of safety of that airspace is to remain unchanged, it was decided that for a pessimistic view, UAS need to adhere to at least a 1E-7 fatalities per flight hour on average.

In general, the authors of the text do not cover in detail the accident category of Unintended/Abnormal System Mobility Operations as this is able to be controlled and mitigated. For Midair Collisions, it was discussed that the acceptable probability of occurrence was 1E-7 per flight hour for Class E airspace, and higher for Class G airspace. The reason for a higher probability of occurrence in Class G is that there are more aircraft, birds, etc. located within this airspace and radios, and radar control is not a fundamental requirement for this airspace since it is uncontrolled. For the case of ground fatalities, it
was determined that the acceptable probability of occurrence is 1E-7 per flight hour. That being said, the authors of the text propose certifying to a probability of occurrence of 1E-8 per flight hour [79, p. 99,100]. This more stringent level of safety is proposed based upon the idea that people are willing to accept a higher level of risk for an operation which they feel benefits them or that they gain something from in return. Since the benefits of UAS to the general public are not yet universally accepted or readily apparent to all, a higher level of safety is proposed.

While 1E-7 is the conservative all-encompassing estimate, the authors discuss the fact that this is not necessarily the number: there are a lot of other factors to consider. One such factor is the idea that not all UAS which experience an accident either in flight and fall or into the ground will have the same effect on that area with respect to force and kinetic energy. If a micro-UAS were to fall unexpectedly and strike a person, it would be unrealistic to assume that a person which is hit will result in a fatality [79]. Therefore, the authors explore different modeling options, including those presented in a MIT Report titled Safety Considerations for Operation of Unmanned Aerial Vehicles in the National Airspace System, and discuss the accuracy of these models for UAS operations. One of the takeaway products of this text was the examination of the model presented in the 2005 MIT report, with further insight and study into a more accurate modeling of kinetic energy of the UAS for ground impact for smaller UAS types. The statistical model presented in the MIT text will follow this section. Information suggested for deriving accurate statistical model inputs include cross sectional areas of the UAS and gliding descents versus vertical falls, and taking a closer look at the impact and mitigation presented by impact to a person located within a shelter.

Dalamagkidis et al. provide suggestions for mitigating the risk posed by UAS operations in the NAS. These include: controlling an “affected population,” operating UAS at a certain time of day or night, or the use of parachutes, pyrotechnics, crash sites, and
preprogrammed procedures. These are intended to mitigate risk to people on the ground in the event of a UAS crash. Some of these mitigation strategies, such as the use of crash sites and preprogrammed procedures are already widely in use for UAS operations. Additionally, current UAS operations for larger aircraft often occur in segregated airspace, thereby controlling the population by isolating the flight to an unpopulated or controlled area [79, Chapter 5].

This textbook is the first on UAS integration into the NAS that specifically addresses the formal safety assessments as an instrumental part in the path to full and complete integration of UAS into the National Airspace System in the United States. It provides a good summary of the well-established discussion that it is necessary to develop a target level of safety for UAS operations in the NAS, and that formal safety assessments and statistical modeling is a necessary step in certifying operations to an acceptable level of risk. Additionally, the authors offer insight into the various areas of modeling to be considered and methods to develop probabilities for inputting into the models, using cross-sectional areas, terminal velocity, and population density. The text proves that there is a need for separate consideration and modeling of UAS accidents as they are fundamentally different than the manned aircraft operations already occurring. Additionally, it proves that there is a need for risk mitigation solutions for UAS operations. The suggestions provided by the authors are relevant and useful as a starting point, and reflect some already widely in use. However, for true integration to be a reality, additional risk mitigation measures are necessary, as those provided offer a solution to only a subset of all UAS operations and are not reasonable for widely occurring operations slated for the future, (such as removing population from an affected area or asking them to remain indoors).
3.3 Safety Considerations for Operation of Unmanned Aerial Vehicles in the National Airspace System

The 2005 MIT report authored by Weibel and Hansman presented models which were covered in chapter five of the On Integrating UAS into the NAS textbook by Dalamagkidis et al.. This report examines UAS accidents and the need for additional formal risk mitigation in order for true integration of UAS into the NAS [80]. A discussion of the risks posed by UAS operations compared to manned aircraft operations is included as well as a statistical look at the problem through development of expected level of safety models. Specifically, the authors of this text look at the levels of safety offered by UAS operations with no formal UAS-specific risk mitigation, or in their existing state (as of 2005). A variety of UAS aircraft types (sizes and weights) are examined and modeled. Based upon the evaluation of the models using population data across the United States, the authors present a series of maps of the United States of America with shaded regions indicating the area of the entire country where the level of safety of 1E-7 per flight hour can be achieved.

These maps show the percentage of the entire US where operations can be conducted for a given mean time between failures. The classes of UAS (called UAVs within the paper) are divided into Micro, Mini, Tactical, Medium Altitude, High Altitude, and Heavy categories. For each of these categories, a specific UAS is presented as an example. The models covered within the text include a ground impact model and a midair collision model, with the ground impact model used to generate the United States population related maps. The ground impact model is presented as Equation 1 located in Chapter 6 of the text, and has been reproduced below.

\[
ELS = \frac{1}{MTBF} \times A_{exp} \times \rho \times P_{pen} \times (1 - P_{mit}) \tag{3.1}
\]
As stated previously, there is no formal mitigation considered in the evaluation of the model within the report. In this ground impact model, MTBF signifies the mean time between failures of the aircraft, with the multiplicative inverse of that giving the failure rate of the aircraft system. $A_{exp}$ is the average area affected by the UAS accident, or the “lethal debris area.” $\rho$ signifies the population density of a given area, so $A_{exp}$ multiplied by $\rho$ gives the number of people harmed. $P_{pen}$ is the penetration factor, or the proportion of time for which debris resulting from a crash will penetrate a sheltered area given the time that that shelter is exposed. For this model, if a shelter containing a person is penetrated it is assumed that a fatality will occur. Lastly, $P_{mit}$ refers to the proportion of accidents for which a fatality is avoided by way of risk mitigation. Therefore, in this report, $P_{mit}$ is always set to 0. This model was further examined in the On Integrating Unmanned Aircraft Systems into the National Airspace System text, in which Dalamagkidis et al. proposed a method of considering the kinetic energy of a falling UAS which would provide greater accuracy for smaller UAS under study [79].

The second model presented in this study is referred to as Equation 2, located in the following chapter, Chapter 7, of the report [80]. This model describes the expected level of safety for a midair collision, and is reproduced below.

$$ELS = \frac{(A_{exp}d)}{(V_t)} * P_{fat\text{icoll}}$$

(3.2)

In this model, $A_{exp}$ is the area of contact subject to a collision. This was calculated to be the frontal area of a manned aircraft. The area of exposure of the UAS is not considered variable because the UAS is considered to be small compared to the manned aircraft. Also, the UAS velocity was considered to be small in comparison to that of the manned aircraft. $d$ is the distance the aircraft flies through the volume of airspace considered in the model (a given cube volume as described in the text). Therefore, given a position of a UAS, a collision is expected to occur if the volume described by the exposure area of the
manned aircraft times the distance traveled by that aircraft (the exposure volume) overlaps with the position of the UAS within the airspace volume under consideration (V). The variable t describes the period of time under calculation. Assuming a collision is expected to occur, this does not necessarily mean that a fatality is guaranteed. Therefore $P_{fat|coll}$ is the conditional probability that a collision results in a fatality given that it occurs. Again in this study, formal mitigation was not considered, so the mitigation term is assumed to be 1 (and is not present in the depicted expression). Expected levels of safety were further examined and calculated within the contexts of jet routes and victor airways.

General conclusions of the study include that small UAS operations are possible over the United States without significant regulations or additional measures [80]. This confirms the developments in UAS regulations which we have seen in the years since 2005. Namely, small UAS are operable under Part 107 under 55lbs with few operator restrictions. Also, this size of aircraft and smaller can fall under hobbyist use and are relevant in the context of model aircraft operations as well. Additionally, the authors conclude that higher mass UAS require additional formal risk mitigation measures correlated to the increased risk presented by the aircraft [80].

This study provides evidence that there is a strong need for additional mitigation of risk in order for integrated UAS operations to become a reality in the National Airspace System. Additionally, the problem is approached by way of formal statistical modeling with the end goal of ensuring and proving that UAS operations adhere to a level of safety comparable to that of their manned aircraft counterparts by way of mitigating the risk of fatalities both on the ground and in the air. The models presented offer some insight into the factors which must be considered and which play a role in the possibility of fatality in each of the accident cases examined. That being said, the models developed are fairly unspecific and are not complete for all UAS operations projected for integration into the National Airspace System. Therefore, there is additional need for examination of statistical
occurrences of UAS accidents and incidents, and there is a need to continue study to gain further insight into exactly how the risks posed by these aircraft systems should be mitigated. This includes non-fatal accidents, such as those which cause injury, posed by UAS operations and their impact. In this vein, it will be useful to understand where additional or different risks are posed by UAS operations in comparison to their manned aircraft counterparts.

### 3.4 An Evidence Theoretic Approach to Design of Reliable-Low Cost UAVs

A study which involves Fault Tree Analyses in application to UAS was published in 2009 by Murtha at Virginia Tech. For this study, a solution was sought to improve the hardware reliability of a UAS used as a research platform for testing by the university, the SPAARO UAV [81]. The ultimate goal was to use a formal method to break down the risk of failure in the UAS and use sensitivity analysis to determine the best ways to make improvements in reliability in the aircraft for reasonable or low costs. The author developed a MATLAB toolbox and studied three different sensitivity analyses pertaining to a given single component. Improvements were made to the system by either adding redundancy to a component, replacing a component with a more reliable (often more expensive) alternative, or investing money into research of that component in order to gain more accurate failure insights and statistics.

An original fault tree analysis is produced of the aircraft operation with the top level event to mitigate as a UAV Crash (Figure 35) [81, p.79]. This is broken down into Control System Failures, Tail Failures, Wing Failures, or Propulsion Failures. One of the improvements made to the aircraft was increased reliability through redundant control surfaces and servo motors. This is showcased in a later fault tree within the report, labeled Figure 42 [81, 92].
In the initial fault tree analysis (before improvements), the Tail Failure Aircraft Level 1 Subsystem is broken down into four event failures connected together through a Boolean OR gate. These include Rudder Servo, Rudder Surface, Elevator Servo, and Elevator Surface component failures. By adding redundancies to the aircraft components, the fault tree for the improved aircraft hardware changes into the Level 1 Subsystem of Tail Failure divided into 8 failure events (instead of 4). These are connected within the fault tree as follows. The Tail Failure subsystem is divided into four sections connected together with an OR gate just as before. However, with the improvements made, each of the four sections consists of two failure events connected to each other with an AND gate. Each of the sets of two failure events consist of a single aircraft component (the same as in the initial tree) and a redundant system component (the improvement). Therefore, with the improved system, both the initial and the redundant system components (rudder servo, rudder surface, elevator servo, and elevator surface) must fail in order for a failure to result in a failure in that part of the tree, and therefore a UAV crash [81].

This study is particularly interesting as it shows the ability to significantly improve the reliability of a small UAS platform for a relatively low cost using strategic reliability improvements. Specifically a recommended method for improvement of sUAS hardware is presented from a reliability vs. cost approach. Thus this study offers a successful demonstration of application of Safety Assessments using the tool of Fault Tree Analyses to improve the reliability of a UAS to be operated within the National Airspace System in the USA. However, there are not many examples of extensive fault tree analyses applied to UAS optimization with the goal of mitigating risk associated with UAS crashes. While this is a great example, it deals with only one specific aircraft. This means the scope is fairly limited, and there exists a need for modeling of UAS crashes as a whole, regardless of aircraft, ground station, or operator type in order to get insight to the operational
differences of UAS operations themselves compared to manned aircraft operations, and inherent differences in the systems.

In conclusion, it is important to note that the amount of literature on the subject of formal UAS integration into the National Airspace System in the United States is fairly limited in nature. This is in part due to the fact that these systems are relatively new, especially for civil applications and at low costs. System Safety Assessments and Fault Tree Analyses have been applied extensively to study manned aircraft operations in the US and other systems which could threaten the life or cause harm to a person, but they have not been applied in the same ways, or to the same extent for Unmanned Aircraft Systems at this time.
4 METHODS

4.1 Fault Tree Analysis

This study consisted of creating a set of fault tree analyses and a database of accidents and incidents involving UAS to create a partial system safety assessment on UAS operations within the US National Airspace System. The fault trees were conducted from both a top down and a bottom up approach. “Top down” here means the course of developing a tree from the top event down. This method consists of modeling the failure paths based upon the top level event and things that could contribute to its occurrence by referencing an industry accepted framework, categorizations, and tools. In contrast, a “bottom up” approach is inspired by taking data from accidents and incidents which have occurred and building them into the tree from the identified failures up to a possible top level event. The failures which warrant and inspire inclusion may or may not have occurred in an accident or incident which caused that top level event, necessarily, but it strongly identifies the occurrence as a failure case which is legitimate and needs to be considered wherever relevant.

In the fault tree itself, each subsystem has labeled with it the probability of a failure of that subsystem per flight hour. These probabilities can be budgets of what is necessary or target for the design of an aircraft or system, or they can be the result of the probabilities of failures of all of the gates and events in the lower subsystems in the fault tree. The top-down approach would be designing by employing a budget, and the bottom-up approach would be testing based upon known failure modes of smaller components. Both achieve the same goal of systematically and scientifically assuring that the system is safe enough for use.
4.1.1 Scope of the Fault Tree Analyses

In order to identify general pilot training needs and system needs for additional supplementation, the trees were kept universal. As these trees are used to model more specific UAS operations, the probabilities of the events and subsystem failure rates will change based upon the characteristics of that system, pilot, and operation. Depending on the operation being modeled, the role of the pilot in certain situations may become more safety critical and require a higher level of training or vice versa. An example of this could be operations near people vs. in a remote area, or operations near mountain terrain where airflow characteristics are significantly different and a much greater concern than operation over flat plains.

A general fault tree framework was created with the goal of identifying and characterizing the roles of the pilot common to all UAS operations. As a product of creating a tailorable framework certain events and subsystem failures within the fault trees may “fall out” or simplify when the tree is tailored to a less complex operation, such as within line of sight of the pilot, or for an aircraft system which is not equipped with an autopilot. However, these specific characteristics may add unique additional events or subsystems to the fault tree as new risks may need to be taken into consideration.

4.1.2 Assumptions for the Fault Tree Analyses

Assumptions for this work include that the pilot of the UAS has received a level of training deemed necessary to perform the operation of interest, and that the pilot is familiar with the system, or has been “checked out.” The framework is designed to be applicable to aircraft as small as the original Parrot AR popular consumer drones up through “racing drones,” more complex aircraft such as MQ-1B Predators and even larger. As a product, the framework is designed to encompass different user interfaces whether they be remote cockpits with similar setups as traditional “in fuselage” cockpits or small
handheld controllers which may or may not feature a video or control screen. These details are not considered as directly influential to the result of a framework.

The current airspace model is employed and assumed in the analyses, with no changes to that model. This is chosen because ultimately UAS operations should be seamlessly integrated into the same volumes of airspace as used by manned aircraft. Any evolutions which affect the airspace structure currently employed by manned aircraft should be designed to further encompass UAS traffic. These evolutions which may or may not occur into the future are considered to be a subject independent of these results. Because the trees model an array of aircraft with different operational capabilities, the surrounding traffic to be considered in the fault trees is a function of the specific operation of a chosen aircraft. The airspace of operation will determine what surrounding traffic can be expected.

The fault trees were constructed with the assumption that the aircraft is equipped with an autopilot, the ability to navigate by use of waypoints, and/or an altitude fencing mechanism. The autopilot and waypoint navigation techniques are programmable by the pilot or UAS operator, while the altitude fencing mechanism is programmable by either the pilot or the manufacturer. Some manufacturers may preprogram altitude limits in an effort to keep sUAS operators under the 400 foot altitude limit, which could be difficult for new hobbyists to judge themselves. The framework is built to consider commercial UAS operations as these are typically more complex and require higher levels of assured safety.

Finally, it is assumed that the UAS has an autopilot mode that will take control in the event of a loss of communication or loss of navigation event. This could be either a loitering pattern or a return to base procedure specific to the aircraft. Most sUAS are assumed to employ a return to base method, but these most likely employ GPS and are hard programmed, not taking into account specific environmental conditions before landing. Therefore, it is possible for these aircraft to run into trees, obstacles, or people if the operators and surrounding onlookers are not aware of this feature.
4.1.3 Fault Tree Development Procedure, References, and Objective

There are many options on the market for fault tree development and analysis software. The fault tree analyses for this research were performed using the Isograph FaultTree+ 11.2. Additionally, Open FTA was explored as a possible option for use. This option was attractive due to its open source nature. However, the software is no longer supported by the developer and while there are some online forum resources, various operational issues were encountered in the creation of the fault trees. FaultTree+ was selected for use as this software is actively managed by Isograph with a formal software manual, extensive modeling capabilities, and continuing technical support.

The fault trees in this research were constructed based upon the practices outlined in the NASA Fault Tree Handbook [82] and the general UAS fault tree framework was created in part based upon the manned aircraft fault tree framework in common use. The initial steps toward creating the fault trees involved the identification of an objective, and the defining of a top level event. Next, the scope was defined and lastly, the resolution objective was identified. Four fault trees were constructed in this research with different top level events. While the top level events were different, the trees are designed to be viewed as a unit. As such, the objectives, general scope, and resolution objectives are shared. However, the ICAO Aviation Occurrence-specific trees have top events which are characterized by the official ICAO definitions [57].

The objective of the general UAS Fault Tree framework is to create a model comparable to the commonly employed model for manned aircraft operations. This new model must accurately reflect the similarities to the manned aircraft model common in industry, while simultaneously incorporating the different aspects specific to the Unmanned Aircraft System. The fault tree framework was to be populated with events which reflect the failures catalogued in the UAS incident and accident database developed for this research.

The ultimate goals of this fault tree and the other occurrence-specific trees are:
• to identify the areas of the UAS which make these systems less safe than manned aircraft aviation, and

• to identify the areas in the fault tree framework for which the (manned or unmanned aircraft) pilot plays an active primary or remedial role in controlling the aircraft to prevent an accident, and prevent or remedy an incident.

By identifying the pilot role and how the role of the pilot in interfacing with and controlling the aircraft differs for in-fuselage cockpits versus remote cockpits, a closer look can be taken from the point of pilot training needs.

The top level event for the system-level fault tree analysis was chosen to be a Crash or Fatal Accident. Typically, the worst top level event is considered to be a “Loss of Hull” or loss of life for manned aircraft. With the parallel modeling of UAS through fault tree analyses, there is one significant difference. If a manned aircraft crashes, there are always souls on board who will likely perish. However, the opposite is true for UAS crashes: there are never souls on board to perish. This is one signal to the departure from the long-accepted industry model for fault trees for aircraft.

A catastrophic event is typically regarded as an event which causes the loss of life. However, this means that the aircraft could be salvageable. The two occurrences are not necessarily tied. For the purposes of this research, the top level event was chosen to be a crash or a fatal accident. This top level event is expected to encompass both a crash in flight and on the ground which could endanger souls whether they are in other manned aircraft operating in the airspace, operators and bystanders, or unknowing people who would be affected based upon statistical population density. If an aircraft comes down unexpectedly, there is a likely chance that life on the ground could be impacted through death, injury, fire, or destroyed property.
The scope of the general system fault tree is aircraft non-specific. Many of the details regarding the aircraft equipage considered were previously discussed in paragraph two of the preceding subsection titled Assumptions for the Fault Tree Analyses. The general system level analysis as well as the three failure-specific fault tree analyses are to be considered as a partial system safety assessment, and a preliminary tool to be modified for specific aircraft and operations, with the further goal of populating the fault tree analyses with quantitative probabilities of occurrences, or sub-system failures. By making a general framework, the path toward specific technical safety assessments becomes clearer and the discussion is initiated. The framework is designed such that it will create a context within which to view more specific scenarios.

The fault trees are approached from the point of reference of failure modes that are occurring in unmanned aircraft operations in their current state. These failure modes are in part supplied by the data collected in the database of UAS incidents and accidents discussed in this work. Most of these UAS operations happen in segregated restricted airspace. Additional failure modes are apparent from examining the similarities between UAS and manned aircraft and deducing their common failure modes.

4.1.4 Introduction to the Fault Tree Analysis Results

The product of this research consists of four qualitative fault tree analyses. No quantitative probabilities of failures have been assigned to the subsystems and events within the trees. It was deemed that there is insufficient data from what has been collected in this work to assign probabilities to these events. Thus a partial system safety assessment for general UAS operations in the NAS has been conducted. The system safety assessment is preliminary, as a system safety assessment requires a multitude of quantitative analyses and aircraft and operation-specific details in order to be deemed complete. As this framework is further applied and tailored to specific circumstances associated with aircraft operation,
the ability to estimate failure rates will become more straightforward as additional details will be available. At this time, it is difficult to model these operations quantitatively as there are no existing quantitative industry standards for reliability or hardware development for these aircraft in the same ways as for manned aircraft airplanes, system requirements, and aviators. These standards have not yet been developed.

The four fault trees produced from this research are: a general UAS system framework, and ICAO Aviation Occurrence-specific fault trees for the three top occurring occurrences in the results of the UAS accident and incident database. These ICAO Aviation Occurrences are: Navigation Errors (NAV) with 74 occurrences, AIRPROX/TCAS Alert/Loss of Separation/Near Midair Collisions/Midair Collisions (MAC) with 101 occurrences, and System/Component Failure or Malfunction (Non-Powerplant) (SCF-NP) with 165 occurrences within the database. The top level events for these fault trees are defined again for the same criteria of the general framework fault tree (independent of airspace of operation and independent of aircraft size/model etc.) but with the additional event-specific detail and scope directly according to that defined by in the ICAO Aviation Occurrence Categories Definitions and Usage Notes [57].

These events were chosen for modeling because they are already existing issues at the forefront of integration due to the fact that they are derived from reported accidents and incidents. Upon entering this research, main concerns which were identified included loss of navigation, loss of communications, and loss of control. These are three events for manned and unmanned aircraft which draw heavily on the pilots ability to debug and assess the situation as well as to select an appropriate action which often lets the aircraft operations continue in a degraded yet safe and functional manner. These losses are considered to have significantly different implications for UAS operations than for manned aircraft operations due to the remote versus direct interfacing capability of the pilot with the aircraft. Additionally, the manned aircraft pilot has an advantage of sitting within the
fuselage of the aircraft and sharing the first person view of the aircraft. This is useful in mitigating risks proposed by losses in system capability, and sometimes a similar view is either not used at all or will be lost as a function of the other losses (e.g. in the case of loss of link). These losses of concern were considered to be completely encompassed within the three ICAO Occurrences listed as those most commonly occurring in the database.

4.1.5 ICAO Aviation Occurrence Category-Specific Fault Tree Analyses: Selection and Objectives

The most commonly occurring ICAO Aviation Occurrence is System/Component Failure or Malfunction (Non-Powerplant) (SCF-NP). This describes any failure or fault within the system that does not have to do directly with the engine or propulsion unit of the aircraft [57]. Keep in mind that these Aviation Occurrences were primarily designed as a taxonomy for categorizing manned aircraft accidents and incidents but have since been updated to include UAS operations. The failures encompassed by the code SCF-NP include: software, database, and rotor system failure, flight control failure, drive system failure, and any components breaking off of the aircraft so long as they are not directly pertaining to the propulsion of that aircraft. In the context of UAS, the failures include those pertaining to any sort of equipment used on the ground for takeoff and landing operations, and any system components that have to do with the ground-based and satellite-based infrastructure used for remote operations. Lastly, if any issues leading to these failures were caused by insufficient maintenance operations, these are still considered SCF-NP. The SCF-NP Aviation Occurrence Category, as well as the other categories listed in the ICAO Aviation Occurrence Categories Taxonomy, pertains to all aircraft- including UAS, helicopters, and more, not just airplanes [57, p. 21].

The second most commonly occurring ICAO Aviation Occurrence was AIR-PROX/TCAS Alert/Loss of Separation/Near Midair Collisions/Midair Collisions (MAC).
This category is fairly self-explanatory and describes any accidents or incidents which result in a loss of separation between aircraft, and perhaps a TCAS alert with separation resolution advisory, or collision depending on how the situation progresses. The category does not include false alerts or resolution advisories, but it does include cases where loss of separation was caused by failures in the air traffic control system [57]. An AIRPROX is the name for a near midair collision as labeled by ICAO [83], while a TCAS alert is an alert which is generated by the Traffic Collision Avoidance System, an aircraft based system which prevents midair collisions by interrogating aircraft transponders in the surrounding area and issuing resolution instructions to aircraft which are on a collision path and in immediate danger of colliding [84].

The third most common ICAO Aviation Occurrence is Navigation Errors (NAV). This event has to do with any accidents and incidents which happen due to incorrect navigation. This failure encompasses airspace incursions both vertical and horizontal resulting from a lack of spatial awareness or insufficient navigation, as well as an inability to maintain headings or altitudes or any other failure to adhere to ATC clearance either in the air or on the ground. This includes using runways which were not assigned to the aircraft as well as closed areas of an airport. This event, however, does not include instances where deviations from assigned instructions and airspace incursions are caused by emergencies, avoiding collisions with other aircraft, and being subject to convective activity, which are considered outside the pilot’s direct control. In these select situations, safety and accident/incident avoidance comes first [57].

These three ICAO aviation occurrences were selected for further modeling due to the fact they occurred most frequently in reported accidents and incidents involving UAS. Additionally, from the description they are particularly relevant for further examination due to their implications when applied to an unmanned aircraft system context. System/Component failures or malfunctions which are non-powerplant are relevant to UAS
as in the switch from an in-fuselage pilot to a remote pilot, a multitude of additional system components are created or modified and many of these components become more safety critical. For example, this encompasses the control link and navigation links used by the aircraft and control station. Additionally, many UAS operators communicate with ATC via uplink to the aircraft and the use of an antenna located upon the aircraft for local (to the aircraft) transmissions. If a pilot loses his/her ability to communicate with ATC while in flight, there are often visual procedures for backup communication, but these become much more complicated and sometimes are not possible for UAS due to the fact that the pilot cannot communicate to a control tower from an in-fuselage cockpit.

Navigation Errors become an increasingly relevant concern for investigation for UAS as opposed to manned aircraft due to the fact that a remote cockpit introduces decreased spatial awareness of the aircraft's state, position, and orientation, as well as other characteristics of flight such as power levels. A pilot is perhaps less likely to notice things such as unnecessarily open throttle or excessive pitch-up attitude on the aircraft in the same amount of time without the same kinesthetic input they would likely experience within the fuselage. This is specifically in the comparison between a manned aircraft pilot and a UAS pilot of comparable aircraft.

Lastly, the AIRPROX/TCAS Alert/Loss of Separation/Near Midair Collisions/Midair Collisions (MAC) event is perhaps the most important occurrence to mitigate, especially for UAS. Typically midair collisions are important to mitigate as it could result in loss of two aircraft. UAS operations are often attractive due to the fact that if these aircraft crash, no one on board will be injured. Therefore, the main cause of loss of human life in the air presented by UAS would be the impact of a UAS with a manned aircraft. So, while UAS are often considered safer for people in the skies, this is only true so long as the aircraft experiences no losses of separation with other aircraft and ultimately no fatal
midair collisions with manned aircraft. Of course there still exists the potential for injuries, loss of life, and property damage resulting from UAS falling and impacting the ground.

Further, the MAC failure is important to be examined for UAS in the NAS because the ability to maintain separation between aircraft is complicated by the introduction of aircraft that do not have in-fuselage pilots. First, the UAS pilot’s position on the ground, as opposed to within the aircraft limits his or her capability to visually see as first person other aircraft to the scope of the camera view which the aircraft system provides. While other systems such as ADS-B can be relied upon for additional traffic information, this is neither required equipage for UAS at the current time, nor is it required for all other aircraft which may be operating within that airspace (such as ultralights or aircraft without radios, etc.).

It is important to note that the FAA has created ADS-B equipage requirements for all airspaces which necessitate a transponder. These requirements are in place for federal enforcement in 2020. However, many UAS applications are not projected to take place within these airspace volumes. For example, Class G airspace will not require ADS-B out nor will Class E airspace below 10,000 feet MSL [85]. If a UAS operator or ATC does recognize that a loss of separation has occurred between the UAS and another aircraft, there are additional concerns to consider such as link latencies, and the ability of the remote pilot to make last minute decisions and course alterations. As a result, manned aircraft are often rerouted by ATC or perform last minute evasive maneuvers. In this way, the introduction of UAS into the NAS could actually add to the manned aircraft pilot’s workload.

Also considering manned aircraft pilots, the MAC occurrence is of great importance to them due to the low-visibility nature of UAS. Often UAS are either of small size and/or they are painted a color which makes them difficult to spot. If manned aircraft cannot see UAS, they cannot avoid them or take evasive maneuvers before loss of separation occurs. Lastly, birds and other “non-cooperative” targets are typically avoided using visual cues as they typically do not show up on ATC radar.
Based upon the definition of the ICAO Aviation Occurrence Categories selected for event-specific fault tree analysis and the reasons of their significance in the transition from modeling manned aircraft to UAS operations, the concerns presented by the loss of communications, loss of navigation and loss of control are considered to be encompassed by the fault tree models. Specifically, the loss of communications, loss of navigation, and loss of control events caused by failing or malfunctioning equipment on the ground, in the air, or loss of link or power are encompassed within the System/Component Failure or Malfunction (Non-Powerplant) event. If a loss of navigation or the event of degraded navigation signal or instrument performance occurs this is also included as part of the SCF-NP event. However, one concern within the loss of navigation, is “what if the pilot fails to navigate properly”? This event has an increased risk of occurrence in remote cockpit flying due to the human factors issues presented by removing kinesthetic input from the pilot. This adverse event would fall under the scope of the Navigation Errors ICAO Aviation Occurrence category [57]. A loss of control could result from damage to the airframe, loss of link, or damage to an antenna. All of these causes are encompassed within the SCF-NP event. Additional possible causes of loss of control such as RF interference, or spoofing, would fall under the Security Related ICAO Aviation Occurrence, or the Weather/Environmental subsystem in the fault tree framework presented in this research [57]. While this is a significant concern, for the purposes of this research it was considered lower priority as it is less common and has lesser ties to pilot performance, specifically in the transition from in-fuselage to remote cockpit flight.

4.1.6 General Resolution Objectives for the Fault Tree Analyses

According to the NASA Fault Tree Handbook, a last part of the preliminary measures for conducting a Fault Tree Analysis involves identifying resolution objectives. Resolution objectives are essentially defining what questions are to be answered by the fault tree
analyses. The resolution objective for this research is to answer certification questions and pilot qualification needs for operation of UAS in the NAS for commercial applications. Additionally, questions to be answered are more specific system requirements necessary for integration to occur. The fault tree analyses produced in this research are qualitative in nature, therefore numerical budgets are not to be a result. However, qualitative insight into these resolutions is a necessary preliminary step.

Certification questions to be answered include: what levels should these UAS be certified to? This applies to contexts of the airframes, ground control units, and the communication and navigation aspects. By looking at how essential these subsystems are for safe operation within a shared volume of airspace, we can take a closer look at what should be required levels of safety for UAS operations, and more importantly what modifications to the system are necessary to achieve them. In this vein, by taking a close look at the role of the pilot in the system for UAS as compared to manned systems we can get an important insight into the ways in which the pilot cannot interact with the system in the same way and therefore identify where increased risk mitigation is needed. This could take the form of additional, or modified/further tailored pilot training requirements, or increased system capabilities in order to close the gap.

Another resolution objective is to get insight into insurance requirements for UAS operations in the NAS and how these insurance requirements may change with respect to the level of safety needed for a given operation, or the amount of risk in possible damages that must be covered. UAS insurance is already available to operators but is not part of the FAR part 107 requirements [23]. However, needs for insurance will ultimately increase with the introduction and integration of larger, heavier, and more complex systems, and for shared airspace operations.
4.2 Database Creation and Categorization

In addition to a fault tree analysis producing both a system framework and three ICAO Aviation Occurrence-specific fault trees, a database of UAS incidents and accidents was constructed. The purpose of the database was to develop a single database which encompassed various other database results but is:

- UAS specific,
- uniformly organized, and
- categorized based upon three different accident/incident cause taxonomies.

The database was then used to analyze trend data in UAS accidents and incidents based upon categorization of operator type, operating entity, event severity, event type, etc. The goal was to realize trends in the most common adverse events currently already happening in UAS operations around the world and identify them for further modeling in the fault trees, but also to use this data to directly identify failure modes of the UAS system which might not be directly apparent or parallel to manned aircraft accidents and incidents. As previously discussed, the study is largely motivated by the issue of identifying and evaluating the pilot training needs for UAS operations. Therefore special attention was given to the human factors facet of the database and the pilot-aircraft interface.

The database consists of 529 entries which take place between 9/11/2001 and 7/31/2016. It is formatted under columns which include the date of the occurrence, the aircraft type or specific model (when known), the country of operation, the official operator (such as academic institution, personal user, or military entity), the criticality of the accident or incident (critical or non-critical), a qualitative description of the cause, a Boolean logic table categorizing as either an aircraft/system failure, a human error, or both, various information source entries and access dates of those sources, and finally the categorization of the UAS accident or incident based upon three different taxonomies.
4.2.1 Database Categorization Taxonomy 1: UAS Fault Tree Framework Subsystem Level 1 Category, and the UAS Fault Tree Framework

The first taxonomy employed in the categorization was the UAS Fault Tree Framework Subsystem Level 1 Category. This taxonomy was developed as part of the research as it is adopted from the system-wide fault tree model created for UAS operations in this research. Specifically, these categorizations correlate to the first level of aircraft subsystems positioned below the fault tree top level event within the fault tree diagrams. This means that these categories are the highest level categorization of failures within the UAS system, and they are directly adapted from the fault tree analysis framework model commonly used to study manned aircraft systems. The manned aircraft system fault tree analysis framework was used as a starting view in which to frame all aircraft operations. The manned aircraft model subsystem level 1 event categories were modified in order to reflect the inherent differences associated with UAS and their remote or autonomous operation by a person who is not within an in-fuselage aircraft cockpit, but the subsystem categories still maintain a strong resemblance to the original accepted subsystems for manned aircraft fault trees used throughout the industry for design and certification. This can be verified in the diagrams Figure 4.1 and Figure 4.2.
Figure 4.1: Example of General Fault Tree Framework for Manned Aircraft. This diagram has been reproduced from a Federal Aviation Administration educational promotional item.

Figure 4.2: Example of Proposed General Fault Tree Framework for Unmanned Aircraft
The fault tree model subsystem level 1 event categories for the accepted manned aircraft system taxonomy are broken down into: Aircraft, Flight Crew, Maintenance, Weather, ATC, and Miscellaneous as seen in Figure 4.1. Figure 4.2 shows the parallel fault tree framework for an unmanned aircraft system (UAS). At first glance, the semblance to the original is readily apparent. The subsystem categorization of the level 1 subsystems are maintained in a way that is true to the accepted model, with six subsystems total comprising level 1 leading to a fatal accident (or catastrophic event). Please note that the definition of catastrophic event can be varied (Class A Mishap vs. catastrophic event) but that a fatal accident either involving death in the air or on the ground is always a catastrophic event. The manned fault tree categories were modified to become: Aircraft/System, Flight Crew/Human Factors, Maintenance, Weather/Environment, ATC, and Miscellaneous. From the two diagrams it can be seen that the level 1 categories Maintenance and ATC have not changed. While the probabilities of failures in these categories are expected to change and shift between the manned aircraft and UAS systems, the categories still are expected to encompass the operations as they stand. The Miscellaneous category was also unchanged in name, but is highlighted to showcase the significant changes in subsystem/event makeup. The miscellaneous occurrences associated with UAS in comparison to manned aircraft are significantly different and will indicate a significant departure from the accepted manned aircraft model.

The categories which changed between the two models are: Aircraft/System, Flight Crew/Human Factors, and Weather/Environment. The Aircraft/System category was expanded to include the other system components used for UAS operation, as the ground and satellite infrastructure is essential to the operations. A UAS cannot function under human control without a working ground system. Additionally, the system components make up a much larger portion of the hardware involved in the operation than for traditional manned aircraft. This also encompasses different levels of autonomous flight associated
with UAS. Flight Crew/Human Factors was expanded to reflect the additional complexity brought to the UAS system when the piloting approach is shifted from an in-fuselage cockpit to a remote cockpit. Due to the pilots decreased direct interface with the aircraft, and the reduced kinesthetic and sensory input associated with flying a traditional non-remote aircraft, human factors and new system components developed with human factors in mind are expected to play a larger role in the operations. Additionally, the operations of UAS in the military often involve pilot changes, even switching over from remote pilots in standalone cockpits to remote pilots who operate with the aircraft within line of sight. While shift changes are common for manned aircraft as well, they are expected to differ. Lastly, Weather/Environment was expanded to account for additional environmental concerns which come along with the transition from manned aircraft to UAS flight. One example of a significant difference in this category compared to manned aircraft would be the issue of RF interference. RF interference can quickly render a UAS completely uncontrollable and can create a serious failure mode of a loss of control where this is not an issue for manned aircraft flight. Another example would be the increased susceptibility of UAS to weather phenomenon such as updrafts and downdrafts within clouds, icing, and spatial awareness to avoid terrain or clouds.

One last difference between the manned and UAS fault tree frameworks is that the UAS framework does not have any probabilities of failure associated with it. One of the goals of this research was to develop a framework that could be applied to all UAS of varying size, complexity, and interfaces. Given the wide variance and non-standardization of UAS operations in general, and the fact that at this point in time the statistical data on accidents and incidents is quite limited, a qualitative approach was taken to the fault tree analyses. At this point in time, many UAS accidents and incidents go unreported to authorities, causing in part the limited resources available to study failure modes and their frequency of occurrence on a large scale. Once a specific operation and unmanned aircraft
system are chosen for modeling, however, this framework can be further tailored to reflect the details of the situation and probabilities of failure will be much easier to approximate, and choose as budgets to design to.

4.2.2 Database Categorization Taxonomy 2: ICAO Aviation Occurrence Categories

The second taxonomy with which the database entries were categorized was the ICAO Aviation Occurrence Categories. The official Definitions and Usage Notes were used for the classification [57]. This taxonomy is the official taxonomy created by ICAO in collaboration with the Commercial Aviation Safety Team (CAST). ICAO is the international civil aviation authority, while CAST is comprised of representatives of both industry and government. The taxonomy was constructed with the purpose of being a single common taxonomy for categorization of accidents and incidents in all international databases [57]. The idea is that trends and areas of concern can be identified more swiftly and certainly by employing a common taxonomy through which to review and regard adverse events in aviation operations around the globe. This taxonomy is not explicitly required, but is provided as a suggested resource in database development and has been used widely, making it an industry standard.

The ICAO Aviation Occurrence Categories are comprised of 36 categories which have official titles and abbreviations and are severity non-specific. Additionally, there is no occurrence classification which directly addresses human error or pilot error. Instead, human error is encompassed in states or events which result from that human error, i.e. pilot mismanagement of fuel is classified under Fuel Related, and a pilots accidental entrance onto a closed runway is classified under “Runway Incursion,” much like an airspace incursion is classified under “Navigation Error” as previously discussed. Therefore an accident and an incident could have the same occurrence categorization, and in that, an occurrence can describe either an accident or an incident [57].
The ICAO Occurrence Categories Definition and Usage Notes do specifically encompass some UAS attributes within the official taxonomy classification text. However, this is a widely used taxonomy for accidents and incidents in manned civil aviation, and has not been largely and completely applied to UAS in the same way. Categorizing of UAS accidents and incidents using this accepted manned aircraft taxonomy was a large goal and contribution of the database development portion of this research.

4.2.3 Database Categorization Taxonomy 3: Human Factors Analysis and Classification System (HFACS) Unsafe Acts

The third taxonomy used to classify the UAS accident and incident database was the Human Factors Analysis and Classification System (HFACS)[58]. This is the only classification taxonomy which was not applied to all database entries. As the taxonomy has directly to do with human factors, it was only applied to accidents and incidents which involved human error. The human error within the accidents classified did not necessarily involve the UAS pilot, but were accidents or incidents where human error was committed either by the pilot, by the aircraft operating entity, by an overseer, or by Air Traffic Control.

The HFACS was developed by Dr. Scott Shapell and Dr. Douglas Wiegmann as a human error classification system for use in government, civil and commercial aviation applications [58]. It was originally applied to analyze human error in US Navy and Marine Corps Aviation, and has since been used by the US Air Force, Coast Guard, and Army. The model was designed to encompass all of human error occurrences in the system, as unsafe acts or specific “error types,” but also accounting for errors that can occur in oversight and higher levels of control or supervision [58]. The Human Factors Analysis and Classification System proposed by Shapell and Wiegmann draws on the approach of the Swiss Cheese model developed by James Reason [86]. This model shares the four level categories on which human error occurs with the HFACS. These categories are Organizational Influences,
Unsafe Supervision, Preconditions for Unsafe Acts, and Unsafe Acts. It is designed such that in order for an adverse event to occur, at minimum, one failure must occur at each level of the taxonomy [87]. Since its applications in military aviation in 1999 [58], the model has been applied to human error studies in and cardiovascular surgery (2007) [88], and mining (2010) [89].

In the context of the database, the Human Factors Analysis and Classification System was applied to all entries which involved human factors. Specifically, events were categorized by Unsafe Act. While according to the HFACS, there is never one single error that causes an accident or incident, the unsafe act is typically the last error which occurs in the flow [58]. Unsafe acts are then divided into Errors and Violations. Errors are further divided into Decision Errors, Skill-Based Errors, and Perceptual Errors, while Violations are further divided into Routine Violations and Exceptional Violations. Errors are accidental in nature, while violations imply that the person committing the deviation from normal procedure is doing so on purpose [58, p.7].

Errors are further broken down into Decision, Skill-Based, and Perceptual, as previously stated. A Decision Error occurs when a human makes a decision and the situation progresses to that end, but they basically made the wrong decision. Either they come to the wrong conclusion about the information at their disposal, they choose an inappropriate method of action, or they are unrealistic about what can be accomplished either by themselves, the system they are using, or other environmental conditions [58, p.8].

A Skill-Based Error occurs when someone fails to perform a task or procedure which they are specifically and extensively taught in their training in the same way that they were taught to do so. This is where forgetfulness, or high-workload comes into effect. Either the person performing the task forgot a step, did not prioritize the tasks at hand, accidentally bumped a button or a control input, or neglected to watch their instruments
carefully and procedurally. In doing so, they could have become fixated on something small when something larger was occurring, completely forgot to do something which is absolutely necessary (like get a clearance from ATC), or fail to notice that something had broken, an instrument was not reading properly, or that they failed to maintain active separation from other aircraft (for example) [58, p.8].

Lastly, a Perceptual Error occurs when the human performing a task think they are making the correct decision in accordance with their training and the information at their disposal, but the decision is incorrect due to the fact that they did not have the complete, true, and undisputed information necessary to make the decision [58, p.8]. One example of this error occurs when a manned aircraft sees a UAS flying nearby and misjudges the aircraft to be another manned aircraft operating much farther in the distance, rather than a very small aircraft up close. Violations, on the other hand are an intentional violation of the law or the rules and constraints which govern a flight. One example of this is if a pilot purposely flies an aircraft outside of its flight envelope. Violations also include intentional breaking of FARs, or choosing to perform a duty for which they are not qualified. It could also be delegating a duty to an unqualified person [58, p.8].

Routine violations are a recurring problem, where the committing party or parties know that a chosen decision path violates a rule or law, but make the decision anyway. Exceptional violations occur more as a one-time occurrence where the person assumed the risk basically under the premise that things would work out that one time, or with the idea that their judgement was best in that single situation even though it violated the laws of the flight [58]. For each accident or incident which involved a human factors occurrence, the occurrence was identified as an Unsafe Act. Further, the entity which was at fault in committing the Unsafe Act involved in the UAS accident or incident was identified.

The other levels of the HFACS, Preconditions for Unsafe Acts, Unsafe Supervision, and Organizational Influences, for which each level must have one occurrence, were
considered to be more difficult to classify (as many reports supplied limited information) but are also more removed from the direct action which caused the accident or incident. In a way, they provide the context for the Unsafe Act to occur. As a result, the Unsafe Acts categorization of the database accidents and incidents which involved human factors was treated as a “primary categorization” of a human error occurrence.

Only a “primary categorization” was conducted for each UAS database accident or incident identified through each of the three taxonomies. Secondary failures or occurrences were included in the notes when available from sources, but were not formally identified. The database is thus designed that it can be consulted for additional secondary factors or contextual information on a case by case basis. Additionally, all entries are tied to their original sources which can be consulted. Secondary failure and adverse event identification was deemed too complex for the desired objectives and deliverables of this research and could distract from the trend data. Ultimately, the data is classified in a way that is most effective for parallel development of fault tree analyses of UAS operations and very commonly occurring failure modes as identified through the data analysis.

4.2.4 Definition of Accident and Incident Terms in the Context of the Database

As stated previously the database is divided into accidents and incidents, but how were these defined? The threshold for an accident within the database is categorized as a Class A Mishap. Mishaps are a military categorization of accidents. According to the US Army Accident Classification Chart, a Class A mishap is an occurrence such that damage to property is greater than or equal to 2 million dollars. Additionally, a Class A mishap involves a “loss of hull” where the aircraft is destroyed, abandoned, or missing, and or the damage to people involved in the accident is death or permanent disability. This definition is for manned aircraft mishaps. For UAS mishaps, the Army categorizes an accident as a Class A mishap if the cost to replace or repair the UAS amounts to 2 million dollars or
greater. If the aircraft is lost or abandoned, but does not cost 2 million to replace, it is not a Class A mishap [90].

The categorization of a Class A mishap for the purposes of the database produced in this research was in accordance with the Army definition with one exception. In this research, a database entry was categorized as an accident if the sum of property damages (UAS and non-UAS, and to government or civilian property) was equal to 2 million dollars or greater. Additionally, if death permanent total disability was caused to someone on the ground, this would be considered an accident. In summary for this research, an accident was an event where damages amounted to 2 million dollars or more, and/or where death or permanent total disability to a person occurred. An incident was categorized as any other reported event which may have caused distraction of manned aircraft pilots, was a self-reported occurrence of distraction or insufficient/missed procedure, caused damages to property or aircraft amounting to less than 2 million dollars, was a deviation from an ATC clearance, or caused injury or risk to people on the ground, etc. The list continues.

A Class A mishap is the highest level of mishap or military aviation accident. In other words, it is a catastrophic event. The concept of catastrophic events are quite different between manned and unmanned aircraft operations considering that no lives are on board the aircraft itself. Therefore, the loss of life or loss of hull that was originally regarded as a catastrophic event within the aviation community, no longer is implied in the same way for UAS operations. For this reason, the interpretation of a Class A mishap used to model a catastrophic event in this research was expanded to include both loss of life in the air (by way of impact with another aircraft) and loss of life upon the ground, as caused by a UAS falling from the sky. Typically the probability of a catastrophic event or a crash in manned aviation is a function of the airspace of operation, the complexity of the aircraft, and the training level of the pilot flying the aircraft. This results in different acceptable levels of safety for different aircraft operations.
Complex military aircraft or large airliners are certified to higher levels of safety than small general aviation aircraft due to the fact that they have redundant systems present for a variety of systems on board, as well as increased navigation system and autopilot system capabilities for example. While general aviation aircraft also often have redundant systems in place in some capacity it is not to the same extent. Additionally, large airliner operations are certified to higher levels of safety since they have many times the amount of lives on board the aircraft for those operations compared to general aviation operations. UAS operations must be certified to levels of safety which are at least as high as general aviation aircraft which occupy those same classes of airspace and which conduct those same operations in order to preserve the levels of safety set in place within the National Airspace System and for full UAS integration to be achieved.

In many ways, the level of safety to which a manned aircraft is certified is dependent upon the pilots role in the aircraft as a “redundant system.” When an autopilot failure occurs on a manned aircraft, the pilot easily takes up the role. Similarly, when a GPS failure occurs on a manned aircraft, the pilot can pull out a sectional and commence navigation by hand. By transitioning from manned to UAS operations, the role of the manned aircraft pilot in the flight of that aircraft or as a “redundant system” within the entire system will change, as the pilot is more dependent on the system’s operation due to the lack of direct interface with mechanical controls. As a product, additional redundancies and safety mechanisms will have to be incorporated as necessary to assure that the same target levels of safety are achieved while the pilot interfaces with the aircraft remotely.

4.2.5 Data Sources, Collection Procedure, and Data Boundaries

The database was constructed through an assimilation of accident and incident reports found in various locations. Many of the reports were military, many were found through official government databases such as those sponsored by the FAA, NASA, and the
Australian Transport Safety Bureau, and some were found through news sources. One large database used for civilian operation data, as well as some military was Drone Wars UK [91]. This website is run by a non-profit organization, but covers a variety of accidents and incidents from around the world dating back to 2007 [91]. It is frequently updated. While this website is more of a blog format, all of the entries are supplied with original sources which were examined and treated as primary sources for the purposes of this database work. Only reports deemed to contain a sufficient amount of detail were included in the database. While there are many UAS incident and accident reports out on the internet, only a much smaller subset contain sufficient information about crashes to gain an insight into operational difficulties experienced during current UAS operations.

Government sponsored reports were largely discovered through the published Washington Post database titled Fallen From the Skies released in 2014 and updated in 2016 [92]. This database provides an insight into Class A mishaps occurring 2001 to 2016 as reported in the Air Force, Army, Navy and Marine Corps. These mishap reports were released to the Washington Post through a request under the Freedom of Information Act. Many times US Air Force reports were found in supplement to the Washington Post published data of the accidents and incidents, providing additional insight.

Civilian data came largely from the FAA sponsored databases, while some data came from the Australian Transport Safety Bureau (ATSB). Only three entries were recorded from the Australian Aviation Safety Investigations and Reports [93]. In general, UAS reports to the government are somewhat limited. UAS incidents and accidents in the civil area can be hard to investigate and report. Up until more recently, there was not much awareness that one could self-report UAS incidents and accidents, largely because many of these pilots began from a hobbyist approach and were not fully aware of the resources at their disposal. Comparable to the ATSB, the FAA collects UAS reports which are then housed within an array of databases.
The FAA sponsors, maintains, and/or endorses several databases which contain UAS reports. The databases used for this research were: the FAA Accident and Incident Data System (AIDS), the NASA Aviation Safety Reporting System (ASRS)[94], the Runway Safety Office Runway Incursion Database (RWS)[95], and the FAA Near Midair Collision System Database (NMACS)[96]. For this research, only a subset of these available databases and search terms were included in the database. With new reports coming in all the time and resources always updating, there comes a limit in the amount of data assimilation that was practical for inclusion in this research. Therefore, the data included and excluded from the database will be summarized.

For the four FAA/NASA databases listed in the previous paragraph, four search terms were used to access reports included in the database. These search terms were: “UAS,” “drone,” “unmanned aircraft,” and “UAV.” All of the specific content discussed for these four databases was included up until the date: August 5th, 2016. For the NASA Aviation Safety Reporting System (ASRS) all of the relevant reports under all four search terms were included. For the FAA Accident and Incident Data System (AIDS), only the terms “UAS” and “drone” were included. It was found that at August 5th, 8 reports were listed under the “unmanned aircraft” term and one report was included under “UAV.” These 9 reports were not included. In this case, and all of the excluded reports from the databases, it is possible that the incidents or accidents are included in the database as sourced from different locations. For the Runway Safety Office Runway Incursion Database (RWS), only one report was present under the four search terms, specifically under the term “UAS.” This report was included. Lastly, for the FAA Near Midair Collision System Database (NMACS) none of the reports under the four search terms were included. At the time of August 5th, there were a total of 156 reports under those four search terms which were not included. This totals 165 entries across the two databases which were available and omitted at the time of August 5th. It is worth mentioning that the FAA also has published
preliminary UAS accident and incident reports [97], but they were deemed to not provide sufficient information to be included in this research.

For the Drone Wars UK database, all of the database entries with sufficient information were included up until the date January 14th, 2016. As stated previously, the work of updating a database is never ending. Given this fact, the best attempt possible was made to clearly indicate exactly which sources were utilized for the creation of the database, including search terms, and which volumes of possible data were excluded from the database for no other purpose than time constraints. While there are a multitude of UAS accident and incident reports on the internet, with that number growing daily, there is still not a sufficient amount of detailed data for the purpose of using statistical analysis for the generation of UAS failure mode statistics. The sparsity of detailed data, in combination with the non-standardized and wide array of equipage and hardware of UAS and different levels of pilot training (between military, part 107 operators, and pre-legislation users) makes generation of quantitative probability of failure data unreasonable at this point in time. However, the data is valid and particularly useful for making qualitative judgements and identification of UAS trends in failure modes and differences in pilot training needs across the board and across the aircraft “fleet.”

Given the variety of resources used to construct the UAS accident and incident database, small hobbyist UAS are included up through large military UAS which have capabilities similar to GA at the very least. As a result, a variety of airspaces are also included in the database. However, many small UAS operate in Class G airspace very close to the ground, when used by hobbyists for example. Many times any accidents or incidents occurring in this volume of airspace have not been reported up to this date. This shows in the fact that only three UAS reports were available for inclusion in the database through the ATSB. Often hobbyists and operators of low-altitude UAS are not fully aware of the reporting procedures at their disposal due to the influx of hobbyists without an RC
aircraft hobbyist history. Additionally, many accidents or incidents which occur with either illegal UAS operations or UAS operations where the pilot is not aware of where they are allowed to fly are reported by the manned aircraft pilots who encounter the aircraft in flight. This implies the aircraft are flying in more stringent or populated airspace categories than Class G. Therefore, more sUAS incidents and accidents reported are for higher than Class G airspace. However, that does not mean there is an absence of low altitude UAS accidents or incidents. Rather, these are the occurrences which often come up in police reports or news articles and are either not readily accessible to researchers or do not contain sufficient aviation or system detail for them to be able to be examined on the same level as the reported UAS incidents and accidents available through other sources. On the other side of the spectrum, UAS operated by the US Department of Homeland Security, or the US Military often occupy more stringent levels of airspace due to the fact that they are more advanced in hardware and software. Additionally, military UAS are not necessarily subject to the same certification levels as those necessary for operations in civil airspace in the United States and operate under different terms (including pilot training), or can be isolated to areas which are rural and/or controlled.

In summary, the database construction produced a total of 529 accident and incident entries spanning the years 2001-2016. The database entries were sourced from a variety of existing databases. The NASA Aviation Safety Reporting System, and the FAA sponsored FAA Accident and Incident Data System [94], the Runway Safety Office Runway Incursion Database (RWS) [95], and the FAA Near Midair Collision System Database (NMACS)[96] were included on varying degrees using four different search terms. These terms were also applied for inclusion of entries for which reports were published by the Australian Transport Safety Bureau [93]. Military mishaps were sourced from the Washington Post Fallen From the Skies Database [92], and UAS accidents and incidents from all over the operational and size spectrum were sourced through the Drone Wars UK database [91].
A detailed description on exactly which search terms were used for data collection and any databases which were only accessed for a partial subset of the search terms is included in this section. Every effort was made to make it clear exactly which UAS reports were not included in the database due to time constraints. However, the main objective of the database construction is to create a standardized assimilation of various UAS accident and incident events which were then categorized based upon three different accident and incident event classification taxonomies: the UAS Fault Tree Framework Level 1 Event Categorization (developed in this research), the ICAO Aviation Occurrence Categories [57], and the HFACS Unsafe Acts [58]. The HFACS Unsafe Acts were further categorized by entity at fault for the accident or incident causing human error occurrence. The recorded UAS accident and incident data as well as the event categorizations by causes were further used for data analysis through histograms, pie charts, and to tabulate additional information for qualitative trend analysis and parallel construction of UAS-specific fault tree analysis frameworks and analysis of specific failure modes.
5 RESULTS

The results of this research are divided into four fault tree analyses and a database of 529 entries of UAS accidents and incidents including entries from military, civil, hobbyist, and public operating entities. Fault trees are divided into a system-wide model framework, and three specific ICAO Occurrence Category top level events which were derived from the top three most frequently occurring ICAO Occurrence events in the UAS database. The accidents and incidents in the database were categorized based on three taxonomies: the UAS Fault Tree Framework level 1 events, the ICAO Aviation Occurrences, and the Human Factors Analysis and Classification System (HFACS). Accidents and Incidents for which a HFACS Unsafe Act occurred were further categorized by the entity which committed that error.

5.1 Database Results

5.1.1 The Database at a Glance

A total of 529 database entries occurring between September 2001 and July 2016 were assimilated in the UAS database of accidents and incidents. The methods of curation and sources of the events included in the database are outlined extensively in Section 4.2 of this work.

5.1.1.1 Results by Year

Figure 5.1 shows the number of combined UAS accidents and incidents by year. It is important to note when looking at this histogram that both 2001 and 2016 are partial years. With the exception of the years 2003 and 2014, the number of UAS accidents and incidents are shown to generally increase over the 15 years of data. Additionally there were significant jumps in the number of adverse events in the years 2010 and 2015. The jump in reported accidents and incidents 2009 to 2010 was likely tied to the increase use of UAS as
ready-made drones began to fly off of consumer shelves. Previous to this year, the majority of UAS operators were likely model aircraft enthusiasts or trained military personnel.

The jump in 2015 could be a result of decreased cost of materials and increased competition in the market, with a continued enthusiasm of new drone hobbyists. The FAA anticipated the increased market activity with the introduction of the Know Before You Fly campaign in December 2014 providing information on the NAS and guidelines for safe hobbyist flight to new operators. Unfortunately, the vastly expanding market likely overshadowed the risk mitigation measures set in place by the FAA, the AMA, and the AUVSI. Additionally, it is likely that in 2015 the issue of unauthorized UAS activity was becoming a significant problem for manned aviation. As such manned aircraft and ATC

Figure 5.1: Unmanned Aircraft System Accidents and Incidents by Year (Database Derived)
likely began to report accidents, incidents, and concerns to the FAA and NASA on a larger scale.

5.1.1.2 Results by Criticality

Figure 5.2 shows the composition of the UAS database in terms of Accidents and Incident events. 47% of database entries were critical, or accidents at 249 entries, and 53% were non-critical incidents at 280 entries. For the purposes of database categorization, a critical event or accident was categorized as a Class A mishap. A Class A mishap is a military definition for which the threshold is 2 million dollars in property damage or loss of hull or death or total disability to a person or persons [90]. Though for UAS accidents, a Class A mishap according the Army applies if the cost of the UAS damages amount to 2 million dollars or greater. For this research, a total sum of damages amounting to 2 million or greater was used as the threshold, and death on the ground is included.

Figure 5.2: Unmanned Aircraft System Criticality of Reported Event as Database Proportion. A critical event is defined as Class A mishap.
5.1.2 Accidents and Incidents by UAS Type

In Figures 5.3 and 5.4 the results of the database are categorized by the UAS involved in the accident or incident. The largest percentage of UAS reported were Unknown. Note, there is also a category of aircraft named Other. The Other category encompasses all UAS models that had five or fewer accidents or incidents present in the database. The Unknown category on the other hand are UAS of undetermined model. This category is comprised of instances where the UAS involved was reported by someone other than the UAS operator. Most of the time, these accidents were reported by a manned aircraft pilot who experienced a traffic conflict or loss of separation with a UAS. The Unknown category was by far the largest with 35% of the database, followed by the Predator with 26%, then the Reaper with 8%, Global Hawk with 7%, and Hunter. This tells us that of the accidents and incidents which were self-reported, they were by in large military or government UAS (not necessarily operated by the U.S.), and there are a significant number of events that were reported by others with no input from the UAS operator.
Figure 5.3: Unmanned Aircraft System Models Involved in Accidents and Incidents by Proportion (Database Derived). The “Other” identifier encompasses all identified models with 5 events or fewer.

Figure 5.4: Unmanned Aircraft System Models Involved in Accidents and Incidents by Number of Reported Events (Database Derived).
5.1.3 Accidents and Incidents by Human Error Involvement

Of the UAS accidents and incidents in the database, almost half of them involved human error. 254 accidents and incidents involved some sort of human error (48%) while 275 did not. This can be seen from Chart 5.5. Therefore the subset of the database which was further categorized by the HFACS is composed of 254 entries.

![Unmanned Aircraft System Accidents and Incidents Involving Human Error](image)

Figure 5.5: Unmanned Aircraft System Accidents and Incidents Involving Human Error by Proportion (Database Derived). Human Error was not necessarily the primary cause in these events.

5.1.4 Database Categorization Results

5.1.4.1 Taxonomy 1: The UAS Fault Tree Framework Level 1 Subsystems

This brings us to the categorization of the database based upon the three different taxonomies employed. Recall that the taxonomies used were the UAS Fault Tree Framework Level 1 Subsystems, the ICAO Aviation Occurrences, and the Human
Factors Analysis and Classification System (HFACS) Unsafe Acts. Figure 5.6 shows the breakdown of adverse events categorized by the UAS Fault Tree Framework Level 1 Subsystems. The three most common subsystem failures were Aircraft/System with 231 instances, Flight Crew/Human Factors with 204 instances, and Unknown with 44 instances. It is apparent that the vast majority of the accidents and incidents fall into the top two categories. Of 529 total entries, 435 had Aircraft/System or Flight Crew/Human Factors failures as their main cause. Air Traffic Control categorized failures (this does not necessarily imply Air Traffic Control human error fault) were the fourth most common subsystem failure with 22 entries, followed by Weather/Environment with 22 and Maintenance and Miscellaneous had very few occurrences with 4 and 3 entries respectively.

Figure 5.6: Unmanned Aircraft System Accidents and Incidents Categorized by UAS Fault Tree Level 1 Subsystem Events (Database Derived). For the purposes of this categorization, the top level event was each occurrence.
5.1.5 Taxonomy 2: ICAO Aviation Occurrence Categories

Moving on to ICAO Aviation Occurrence categorization, the results may be viewed in Figure 5.7. The top three occurring categories were System/Component Failure or Malfunction (Non-Powerplant) with 165 entries, followed by AIRPROX/TCAS Alert/Loss of Separation/Near Midair Collisions/Midair Collisions (MAC) with 101 entries, and Navigation Errors (NAV) with 74 entries. Definitions of the ICAO Aviation Occurrence Category abbreviations are included in Table 5.1. Note that there are 36 categories total. The table only defines the categories of relevance in this set of results. The following categories which make up the top five most commonly occurring are System/Component Failure (Powerplant) with 57 entries and Unknown with 46. The remainder of the Aviation Occurrences drop significantly in the number of events within the database. The SCF-NP event has the most database occurrences by quite a large spread of 64 instances more than the second most common. In categorization of aviation accidents and incidents many times it is not the case that the adverse event results from a single failure or fault, but multiple. For the purposes of categorizing the UAS database, only the primary aviation occurrence which took place and ultimately “caused” the event was categorized.
Figure 5.7: Unmanned Aircraft System Accidents and Incidents Categorized by ICAO Aviation Occurrence.
Table 5.1: Glossary of ICAO Aviation Occurrence Category Abbreviations Which Occur in the UAS Accidents/Incidents Database

<table>
<thead>
<tr>
<th>Abbreviated Term</th>
<th>Full Occurrence Category Term</th>
</tr>
</thead>
<tbody>
<tr>
<td>SEC</td>
<td>Security Related</td>
</tr>
<tr>
<td>RI</td>
<td>Runway Incursion</td>
</tr>
<tr>
<td>GCOL</td>
<td>Ground Collision</td>
</tr>
<tr>
<td>CFIT</td>
<td>Controlled Flight Into or Toward Terrain</td>
</tr>
<tr>
<td>BIRD</td>
<td>Bird</td>
</tr>
<tr>
<td>TURB</td>
<td>Turbulence Encounter</td>
</tr>
<tr>
<td>ICE</td>
<td>Icing</td>
</tr>
<tr>
<td>CTOL</td>
<td>Collision With Obstacle(s) During Takeoff and Landing</td>
</tr>
<tr>
<td>FUEL</td>
<td>Fuel Related</td>
</tr>
<tr>
<td>USOS</td>
<td>Undershoot/Overshoot</td>
</tr>
<tr>
<td>F-NI</td>
<td>Fire/Smoke (Non-Impact)</td>
</tr>
<tr>
<td>AMAN</td>
<td>Abrupt Maneuver</td>
</tr>
<tr>
<td>WSTRW</td>
<td>Wind Shear or Thunderstorm</td>
</tr>
<tr>
<td>ATM</td>
<td>ATM/CNS</td>
</tr>
<tr>
<td>ARC</td>
<td>Abnormal Runway Contact</td>
</tr>
<tr>
<td>OTHR</td>
<td>Other</td>
</tr>
<tr>
<td>LOC-I</td>
<td>Loss of Control-Inflight</td>
</tr>
<tr>
<td>UNK</td>
<td>Unknown or Undetermined</td>
</tr>
<tr>
<td>SCF-PP</td>
<td>System/Component Failure or Malfunction (Powerplant)</td>
</tr>
<tr>
<td>NAV</td>
<td>Navigation Errors</td>
</tr>
<tr>
<td>MAC</td>
<td>AIRPROX/TCAS Alert/Loss of Separation/ Near Midair Collisions/ Midair Collisions</td>
</tr>
<tr>
<td>SCF-NP</td>
<td>System/Component Failure or Malfunction (Non-Powerplant)</td>
</tr>
</tbody>
</table>
5.1.6 Taxonomy 3: HFACS Unsafe Acts

The last categorization of the database was by HFACS Unsafe Act. As stated previously, the HFACS is designed such that one event or human error/failure occurs on each of the four levels of the classification system. Each of these levels pertains to a different level of human factors occurrences, and consist of Organizational Influences, Unsafe Supervisions, Preconditions for Unsafe Acts, and the Unsafe Acts themselves. The database subset for which human error was a factor was categorized only by Unsafe Acts and further by the corresponding entity at fault for the error. Definitions of these unsafe acts were discussed within the Methods section. Of the database entries, 254 entries were categorized. For these entries, the vast majority of them involved human error, with only 16 of the unsafe acts categorized as violations. Decision errors were by far the majority with 137 occurrences, followed by about half as many skill-based errors (74) and few perceptual errors (16) as seen in Figure 5.8.
Figure 5.8: Unmanned Aircraft System Accidents and Incidents Involving Human Error Classified by HFACS Unsafe Acts (Database Derived). This is a subset of the database data.

5.1.6.1 Categorized by Entity at Fault: Definitions of Formal and Other UAS Operators

All of the database entries which were categorized by HFACS were further categorized by the entity at fault in committing the error or violation. By in large, the errors and violations were committed by UAS operators, as opposed to manned aircraft operators or air traffic control personnel. Figure 5.9 outlines the distribution.

Formal UAS Operator is a title developed to characterize this research.

- For the purposes of this dataset, a Formal UAS Operator is an established aircraft operating entity which performs formal non-hobbyist flight. These operators operate within the law either through military, government or educational sectors or may be operating for hire with a waiver.
• The pilots of the aircraft are considered to have formal training and or familiarity with the system and have been deemed qualified for operations.

• Additionally, the operators are expected to conduct operations within either an understanding of rules set up with a governing body and possibly employ checklists and other risk mitigation techniques.

• These operators are expected to have an understanding of airspace and other formal national airspace system or aircraft system knowledge.

• A Formal UAS Operator can also pertain to the operating entity in terms of decision making in management or maintenance operations and management for larger aircraft.

Other UAS operators are all other UAS operators which operate on behalf of themselves or informal organizations respectively. The results are presented in Figure 5.9 with 117 acts originating from Formal UAS Operators, a close 113 acts originating from Other UAS operators, 17 acts committed by air traffic control, 5 by manned aircraft, and only one instance of an unknown perpetrator.
Figure 5.9: Unmanned Aircraft System Accidents and Incidents Involving Human Error Classified by Entity at Fault (Database Derived). These are the entities which committed the errors and violations which progressed to HFACS Unsafe Acts. This is a subset of the database data.

5.2 Fault Tree Analyses

5.2.1 FT1: System Wide Fault Tree

The first fault tree analysis is essentially an extension of the general UAS fault tree framework. It models the top level event of a fatal accident, a catastrophic event, on a system-wide level. As with the framework and the fault trees which follow, the fault trees were developed with the goal of being further tailored and quantified to a specific UAS operation. Given the nature of the data, the paginated fault tree analyses are included in Appendix A. References to the tree will be by gate and event numbers. Additionally, note that the page numbers referenced by the software are off in the appendix as the results were consolidated. Instead of page number, the number will refer to the figure number in order from the beginning of that appendix.
The first level of subsystems is broken into Aircraft/System, Flight Crew/Human Factors, Maintenance, Weather/Environmental Factors, Air Traffic Control, and Miscellaneous. The HFACS taxonomy of Unsafe Acts was applied in this fault tree and additional ICAO Aviation Occurrence fault trees where it is relevant. In terms of HFACS categorizing and modeling, the system was applied with a focus on the UAS pilot and associated crew. No attempt was made to model HFACS unsafe acts originating from manned aircraft pilots in traffic conflict for example, as this was outside the scope of the research.

5.2.1.1 Aircraft/System Level 1 Subsystem

Of the six level 1 subsystem categories, the first two Aircraft/System and Flight Crew/Human Factors make up the bulk of the tree in terms of lower level subsystems (gates) and events. In the Aircraft/System category, the level 2 subsystems are as follows: loss of power, loss of control, fire, loss of communication, and partial damage on the ground or in flight. Loss of power is broken down into three events: powerplant, battery, and operating system failures. Loss of control is further broken down into three more levels of gates in total. The first level (level 3) is broken down into the inability to input commands, the handheld is unable to transmit commands, the aircraft is unable to receive commands, and the aircraft is unable to execute commands. Additional gates/events can be viewed in Appendix B under Gates 15-18. The level 2 subsystem fire is broken into 3 events: electrical fire, mechanical overheat and unforeseen combustible material leak. Loss of communication is broken down into 2 events: failure of pilot/ATC connection and failure of pilot-observer or ground crew connection. Partial damage on the ground or in flight is broken down into level 3 subsystems: damage to the fuselage, damage to the control surfaces, and damage to the sensor payload. The first two of these subsystems are further broken down into a pilot-caused collision, failure of other aircraft to remain well clear, and
weather caused damage. There are an additional two levels of gates/events under these level 3 subsystems. Refer to gates 43-45, 51-53.

5.2.1.2 Flight Crew/Human Factors Level 1 Subsystem

The level 1 subsystem Flight Crew/Human Factors is broken into level 2 subsystems as follows: Attention lapse, Incorrect input, failure to follow procedure, failure to follow checklist, incorrect airworthiness approval (pre-flight inspection) from the pilot, and a failure to recover from an abnormal attitude or state. Attention lapse was broken down into 2 events: no response and late response. Incorrect Input was broken down into the options of an overaggressive maneuver, opposite maneuver or insufficient (under-aggressive) maneuver. These were further broken down into level 4 and 5 subsystems and events. See gates 252-257. Failure to follow procedure was broken down into skipped steps and not followed, with a possible cause of pilot distraction due to heavy workload. Failure to follow a checklist was broken down into similar subsystems and events (see gates 290-291 and event 73). Incorrect pilot preflight airworthiness approval was broken down into the subsystems of a perceptual error or skill-based error of the pilot according to the HFACS. Level 4 events were expanded and include the possibilities of undiagnosed maintenance condition, other perceptual error, or skill-based errors including an undiagnosed maintenance condition or an insufficient preflight procedure.

The last level 2 subsystem under Flight Crew/Human Factors, failure to recover was broken down into level 3 subsystems as follows: undiagnosed failure/hazardous condition, incorrect response, insufficient response, and insufficient altitude (for recovery). Undiagnosed failure/hazardous condition was broken down into level 4 subsystems where the aircraft is in a dangerous attitude or one or more wings have stalled. The aircraft in a dangerous attitude subsystem can be caused by a pilot-commanded excessive attitude, or a case where a wind pattern has pushed the aircraft into the abnormal attitude. Both of these
level 5 subsystems are broken into excessive pitch-up attitude, excessive bank angle, and excessive pitch-down attitude which can result from perceptual and skill based errors in the case of the pilot-commanded excessive attitude. See gates 295, 296, 298, 299, 189, and 301. For excessive pitch-up attitude a perceptual error could result from pilot disorientation of controls, unexpected aircraft performance due to weather or environmental conditions, or another error. A skill based error could result from a case where the aircraft controls have been configured incorrectly, the pilot lacks sufficient understanding of the control interface, the pilot commits an accidental control error, or another skill-based error. An accidental control error could be the result of an accidental shut off of the stability, altitude or location holding system. These are also the possible causes of an excessive bank angle. An excessive pitch-down attitude could be a result of a perceptual error in the form of decreased pilot situational awareness due to weather or haze interference on approach, or a skill-based error resulting again from a case where the aircraft controls were configured incorrectly, the pilot lacks sufficient understanding of the control interface, or where a pilot commits an accidental control error, as well as the possibility of another skill-based error.

For a case where the wind pushed an aircraft into an unusual attitude, the events were progressions from either a decision error (gates 303-305) or anomalous wind or weather condition. If one or more of the wings have stalled (level 4), this was caused by either a perceptual or skill-based error on the pilots behalf. One of the skill based errors could have been that the pilot failed to recognize the aircraft state. An incorrect response was the result of either a skill-based or perceptual error (see gates 182, and 191) where the pilot has an insufficient understanding of the controls or experiences disorientation. An Insufficient response was broken down into level 4 subsystems of excessive delay, insufficient magnitude of correction, and no response. Each of these subsystems were broken into perceptual errors and skill-based errors on behalf of the pilot. Examples of these errors are if the pilot does not recognize the condition of the aircraft due to tunnel-
visioned trust in instrumentation, or not responding properly due to insufficient knowledge of the recovery procedure. See Gates 175-177 ad events 120-136 for more detail.

5.2.1.3 Maintenance Level 1 Subsystem

Adverse events contributing to the level 1 subsystem, Maintenance, include insufficient maintenance management, unforeseen maintenance issues and improperly corrected maintenance issues. Insufficient maintenance management could result from widely repeated errors or failures without additional risk mitigation procedures being set into place or insufficient maintenance training to personnel.

5.2.1.4 Weather/Environmental Factors Level 1 Subsystem

The Weather/Environmental Factors level 1 subsystem was broken down into the following lower subsystems: unforeseen weather conditions, an insufficiently supported go decision, unforeseen environmental conditions or a failure of others to remain well clear. Unforeseen weather conditions was broken down into the level 3 subsystems of unforeseen icing activity, unforeseen convective activity, unforeseen wind conditions and unforeseen low visibility. Unforeseen icing activity could be the result of a skill-based error of the pilot by unintentionally flying into clouds, or it could be a result of accidentally encountered weather. Unforeseen convective activity could be a result of updrafts/downdrafts, a microburst, hail, or lightning strike, and unforeseen wind conditions could be a result of wind gusts, increased wind speeds, or high winds aloft. An insufficiently supported go decision is the result of a decision error, perceptual error, or skill-based error of the pilot. For a decision error this could be a bad judgement of weather conditions, or unrealistic expectation of the performance capability of the aircraft. For a perceptual error, it could be the result of incomplete or outdated weather information, and for a skill-based error it could be a result of incomplete weather information, insufficient knowledge of weather resources, or another cause. Unforeseen environmental conditions could be a
result of unplanned human interference or unforeseen wake turbulence. Unforeseen human interference could manifest itself in the form of person interference, vehicle interference, or signal interference. Person interference is broken down into the failure of the ground crew to coordinate, the failure to maintain an isolated operation area, or the failure of the ground crew to clear persons. Vehicle interference is broken down into parallel events, and signal interference could be the result of radio control interference or navigation interference on the local level. On the other hand, unforeseen wake turbulence could result from failure of the UAS pilot to coordinate with other aircraft or ATC, or failure for the other aircraft to coordinate, causing an unforeseen interference. The failure of others to remain well clear (level 2 subsystem) could be the result of an aircraft strike, bird strike, or operating crew interference. The aircraft strike subsystem is broken down into the events of an unplanned emergency landing attempt by manned aircraft or an airspace incursion from a local UAS.

5.2.1.5 Air Traffic Control and Miscellaneous Level 1 Subsystems

The air traffic control subsystem was broken down into a subsystem where air traffic control fails to accommodate a UAS operation or the events of a failure of a UAS operator to publish their intentions or an improper notification to ATC from the pilot or flight crew. The subsystem where ATC fails to accommodate was further broken down into the subsystems where there is an unrealistic expectation of the UAS pilot or there is an issuance of an instruction which conflicts with a previously obtained certificate of authorization (COA). Both of these subsystems could be the result of a perceptual error or skill-based error. Lastly, the miscellaneous subsystem was left undefined as this is aircraft system and operation/application defined.
5.2.2 FT2: ICAO Occurrence Category 1: System/Component Failure or Malfunction (Non-Powerplant)

The second fault tree analysis conducted was for the most commonly occurring ICAO Aviation Occurrence in the database results, System/Component Failure or Malfunction (Non-Powerplant). As a main goal of the fault trees was to keep them general and tailorable, this fault tree analysis is fairly general in nature and seeks to cover the components common to most UAS. This fault tree is expected to be expanded into more detail when applied to a specific operation or aircraft type as additional system knowledge will be available. The top level event of SCF-NP was broken down into the following level 1 subsystems: aircraft, ground station, air infrastructure, and ground infrastructure. All of the level 1 subsystems were broken down into the level 2 subsystems of hardware and software failure.

Aircraft hardware failures were broken down into mechanical and electrical failures (level 3). Level 4 subsystems to the mechanical subsystem included airframe component failures, antenna failures, landing gear failures, sensor payload component failures, and servo failures (gates 35-38, 52). Note that gates 35, 36, and 52 (Airframe component failure, antenna failure, and servo failure) have no additional subsystems or events defined beneath them. Though there are no additional details in the tree at this point, it is expected that these are in fact subsystems, and not events. Therefore they are preserved as such and open for additional expansion when tailored to a more specific case of operation or aircraft. The landing gear failure subsystem was broken down into maintenance errors or other errors. Maintenance errors could manifest themselves in the form of skill-based, decision, or perceptual errors, but no attempt was made to model these further as they were considered outside the scope of this research. A sensor payload component failure could result from a camera failure, altimeter failure, airspeed indicator failure, or a GPS failure. The GPS failure modes are left for additional expansion. A camera failure is single or multiple camera failure. An altimeter failure is divided into a pitot-static failure
subsystem, or another failure. The pitot-static failure could arise from a maintenance error, an event where the aircraft’s static port is obstructed, or other failure. The non-GPS airspeed indicator failure could be the result of a pitot-static failure or a failure of other type. A pitot-static failure in this case could result from a maintenance error, an event where the pitot tube is obstructed, a pitot heat failure, or another event. An event where the pitot tube is obstructed could be the result of debris such as insects or dirt, becoming lodged in the intake or it could result from a case where the pilot or crew failed to remove the pitot tube cover in preflight preparations. This could be a skill-based, decision, or perceptual error.

Electrical failures (level 3 subsystem) are broken down into four level 4 subsystems: total loss of link, battery failure, alternator failure, and circuit failure. Total loss of link could result from a lightning strike or other event, and a battery failure could result from a maintenance error or other subsystem or event failure. An alternator failure is broken down into single and double alternator failure (based upon the equipage of the aircraft), either of which could be the result of a maintenance failure or other subsystem/event failure. Lastly, a circuit failure could be the result of a wiring failure or board failure. The second level 2 subsystem under aircraft was a software failure, which was broken down into the level 3 subsystems of loss of communication, loss of control, loss of navigation, and other software failure. The other software failure subsystem was broken down into aircraft diagnostics software and other.

The second level 1 subsystem of ground station was broken down into hardware and software failures. Hardware failures were broken down into 3 level 4 subsystems of control failure, communication failure, and situational awareness-type failure. Situational awareness-type failures were broken down into display failures and map display failures. Software failures were broken down into control failures, communication failures and situational awareness-type failures as well.
Air infrastructure failures (level 1 subsystem 3) were broken down into hardware and software failures, which were both broken down into uplink and downlink failures in terms of level 4 subsystems. On the hardware side, the uplink and downlink failures were further broken down into maintenance errors and other failures. Maintenance errors could be the result of skill-based, decision, or perceptual errors. The fault tree analysis breakdown for the ground infrastructure level 1 subsystem was broken down in a parallel manner. The complete fault tree is included in Appendix C.

5.2.3 FT3: ICAO Occurrence Category 2: AIRPROX/TCAS Alert/Loss of Separation/Near Midair Collisions/Midair Collisions (MAC)

The third fault tree developed for this research was for the second most commonly occurring ICAO Aviation occurrence of an AIRPROX/TCAS Alert/Loss of Separation/Near Midair Collisions/Midair Collisions. Complete details on the formal definitions of these events are included in the Aviation Occurrence Categories Definitions and Usage Notes [57]. The top level event was broken down into three level 1 subsystems: midair collision, near midair collision, and loss of separation. In the fault tree modeling within this research normal operations were modeled. This means that it is expected that the operator of the aircraft has received training and was deemed qualified to conduct the operation of interest and utilize all normal procedures and checklists. Additionally, intentional violation of law or flight rules or cases of intentional sabotage were not included in these analyses. Given that the UAS operator is to follow all separation rules the midair collision and near midair collision subsystems were divided into the subsystems titled onboard alert issued to manned aircraft and no onboard alert issued to manned aircraft, which were left to further expansion and are directly associated with the other conflicting traffic, not the primary UAS aircraft (for which the model has been produced).
The third level 1 subsystem, loss of separation, was broken down into three level 2 subsystems. These subsystems were failure of self-separation, failure of ATC managed separation, and airspace incursion. The failure of self-separation subsystem was broken down into four level 3 subsystems: pilot failed to recognize threat, UAS pilot recognized threat but did not mitigate risk, loss of separation with life (such as birds or people on the ground) and loss of control of aircraft. The first level 3 subsystem, pilot of UAS failed to recognize threat, was broken down into four events: pilot inattention, observer/flight crew inattention, insufficient understanding of the right of way rules, and insufficient understanding of separation rules/definitions. UAS pilot recognized threat but did not mitigate risk was divided into six (level 4) subsystems and events: increased reaction time, other aircraft made insufficient avoidance maneuver, other aircraft did not see need to self-separate, other skill based error, or other perceptual error, and other aircraft made inappropriate avoidance maneuver (Event 14). Increased reaction time was divided into three subsystems: skill-based errors, perceptual errors, and system errors. A skill-based error could be pilot inattention, a perceptual error could occur if the pilot is affected by link latency, and a system error could also occur through increased link latency.

The next two level 4 subsystems, other aircraft made insufficient avoidance maneuver and other aircraft did not see need to self-separate were each divided into two level 5 subsystems which were not expanded further. For the subsystem titled: Other aircraft made insufficient avoidance maneuver, these subsystems were incorrect perceived distance to impact and insufficient reaction time. For the subsystem titled: other aircraft did not see need to self-separate, the subsystems were either that aircraft did not recognize the aircraft as a UAS or other. Skill-based errors that would contribute to the state where a UAS pilot recognized the threat but did not mitigate it include cases where the pilot did not assume control of the aircraft that was in autopilot mode, the pilot made an inappropriate avoidance maneuver, or the pilot made an insufficient avoidance maneuver. If the pilot
made an inappropriate avoidance maneuver, this could be the result of and insufficient understanding of right of way rules, or an accidental control input. If the pilot made an insufficient avoidance maneuver, this could be the result of an insufficient reaction time, insufficient training, or another skill-based error. If the pilot recognized the risk but did not mitigate it due to a perceptual error, this could result from a case where the pilot made an insufficient avoidance maneuver due to either an incorrect perceived distance to impact or insufficient aircraft performance.

If a failure to self-separate was the result of the loss of separation with life, this could have resulted from two level 4 subsystems. Either a loss of control of the aircraft occurred (a gate which was not expanded here), or a skill-based error occurred. A skill-based error could be the result of the failure of the flight crew to clear the area or to enforce the cleared area of operation. The last level 4 subsystem of this portion was the loss of control of the aircraft, which could result from a lost link, loss of power in the ground station, or unexpected system reset.

The next level 2 subsystem was failure of ATC managed separation. This could be the result of four level 3 subsystems: a decision error, a perceptual error, a system error, or a skill-based error. A decision error could result from three events: where ATC was unaware of UAS operations and had no information on them, an insufficient separation buffer for UAS traffic, or another decision error. One additional subsystem was the possibility of insufficient UAS coordination with ATC. This was further broken down into the possibility that the UAS was not in contact with ATC at all, or there was no lost link procedure provided to ATC for consultation. A perceptual error which could result in a failure of ATC managed separation is where the UAS failed to adhere to ATC instruction. A system error which could cause a failure in ATC managed separation could be a loss of ATC communication with the pilot, an unexpected UAS path due to a loss of control of the aircraft, or another system error. Lastly, a skill-based error which would cause a failure of
ATC managed separation would be if the preprogrammed lost link procedure of the aircraft conflicts with that provided to ATC, if no lost link procedure was provided, or another skill-based error.

The last level 2 subsystem under loss of separation is an airspace incursion. This could result from either the UAS pilot entering unauthorized airspace or another aircraft entering unauthorized airspace. The latter event was not expanded in this fault tree. If the UAS pilot enters unauthorized airspace, this could be the result of a system error, skill-based error, perceptual error, or decision error. The system error level 4 subsystem was broken down into a failure of the geofencing or altitude hold feature on the aircraft, an unexpected path of the UAS due to a loss of control or another system error. Skill based errors were broken down to include an unexpected aircraft path under pilot control, an unexpected path due to a loss of control, or another skill-based error. An unexpected path of the UAS under pilot control could result from pilot inattention, or if the pilot fails to adhere to an ATC clearance due to insufficient training. In this example, the pilot could have difficulty maintaining heading or altitude. In the case where the path of the aircraft was unexpected due to a loss of control, this could result from an error where the preprogrammed mission conflicts with the lost link procedure provided to ATC or a case where no lost link procedure was provided. A perceptual error which causes a pilot to enter unauthorized airspace could result from the pilot failing to adhere to a clearance. Lastly, this could also be a decision error in the case where the pilot or operator is conducting operations with unreasonable aircraft performance expectations or tolerances. To reference the fault tree analysis diagrams, see Appendix C.

5.2.4 FT4: ICAO Occurrence Category 3: Navigation Errors (NAV)

The last ICAO Occurrence Category fault tree developed in this research was for the third most commonly occurring ICAO Aviation Occurrence category in the UAS database of accidents and incidents, Navigation Errors. This top level event was broken down into
two subsystem level 1 events: ground navigation errors and in-flight navigation errors. Ground navigation errors were broken down into five level 2 subsystems and one event. These include: ATC instruction unclear to pilot, insufficient communication with ATC, taxiway or ramp incursion, runway incursion or excursion (gates 20, 22, 47, 48) the event of the pilot experiencing control disorientation (event 3) and the case of insufficient reaction time (gate 55). If an ATC instruction is unclear to the pilot, this could be the result of either a skill-based or a decision error. A skill based error would be insufficient knowledge on the pilots part, causing him/her to not understand the instruction, or a decision error on behalf of the air traffic controller who may have unrealistic expectations of the pilot. Insufficient communication with ATC could result from three events: either the operator did not engage in an ATC coordination procedure, the operator engaged only partially in the ATC coordination procedure, or another skill-based error occurred. A taxiway or ramp incursion is the result of either the pilot entering a secure taxiway area without instruction or the pilot entered a closed taxiway or ramp area. Runway incursions or excursions are the result of a skill-based error or a perceptual error of pilot situational awareness. Either of these are manifested by the pilot either entering a closed runway or entering a secure runway without instruction. The last subsystem of a ground navigation error is insufficient reaction time which was split into events of pilot distraction, increased reaction time due to link latency, or insufficient situational awareness of the pilot.

The second half of this fault tree is under the level 1 subsystem of an in-flight navigation error. This subsystem is broken down into level 2 subsystems of airspace incursions and failure to follow ATC instruction. Airspace incursions are broken down into lateral and vertical airspace incursions, and from there into level 4 subsystems: navigation errors occurring under autopilot control, and navigation errors occurring under pilot control. For lateral airspace incursions, navigation errors under autopilot control can be a result of either a system-error or a skill-based error. A system error could be
an improper preprogrammed autonomous route, while a skill-based error could be if no preprogrammed route information has been supplied to ATC, if the preprogrammed route is in conflict with the lost link route provided to ATC or an improper preprogrammed route is executed. Navigation errors under pilot command could result from pilot control disorientation or a skill-error such as control disorientation due to insufficient training or insufficient coordination with ATC either by the pilot not engaging in coordination or only partially coordinating with air traffic control.

For vertical airspace incursions, the subsystem of navigation error under autopilot control is divided into system error and skill-based error subsystems (level 6). A system error would be an improper preprogrammed route, a geofencing or altitude limit software error, or other error. A skill based error would be if no preprogrammed route has been supplied to ATC, the preprogrammed route executed is in conflict with that provided, or if an improper preprogrammed route is executed. Vertical navigation errors which occur under pilot control are divided into the subsystems of perceptual errors, skill-based errors, and decision errors. Perceptual errors include unexpected aircraft performance, or pilot control disorientation. Skill-based errors could arise from unexpected aircraft performance, pilot control disorientation, or insufficient coordination with ATC either by neglecting to engage in coordination procedures or only partially doing so. Decision errors which would cause a navigation error could result from unexpected pilot expectations of the system, which could be through employing unrealistic lateral positioning tolerances for the operation.

In-flight navigation errors could also be the result of the UAS pilot to fail to follow ATC instruction. This level 2 subsystem was broken down into four level 3 subsystems/events. The subsystems are defined as the ATC instruction is unclear to the pilot, the pilot has difficulty holding altitude or heading, a skill-based error (gates 19, 31, and 84) or the event where an ATC instruction conflicts with an approved Certificate of
Authorization (COA) operation. The first level 3 subsystem, where the ATC instruction is unclear to the pilot could result from a skill-based error or decision error. A skill-based error could be caused by insufficient pilot knowledge, while a decision error could result from unrealistic expectations of the pilot by ATC. Difficulty holding altitude or heading could result from any of five subsystems: insufficient reaction time, decision error, system error, skill-based error, or perceptual error. Insufficient reaction time is broken down into three level 6 subsystems or events, and could result from a pilot distraction (event 41), a skill based error, or a perceptual error. An example of a skill-based error in this context would be insufficient situational awareness of the pilot, while a perceptual error could be increased reaction time due to link latency or insufficient situational awareness of the pilot for perceptual reasons. A decision error could result from unrealistic aircraft performance expectations from the pilot, while a system error could result from path correction issues due to link latency, unrealistic aircraft performance tolerances, or another system error. Skill-based errors could manifest themselves through insufficient pilot training, and perceptual errors could result from unrealistic aircraft performance expectations or path correction issues presented by increased link latency. Skill-based errors which would contribute to the pilot’s failure to follow ATC instruction would include the case where ATC issues an instruction which conflicts with an approved COA operation (event 34), or an insufficient reaction time caused by insufficient situational awareness of the pilot. The complete fault tree for this ICAO Aviation Occurrence is presented in Appendix E.
6 Discussion

6.1 Interpreting the Results

From the results of this work we see significant changes in the role of the pilot and the way which the pilot interfaces with the aircraft through the transition from an infuselage cockpit to a remote cockpit. Additionally, it is implied that Unmanned Aircraft Systems are significantly different than traditionally piloted aircraft. The issues presented by flight of UAS in the airspace are felt by UAS pilots and operators, manned aircraft operators, and air traffic controllers. As the switch from manned aircraft to UAS occurs (for limited applications) it is apparent that additional training and redefinition of operations, procedures, checklists, systems, and requirements are necessary for all active parties in the NAS. As “off the shelf” UAS continue to spread in popularity and applications of use, the issues presented and the need for equivalency is pressing in order to reduce accident and incident rates.

6.1.1 Accidents and Incidents by UAS Type

From the pie chart and histogram of the Types of UAS Involved in Accidents and Incidents we see that the largest pie slice pertains to aircraft of unknown types, which implies that the accidents and incidents are being reported not by the UAS operator, but by other manned aircraft, ATC, or onlookers. Therefore, there is a large problem presented by limited self-reporting of accidents and incidents by UAS operators. It is likely that these pilots are not aware of the self-reporting procedures in place and utilized by manned aircraft. The next several larger proportions of aircraft types are military aircraft. While this is likely related to the database composition, it shows that formal UAS operators are reporting accidents and incidents. This is probably a condition of their operational requirements, but it shows that increased procedural knowledge and formal flight rules are effective in transferring this facet of manned aircraft piloting to UAS operations.
6.1.2 Accidents and Incidents by Human Error Involvement

From the categorization of the database into accidents and incidents involving human error, it is seen that human error plays a large part in UAS accidents and incidents as it does for manned aircraft accidents and incidents. It is important to note, however, that the human errors being committed in UAS flight are similar to those of concern in mitigating risk in manned aircraft operations, but they are fundamentally different as a product of the inherent differences between UAS and manned aircraft. Therefore, while the adoption of aircraft and maintenance procedures and checklists used in manned aircraft flight is a great starting point, risk mitigation measures need to be tailored specifically to suit these differences. However, one large issue is that for sUAS especially these aircraft are being adopted for use without the establishment of formal procedures and checklists to the level that is used in manned aircraft operations.

In contrast, the Academy of Model Aeronautics employs extensive flight rules, guidelines, promoted safe practices, and supplies its users with a wealth of informational guidance in order to provide tailored and appropriate risk mitigation. As a result, the number of AMA liability insurance claims per year by members is quite low with around 35 total annual claims in 2012, and 15 of those involving injury [52]. While human error is always expected to be present in human operations, decision and skill based errors are able to be mitigated. Additionally, intentional routine violations should be able to be eliminated through strong collaboration between the entities at play. One example would be through UAS operators and ATC in order to establish appropriate and enforceable procedures.

6.1.3 Taxonomy 1: The UAS Fault Tree Framework Level 1 Subsystems

By categorizing the database results by Fault Tree Level 1 Subsystem framework, it is seen that the Aircraft/System, and the Flight Crew/Human Factors Categories of accidents and incidents are the most common, with 231 and 204 entries respectively. This shows
that two significant concerns are the Aircraft/System hardware and software as well as the role of Flight Crew and Human Factors in the system as a whole. These are two categories which have changed drastically in the analysis of UAS in comparison to manned aircraft. UAS are not subject to extensive system standardization or aircraft certification procedures that are mandatory for manned aviation. Additionally, there are no requirements for design safety for UAS on the shelves of stores other than those for model aircraft toys. This presents a huge problem, as the manufacturers of popular hobbyist UAS are likely not approaching design problems from an aviation point of view and may have a limited understanding of how to mitigate risks these new aircraft pose toward manned aviation.

One example of a risk mitigation measure which has since been put into place by many manufacturers is the use of geofencing or altitude/GPS hold software in their sUAS. This can help prevent conflicts with manned aircraft traffic by forcing sUAS operators not to conduct operations within a certain distance of a GPS tagged airfield. However, an example of a risk which needs additional consideration is the building materials used to construct these UAS. In specific, these aircraft are often made of strong materials and carry lithium ion batteries which creates a huge hazard for ingestion into a manned aircraft engine. Also, if materials are not designed to break apart on impact, if a person is struck by a falling UAS the chances of fatality are significant. As UAS have presented a convenient way to conduct operations without the presence of lives on board, the perceived reduced risk to the pilot has trickled through the system to manifest itself as decreased system reliability with fewer redundancies and fail safe measures. While it is true that fewer lives are in danger on the primary aircraft, the risk of catastrophic event remains and must be effectively mitigated in a formal manner.
6.1.4 Taxonomy 2: ICAO Aviation Occurrence Categories

Many of these points are confirmed again within the context of the database results categorized by ICAO Aviation Occurrence. The top three most commonly occurring categories were System/Component Failure or Malfunction (Non-Powerplant), AIRPROX/TCAS Alert/Loss of Separation/Near Midair Collisions/Midair Collisions, and Navigation Errors. While many of these entries are from unauthorized UAS activity, this proves to us that significant problems lie in areas such as pilot situational awareness, see and avoid strategies and right of way rules, collaboration with Air Traffic Control and traffic management both in the air and on the ground, and in system reliability.

The results found through the ICAO categorization showed that System/Component Failures or Malfunctions (Non-Powerplant) comprised 31.2% of the data, while AIRPROX/TCAS Alert/Loss of Separation/Near Midair Collisions/Midair Collisions made up just over 19% of the accidents and incidents assimilated in the database. Lastly, Navigation Errors made up 13.99% of the accidents and incidents of the 529 database entries. In contrast, a report published by Airbus on Commercial Aviation Accidents analyzed data 1995-2014 on the causes of fatalities and hull losses in these accidents. The top three categorizations of ICAO Aviation Occurrences for these cases were as follows. For fatal accidents, the three greatest causes were Loss of Control-Inflight (LOC-I) at about 27.5%, Controlled Flight Into or Toward Terrain at approximately 22% and Runway Excursions (RE) at approximately 12% of total accidents worldwide. For accidents involving loss of hull, the top Occurrences by percentage of total accidents (Commercial Aviation) were Runway Excursions (RE) at approximately 32.5%, followed by System/Component Failure or Malfunction (Powerplant and Non-Powerplant) (SCF) at approximately 12.5%, and Loss of Control-Inflight (LOC-I) at approximately 11.5% [98].

Details on how all of these factors play roles within the larger system and breakdowns of possible faults, failures, and human errors which contribute to the occurrence of these top
three significant events for UAS are outlined extensively in the fault tree analyses located in the appendices. In particular, the UAS System-wide Fault Tree shines a light on the fundamental differences in distribution of statistical significance and the role of system reliability, certain system aspects (such as communication, and control), and the role of the pilot in the system, when compared to manned aircraft operations. Additionally it shows areas of concern when viewed in conjunction with the database and its results, such as errors presented by insufficient collaboration between UAS operators (both formal and other) with Air Traffic Control officials.

6.1.5 Taxonomy 3: HFACS Unsafe Acts

The HFACS categorized data shows that decision errors are the most prevalent in the dataset, followed by skill-based errors. Violation occurrences were low, indicating that most illegal UAS activity taking place is attributed to decision errors, rather than violations by definition. In this way, decision errors could likely be mitigated through increased support and continued spread of awareness of manned aircraft operations for UAS operators. The training requirements proposed by part 107 may have a positive impact on these results into the future, but it remains that sUAS can be operated for hobbyist purposes without passing a knowledge test, yet still do not have the same understanding of restrictions and safety interests as typical model aircraft operators. Skill-based errors will also likely be reduced as a result of knowledge tests, but the same issue occurs for hobbyist flight.

Looking at the HFACS data categorized by entity at fault, UAS operators make up the vast majority. While Formal UAS Operators have slightly more entries than Other UAS Operators (117 vs. 113 accidents and incidents), this is probably attributed to the fact that Formal UAS operators are strong self-reporting entities. Other UAS operators were mostly reported by aircraft which were in traffic conflict with the UAS or experienced a
traffic sighting which was not informed to them through traditional techniques such as self-separation radio calls or ATC where the aircraft was on flight following or an IFR flight plan. Some of these were near the ground such as at tourist locations where helicopters were also conducting flights, but many also were reported on final approaches into popular airports or at high altitudes. This means there are probably significantly more cases of UAS operating at illegally high altitudes than those reported which were lucky enough to be outside of conflict with other aircraft. While there was a large number of Formal UAS Operators at fault, the strong self-reporting practices indicate the strong role of procedure, knowledge of resources at the pilots disposal, and strong sense of right and wrong in terms of FAR and rules of flight. Additionally, chances are if the pilots are self-reporting their accidents and incidents, the Formal UAS Operators are monitoring occurrences with the goal of mitigating risks.

6.2 Challenges and Areas of Need in UAS Integration

In terms of areas of significance, aircraft and system reliability and flight crew training and human factors are at the top of the list. The fundamental differences between in-fuselage cockpit flight vs. remote, remote autonomous, or autonomous flight by definition indicate an increased dependency on infrastructure through communication, navigation, and control systems. Additionally, the methods of UAS flight place an increased dependency on the pilot to monitor systems and “be ahead of the airplane” with the reduced sensory input and spatial orientation qualities which come from the use of an in-fuselage cockpit. The pilot must be ready to identify and diagnose degraded states, unusual attitudes, and failures without being able to see or hear them in the same visual and physical manner. One large difference that must be accounted for is the reduced or nonexistent kinesthetic input to the pilot during flight. This alone can increase reaction times significantly. Link latency also presents a risk of increased reaction time.
6.2.1 UAS Aircraft System Needs

In order for UAS to advance in integration efforts into the NAS certain gaps must be bridged. UAS development on the path toward full integration and level of safety preservation in the National Airspace System requires formal standardization and minimum system requirements on a per-airspace of operation basis and on an Unmanned Aircraft System complexity basis. Here, UAS system complexity means complexity in the same sense of a manned aircraft in terms of avionics equipage and mechanical aspects (i.e. retractable vs. fixed gear, variable vs. pitch propeller). This requires the use of system redundancies standardized across all UAS of a single class in order to ensure stringent enough levels of safety to not adversely affect the safety levels of operation of the pre-integrated national airspace.

An additional need for UAS operations is a way to signal not only to ATC, but also to other aircraft in the vicinity of operation that a UAS is operating in a degraded mode, similar to strategies already employed in manned aviation. One example of this would be the use of special transponder codes to indicate a loss of communication or high jacking occurrence on a manned aircraft. While this works well for transponder equipped aircraft, not all UAS are transponder equipped. Another manifestation of this need could be through visual lighting in the same way as light gun signals are used for air traffic control towers to send signals to manned aircraft that do not have operable communication systems. UAS may be in positions where light gun signals would be utilized by ATC to communicate with manned aircraft, but they may not be able to achieve communication in this way with UAS. However, one benefit could be equivalency through phone communication as a backup for ATC-UAS pilot communication. This is a strategy that is often employed in current operations, and would be an example of bridging the gap, though statistical equivalence is not necessarily achieved. Lastly, UAS need a way to accurately and effectively announce their position to other aircraft operating in their
vicinity comparable to the use of transponder squawk codes for manned aircraft. While this is a reality for transponder-equipped UAS, a large subset of UAS in operation are not transponder equipped or have limited power and weight budgets.

### 6.2.2 UAS Flight Crew/Operator Needs

The increased role of the pilot in the aircraft system of a UAS compared to a manned aircraft has additional needs in order to achieve equivalency in statistical safety of operations. As previously discussed, there are additional considerations that need to be taken into account for human factors. Pilot attention becomes a significantly different issue for UAS operations. Additionally, flight crew qualifications are relatively incomplete at this point in time and are not necessarily the most appropriate and effective requirements for UAS operations.

Traditional manned aircraft pilots may experience significant difficulties developing the skills for remote flight. Model aircraft pilots on the other hand may excel at operating very capable and high performance remotely piloted aircraft. The traditional manned aircraft pilots, however, likely have a well-rounded and extensive understanding of the utilization of procedures, checklists, IFR flight, and airspace operations for manned aircraft of all types and in all classes of airspace. While many model aircraft operators have significant knowledge and interest in safe airspace and aircraft operations including collaboration with nearby airports and self-announcement of intentions, it is not on the manned aircraft knowledge level, and it is not tested. Ideally all hobbyist sUAS operators should have at least the same level of knowledge of that encouraged by the AMA of its members. If sUAS hobbyists could peer-regulate and practice safe operations on the same level as what is employed in the AMA, the number of hobbyist accidents and incidents would likely decrease.
Through this discussion it is seen that UAS pilots require substantial awareness of manned aircraft operations in order to anticipate and avoid risk. Additionally, increased and uniform collaboration with ATC is needed. Many entries in the UAS database of accidents and incidents involved partial or no collaboration with ATC in the form of providing lost link procedures or even aircraft model when filing plans before flight. UAS pilots will also need to apply manned aircraft pilot resources and procedures, such as the use of sectionals, formal procedures to contact Air Traffic Control, radio call procedures and etiquette, radio frequencies of operation, recommended checklists and procedures, and awareness of self-reporting systems for accidents and incidents.

Additionally, there is a need for increased oversight of UAS operations and their collaboration with ATC. Flight plan filing and submission of loss of communication or navigation procedures should be required for flights as deemed necessary, and these practices should be enforced prior to when a controller attempts to access them when the aircraft is in a degraded mode. As the FAA has already presented Airman Certification Standards as part of FAR Part 107, there is a need for formal and systematic evaluation of these pilot requirements based upon the trend findings in accident and incident reports and the unique needs of UAS operations in comparison to model and manned aircraft.

As UAS pilots are a completely new branch of aircraft operator, training needs to be tailored to the operations, applications, and aircraft, and widespread training of operators is necessary for their integration. Also, there are additional training needs which need to be taken into account for manned aircraft operators and ATC as well in order to achieve integrated operations where UAS and manned aircraft can operate in the same volumes of airspace. For example, manned aircraft operators could benefit from scanning techniques tailored to looking for UAS traffic and tips on how to identify UAS as opposed to mistaking them for larger aircraft at greater distances. This information would be beneficial as part of private pilot or sport pilot knowledge for example, as many student pilots or certified
airmen may be susceptible to increased skill-based or perceptual errors. Air Traffic Control could also benefit from additional training in order to avoid instances where controllers may have unreasonable expectations of UAS operators (in terms of issuing clear instructions) or having increased awareness of operations under Certificates of Authorization so as to avoid issuing conflicting instructions to the pilot.

6.2.3 Aircraft Development and Certification Needs

Lastly there is a need for mechanical standards and testing. Materials usage is a significant concern for UAS operations near other aircraft as they could cause significant damage different than that posed by bird strikes. Birds already cause a large risk to manned aircraft, but current manned aviation uses this as a benchmark to design material surfaces and aircraft engines to withstand impact as well as possible. A UAS on the other hand may destroy a jet engine on an airliner to a much larger degree than a bird. Therefore an investigation into aircraft ingestion of UAS would be relevant.

Additionally standardized maintenance procedures, comparable to manned aircraft aviation would promote safer and more reliable UAS operations through mitigation of maintenance risks. One example of this would be requiring Inspection Authorizations for significant UAS repairs in the same ways which they are required for manned aircraft in order to ensure oversight, accountability, and safe practices. Other suggestions include possible investigations into fuel requirements, such as how much fuel UAS are allowed to carry or specific battery requirements would be relevant. In this vein, materials and equipage of UAS should be analyzed as well in term of risk to persons on the ground. For example, many sUAS manufacturers attempt to utilize materials which are designed to break apart easily for the propellers on quadrotor aircraft. Another example of this was the use of a Styrofoam bumper on the popular Parrot AR Drone in order to reduce risk of injury to people.
Lastly, it would be particularly beneficial for traffic avoidance if UAS were equipped with required, standardized lighting systems comparable to those for manned aircraft associated with Day and Night operations. Lighting could make the small aircraft more detectable. UAS-specific lighting may also help other aircraft identify UAS traffic from manned aircraft traffic and facilitate distance to impact perception in cases where loss of separation occurs.

6.2.4 UAS Hobbyist Community Development

The tried-and-true strategies employed by the AMA and model aircraft hobbyists are a good model for hobbyist UAS operators. It would be beneficial to create a UAS-specific club in order to increase advocacy and community for UAS operators. While it is easy to associate UAS with model aircraft, they have differences from both model aircraft and manned aircraft. Creation of UAS specific groups would further encourage legislation and structured input from hobbyists while encouraging peer enforcement practices and would help increase awareness of self-reporting systems for accidents and incidents. In fact, such a group could organize a separate database for study in an effort to increase the data available to us on UAS operational structure and risks.
7 SUMMARY AND CONCLUSIONS

The goal of this research was to gain insight into the integration of Unmanned Aircraft Systems into the National Airspace System, in all airspaces and with varying aircraft complexity through a fault tree approach. An accepted manned aircraft framework used in the manned aircraft industry for aircraft design and aircraft certification was used as a starting point to statistically frame the failure modes and probabilities of catastrophic events for UAS operations in the National Airspace System. The fault tree analysis approach to designing aircraft operations and mitigating risk in the National Airspace System is tried and true as a staple approach employed by the FAA, NTSB, and NASA for example. As part of a System Safety Assessment this modeling strategy is significant in its ability to explore and convey failure modes and possible errors and failures on the smallest resolution to the largest subsystems in order to identify root causes of risk in complex systems. This made it ideal for drawing tangible results on the way in which pilot interface, system components, human factors, environmental concerns, and other aspects play different roles of differing statistical and logical significance in unmanned or remotely piloted aircraft systems compared to manned aircraft systems.

- Through the fault tree analysis and data processing of a UAS accident and incident database, trends in UAS accidents and incidents already occurring in the past 15 years were identified and the components and facets risk within UAS system operations were able to be modeled with increased detail.

This provides increased insight into the requirements necessary of UAS pilots from both a top-down and a bottom-up UAS-specific approach as opposed to modeling strictly from a model aircraft or manned aircraft approach.
Analysis of the database indicated that responsibility for risk mitigation lies with the UAS Operator but also with Air Traffic Control and manned aircraft operations, and airport traffic management as through integration, all of these operations are projected to evolve.

- There is a significant issue presented by the fact that a large portion of UAS accidents and incidents are of Unknown aircraft type. This means that a large number of UAS operators are not self-reporting entities.

In contrast, Formal UAS Operators such as government, military, and organizations hold strong self-reporting strategies and use of formal procedures.

- Human error plays a large role in UAS accidents and incidents with half of database events involving human error. While human error is a concern in all aviation operations, it plays a much different role in UAS operations than in manned due to the use of a remote cockpit.

Categorization of the database using the UAS Fault Tree Level 1 Subsystems indicated that the Aircraft/System and Flight Crew/Human Factors subsystems dominate the causes of UAS accidents and incidents, making up 435 out of 529 accidents and incidents.

- The number one cause was Aircraft/System failures, calling for increased requirements in aircraft equipage, redundancies, and formal evaluation and standardization on this front.

Additional concerns presented include issues arising from UAS building materials and the risk they present on impact.

- Of human errors present within the database accidents and incidents, decision errors held a significant lead.

They are followed by skill-based errors and perceptual errors. Violations are present in the data but uncommon. There is a need for increased self-reporting practices in UAS
accidents and incidents as many adverse events are reported by manned aircraft which come in conflict with UAS.

- Use of checklists, guidelines, formal procedures, and increased training standards are effective in manned aircraft operations, as well as operations conducted by Formal UAS Operators and model aircraft operators, but must reflect the differences between UAS and operations of these other aircraft.

   Academy of Model Aeronautics is effective in promoting safe model aircraft use through peer-oversight, education, and training and hobbyist UAS would benefit from a parallel group and community.

- UAS are not subject to the stringent requirements of manned aircraft certification, and hobbyist sUAS present a large problem as they are subject only to the standards for toys and largely not designed with formal aviation safety requirements in mind.

- ICAO Aviation Occurrences most common to UAS accidents and incidents were found to be System/Component Failures or Malfunctions (Non-Powerplant), AIRPROX/TCAS Alert/Loss of Separation/Near Midair Collisions/Midair Collisions (MAC), and Navigation Errors (NAV) which differ significantly both statistically and operationally from the results for fatal manned commercial aircraft catastrophic accidents.

   In terms of human factors concerns, risk of pilot disorientation is significantly greater for UAS pilots than for manned aircraft pilots due to reduced kinesthetic input, and increased reaction times can result with link latency as an additional concern.

   In general, remotely piloted aircraft operations show significantly different logical and statistical distribution of failure modes and risk mitigation strategy in the categories of Aircraft/System, Flight Crew/Human Factors, and Weather/Environment.
• One large factor is an increased dependency on communication, navigation, and control systems, and a strong need for reliable procedures for any failure modes caused by degradation of these systems.

• UAS pilot requirements are different from both manned and model aircraft operations, and UAS operators would benefit from extensive training on ground knowledge of manned aircraft pilots including communication practices, emergency procedures, use of sectionals and extensive weather information, airspace knowledge, collaboration with air traffic control and participation in self-reporting systems.

Additionally, ATC and manned aircraft pilots would benefit from additional training, awareness of UAS operations, and risk mitigation strategies. These are necessary tools in the path away from accommodation and toward full integration of UAS into the NAS.
8 Recommendations

Recommendations for future work following this research include additional UAS accident and incident database curation. Statistical assessments of UAS operations are concrete and essential parts of aircraft and airman certification processes and design processes which are instrumental in upholding the safety of our National Airspace System. The Federal Aviation Administration has formally implemented FAR Part 107 regulations for Commercial UAS flight at low altitudes complete with a Remote Pilot-Small Unmanned Aircraft Systems Airman Certification Standards (ACS). These pilot certification standards would benefit from formal and systematic comparisons to pilot requirements for Instrument Rating Airplane: ACS, Sport Pilot Practical Test Standards for Airplane, Gyroplane, Glider, and Flight Instructor, Recreational Pilot Practical Test Standards for Airplane, Rotorcraft/Helicopter, and Rotorcraft/Gyroplane, and Private Pilot Practical Test Standards for Rotorcraft: Helicopter and Gyroplane. As more statistics become available with the increased number of UAS operations being conducted around the globe, statistical analyses and modeling pertaining to System Safety Assessments will become increasingly more effective at smaller scopes. They will be able to provide additional insights to more detailed aspects of integration.

Another point of future work would be further tailoring of the Fault Tree Analyses presented in this research for specific UAS operations whether by application, pilot training, aircraft complexity, airspace of operation, or any combination thereof. It is expected that aircraft complexity will be correlated to airspace of operation, as equipage requirements are expected to be more stringent as they are for manned aircraft. In the vein of aircraft complexity, it would be beneficial to explore a comparison of levels of aircraft autonomy and how the role of the pilot and the effects of human factors will change with varying complexity of autonomous operations, from fully remotely piloted aircraft, to various stages of partial autonomy, to fully autonomous vehicles. This would be well analyzed
and compared through a fault tree approach, again with the further goal of quantitative analyses as increasingly large data sets become available.
REFERENCES


[90] U. A. Combat and R. Center, “Army Accident Classification Chart.”


Appendix A: Fault Tree Analysis Results at a Glance

The following selection of results were presented as part of the thesis defense. A subsection of each of the four trees developed is presented. The goal of this section is to provide insight into the flow of the paginated fault tree results and how sections of the fault trees fit into each of the full trees. Additionally, the ICAO Aviation Occurrence category fault trees are tied to the UAS Accident and Incident Database results.

At the top of each slide the full fault tree analysis of that top level event is presented. Page 8 is an exception, as only a subset of the full tree is presented as indicated. Areas of interest are highlighted in colors corresponding to the paginated piece shown. Level labels are employed to indicate the level of the full fault tree that the paginated piece belongs to. The fault tree graphics presented in this appendix were created using Isograph FaultTree+ 11.2.
FT1: UAS System-wide Analysis
FT1: UAS System-wide Analysis (cont.)

Level 1
- Aircraft System
- Gate 1
- Gate 2
- Gate 3

Level 2
- Loss of power
- Loss of control
- Fire
- Loss of communication
- Power
- Carriage
- Ground/flight

- Attention lapsed
- Incorrect logic
- Failure to follow procedure
- Failure to follow guidance
- Unidentified/unknown air/ground

Ohio University EECS
A2
FT1: UAS System-wide Analysis (cont.)
FT1: UAS System-wide Analysis (cont.)

Level 1 (cont.)

Maintenance

- Insufficient Maintenance Management
  GATE 141
  Page 71

- Unforscen maintenance issue
  EVENT 137
  i=0

- Insufficiently Correlated maintenance issue
  EVENT 138
  i=0

Weather

- Unforscen weather conditions
  GATE 104
  Page 58

- Supported Go Decision
  GATE 105
  Page 59

- Unforscen environmental conditions
  GATE 106
  Page 60

- Failure of others to remain well clear
  GATE 107
  Page 61

Ohio University EECS

A4
FT1: UAS System-wide Analysis (cont.)

Level 1 (cont.)

ATC

- GATE6
  - ATC fails to accommodate
  - Failure of UAS operator to publish
  - Improper notification from pilot/crew

- EVENT174
  - n=0

- EVENT175
  - n=0

Miscellaneous

- GATE7

Ohio University EECS

A5
Database Categorization 2: ICAO Aviation Occurrence

Accidents/Incidents Categorized by ICAO Aviation Occurrence

<table>
<thead>
<tr>
<th>Abb.</th>
<th>Occurrence</th>
</tr>
</thead>
<tbody>
<tr>
<td>SCF-NP</td>
<td>System/Component Failure/Malfunction (Non-Powerplant)</td>
</tr>
<tr>
<td>MAC</td>
<td>Airprox/TCAS Alert/Loss of Separation/Near Midair Collisions/Midair Collisions</td>
</tr>
<tr>
<td>NAV</td>
<td>Navigation Errors</td>
</tr>
<tr>
<td>SCF-PP</td>
<td>System/Component Failure/Malfunction (Powerplant)</td>
</tr>
<tr>
<td>UNK</td>
<td>Unknown</td>
</tr>
<tr>
<td>LOC-I</td>
<td>Loss of Control - In flight</td>
</tr>
<tr>
<td>OTHR</td>
<td>Other</td>
</tr>
<tr>
<td>ARC</td>
<td>Abnormal Runway Contact</td>
</tr>
<tr>
<td>ATM</td>
<td>ATM/CNS (Air Traffic Management)</td>
</tr>
<tr>
<td>WSTRW</td>
<td>Wind Shear/Thunderstorm</td>
</tr>
</tbody>
</table>

Ohio University EECS
FT2: System/Component Failure or Malfunction (Non-Powerplant)
FT2: System/Component Failure or Malfunction (Non-Powerplant) (cont.)
FT2: System/Component Failure or Malfunction (Non-Powerplant) (cont.)
Database Categorization 2: ICAO Aviation Occurrence

<table>
<thead>
<tr>
<th>Abb.</th>
<th>Occurrence</th>
</tr>
</thead>
<tbody>
<tr>
<td>SCF-NP</td>
<td>System/Component Failure/Malfunction (Non-Powerplant)</td>
</tr>
<tr>
<td>MAC</td>
<td>Airprox/TCAS Alert/Loss of Separation/Near Midair Collisions/Midair Collisions</td>
</tr>
<tr>
<td>NAV</td>
<td>Navigation Errors</td>
</tr>
<tr>
<td>SCF-PP</td>
<td>System/Component Failure/Malfunction (Powerplant)</td>
</tr>
<tr>
<td>UNK</td>
<td>Unknown</td>
</tr>
<tr>
<td>LOC-I</td>
<td>Loss of Control- In flight</td>
</tr>
<tr>
<td>OTHR</td>
<td>Other</td>
</tr>
<tr>
<td>ARC</td>
<td>Abnormal Runway Contact</td>
</tr>
<tr>
<td>ATM</td>
<td>ATM/CNS (Air Traffic Management)</td>
</tr>
<tr>
<td>WSTRW</td>
<td>Wind Shear/Thunderstorm</td>
</tr>
</tbody>
</table>

Accidents/Incidents Categorized by ICAO Aviation Occurrence
FT3: Airprox/TCAS Alert/Loss of Separation/Near Midair Collisions/Midair Collisions
FT3: Airprox/TCAS Alert/Loss of Separation/Near Midair Collisions/Midair Collisions (cont.)
FT3: Airprox/TCAS Alert/Loss of Separation/Near Midair Collisions/Midair Collisions (cont.)
Database Categorization 2: ICAO Aviation Occurrence

Accidents/Incidents Categorized by ICAO Aviation Occurrence

<table>
<thead>
<tr>
<th>Abb.</th>
<th>Occurrence</th>
</tr>
</thead>
<tbody>
<tr>
<td>SCF-NP</td>
<td>System/Component Failure/Malfunction (Non-Powerplant)</td>
</tr>
<tr>
<td>MAC</td>
<td>Airprox/TCAS Alert/Loss of Separation/Near Midair Collisions/Midair Collisions</td>
</tr>
<tr>
<td>NAV</td>
<td>Navigation Errors</td>
</tr>
<tr>
<td>SCF-PP</td>
<td>System/Component Failure/Malfunction (Powerplant)</td>
</tr>
<tr>
<td>UNK</td>
<td>Unknown</td>
</tr>
<tr>
<td>LOC-I</td>
<td>Loss of Control - In flight</td>
</tr>
<tr>
<td>OTHR</td>
<td>Other</td>
</tr>
<tr>
<td>ARC</td>
<td>Abnormal Runway Contact</td>
</tr>
<tr>
<td>ATM</td>
<td>ATM/CNS (Air Traffic Management)</td>
</tr>
<tr>
<td>WSTRW</td>
<td>Wind Shear/Thunderstorm</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
</tr>
</tbody>
</table>

Ohio University EECS
FT4: Navigation Errors

Ohio University EECS
FT4: Navigation Errors (cont.)

Level 4
- Perceptual error
- Skill-based error
- Check for error

Level 5
- Perceptual error
- Skill-based error
- Unlikely aircraft performance
- Unlikely aircraft support
- Other perceptual error

Level 6
- Insufficient navigation with ATC
- Insufficient navigation with ATC
- Operator did not engage IATC coordination procedures
- Operator engaged IATC coordination procedures

Ohio University EECS
FT4: Navigation Errors (cont.)

Level 4
- Navigation Error
  - Perceptual error
  - Skill-based error
- Decision error
  - Unrealistic expectations from the system
  - Unrealistic expectations (differences from) simulation
- Unusual error
  - Other unusual error

Level 5
- Decision error
  - Unrealistic expectations from the system
  - Unrealistic expectations (differences from) simulation

Level 6
- Unrealistic expectations (differences from) simulation
  - Other unusual error

Ohio University EECS
APPENDIX B: FAULT TREE ANALYSIS: GENERAL UAS SYSTEM

FRAMEWORK

Note: The following paginated fault tree contains page numbers to tie the pages together. Additionally, the fault tree subset figures have been captioned with figure numbers. The page numbers within the fault tree correspond to the captioned figure numbers, as opposed to the appendix pages. All event probabilities are set to 0 to reflect the qualitative nature of the tree. The fault tree graphics presented in this appendix were created using Isograph FaultTree+ 11.2.
Flight Crew/Human Factors

Attention lapse
Incorrect input
Failure to follow procedure
Failure to follow checklist
Incorrect preflight airworthiness approval (pilot)
Failure to recover

Note Gate 62: Skill-based error
Note Gate 63: Skill-based error

Maintenance

Insufficient Maintenance Management
Unforseen maintenance issue
Improperly corrected maintenance issue

EVENT137
EVENT138

r=0
r=0
Weater/Environmental Factors

GATE5

Unforseen weather conditions
GATE104
Page 58

Insufficiently Supported Go Decision
GATE105
Page 59

Unforseen environmental conditions
GATE106
Page 60

Failure of others to remain well clear
GATE107
Page 61
ATC fails to accommodate

Failure of UAS operator to publish

Improper notification (from pilot/crew)

Page 87

r=0

r=0

Miscellaneous

GATE7
Loss of power

GATE8

Powerplant failure

Battery failure

Loss of power in operating station

EVENT13
r=0

EVENT14
r=0

EVENT15
r=0

Loss of Control

GATE9

Inability to input commands

Handheld unable to transmit commands

Aircraft unable to receive commands

Aircraft unable to execute commands

GATE15
Page 14

GATE16
Page 15

GATE17
Page 16

GATE18
Page 17
Partial Damage - Ground/Flight

- Damage to fuselage
  - GATE23
  - Page 18
- Damage to control surfaces
  - GATE24
  - Page 19
- Damage to sensor payload
  - EVENT57
  - $r=0$

Inability to input commands

- Hardware failure in handheld
  - GATE26
  - Page 20
- Power failure in handheld
  - EVENT16
  - $r=0$
- Software failure in handheld
  - EVENT17
  - $r=0$
Handheld unable to transmit commands

GATE16

Hardware failure in handheld

GATE30

Software failure in handheld

EVENT20

r=0

Page 21

Aircraft unable to receive commands

GATE17

Hardware failure on aircraft

GATE34

Page 22

r=0

Software failure on aircraft

EVENT25

r=0

Environmental RF interference

EVENT26

r=0

Aircraft outside radio range

EVENT27

r=0
Aircraft unable to execute commands

- Hardware failure on aircraft
  - GATE36
  - Page 23
- Software failure on aircraft
  - GATE37
  - Page 24

Damage to fuselage

- Pilot-caused collision
  - GATE43
  - Page 26
- Failure of others to remain well clear (environmental)
  - GATE44
  - Page 27
- Weather-caused damage
  - GATE45
  - Page 28
Hardware failure in handheld

EVENT21: Hardware has been damaged
r=0

EVENT22: Other hardware failure
r=0

Hardware failure on aircraft

EVENT23: Hardware has been physically damaged
r=0

EVENT24: Other hardware failure
r=0
Hardware failure on aircraft

Control surfaces have been damaged

Airframe has been damaged (other)

Other hardware failure

Software failure on aircraft

Unexpected system reset

Other software failure

EVENT31
r=0

EVENT32
r=0

EVENT33
r=0

EVENT34
r=0
Control surfaces have been damaged

EVENT28
Damage to control surfaces
r=0

EVENT29
Damage to linkage
r=0

EVENT30
Damage to flight control electronics
r=0

Pilot-caused collision

EVENT43
Failure of pilot to remain well clear

EVENT46
Failure of pilot to see and avoid

Page 29

Page 30
Failure of pilot to remain well clear

EVENT40
Perceptual error
r=0

EVENT41
Skill-based error
r=0

Failure of pilot to see and avoid

EVENT42
Perceptual Error
r=0

EVENT43
Skill-based error
r=0
Pilot-caused collision

Failure of pilot to remain well clear

Failure of pilot to see and avoid

Failure of others to remain well clear (environmental)

Failure of people to remain well clear

Failure of other locally operated UAS to remain well-clear

EVENT53 r=0

EVENT54 r=0
Weather caused damage

GATE53

Hail damage
EVENT55
r=0

Lightning strike
EVENT56
r=0

Failure of pilot to remain well clear

GATE54

Perceptual error
EVENT49
r=0

Skill-based error
EVENT50
r=0
Failure of pilot to see and avoid

Perceptual error

EVENT51

r=0

Skill-based error

EVENT52

r=0

Attention lapse

EVENT58

r=0

No response

EVENT59

r=0

Late response
Note Gate 63: Skill-based error
Failure to recover

GATE65

Undiagnosed failure/hazardous condition
GATE81
Page 45

Incorrect response
GATE83
Page 47

Insufficient response
GATE82
Page 46

Insufficient altitude
EVENT119

r=0

Overaggressive maneuver
GATE68

Perceptual error
GATE252
Page 98

Skill-based error
GATE253
Page 99
Incorrect response

Skill-based error

Perceptual Error

Aircraft in a dangerous attitude

Pilot has commanded excessive attitude

Wind pattern has pushed aircraft into excessive attitude

Page 82

Page 84

Page 50

Page 51
One or more wings have stalled

GATE87

Skill-based error

GATE210

Perceptual error

EVENT111

Page 86

Pilot has commanded excessive attitude

GATE88

Excessive pitch-up attitude

GATE90

Page 52

Excessive bank angle

GATE91

Page 53

Excessive pitch-down attitude

GATE92

Page 54
Wind pattern has pushed aircraft into excessive attitude

Excessive pitch-up attitude

Excessive bank angle

Excessive pitch-down attitude

Perceptual error

Skill-based error

Page 55

Page 56

Page 57

Page 108

Page 109
Excessive pitch-up attitude

GATE93

Anomalous wind/weather condition

EVENT99

Decision error

GATE303

r=0

Page 116

Excessive bank angle

GATE94

Anomalous wind/weather condition

EVENT103

Decision error

GATE304

r=0

Page 117
Person interference

GATE115

- Failure of ground crew to coordinate
- Failure to maintain isolated operation area
- Failure of ground crew to clear persons

Vehicle interference

GATE116

- Failure of ground crew to coordinate
- Failure to maintain isolated operation area
- Failure of ground crew to clear vehicles

Event 162
Event 163
Event 164
Event 165
Event 166
Event 167

r=0

B66

B67
Aircraft strike

Unplanned emergency landing attempt by manned aircraft

EVENT170

r=0

Airspace incursion from local UAS

EVENT171

r=0

Insufficient Maintenance Management

Widely repeated errors or failures without additional mitigation

EVENT139

r=0

Insufficient maintenance training

EVENT140

r=0
Excessive delay → GATE163

Perceptual Error → GATE166
Skill-Based Error → GATE167

Insufficient magnitude of correction → GATE164

Perceptual Error → GATE168
Skill-Based Error → GATE169
No response

GATE165

Perceptual Error

GATE170

Page 77

Skill-Based Error

GATE171

Page 78

Pilot does not recognize condition of aircraft

GATE177

Page 81

Other perceptual error

EVENT120

r=0
Skill-Based Error

GATE167

Pilot does not see need for correction
EVENT123
r=0

Pilot has insufficient knowledge of recovery procedure
EVENT124
r=0

Other skill-based error
EVENT125
r=0

Perceptual Error

GATE168

Pilot does not recognize condition of aircraft
GATE176
Page 80
r=0

Other perceptual error
EVENT128
r=0
Skill-Based Error

EVENT129
Pilot does not see need for correction
r=0

EVENT130
Other skill-based error
r=0

Perceptual Error

EVENT132
Other perceptual error
r=0
**Skill-Based Error**

EVENT134: Pilot does not see need for correction
  - r = 0

EVENT135: Pilot has insufficient knowledge of recovery procedure
  - r = 0

EVENT136: Other skill-based error
  - r = 0

**Pilot does not recognize condition of aircraft**

EVENT131: Tunnel visioned trust in instrumentation
  - r = 0

EVENT133: Other reason
  - r = 0
Pilot does not recognize condition of aircraft

75

GATE176

Tunnel visioned trust in instrumentation

OTHER REASON

EVENT126

EVENT127

r=0

r=0
Pilot does not recognize condition of aircraft

GATE177

Tunnel visioned trust in instrumentation

EVENT121

r=0

EVENT122

r=0

Skill-based error

GATE182

Pilot lacks sufficient understanding of control interface

EVENT115

r=0

EVENT116

r=0

Other skill-based error

B81

B82
Perceptual error

GATE189

Pilot experiences decreased situational awareness

GATE197

Other perceptual error

EVENT91

r=0

Perceptual Error

GATE191

Pilot experiences disorientation of controls

EVENT117

r=0

Other perceptual error

EVENT118

r=0
Pilot experiences decreased situational awareness

GATE197

Weather/haze interference on approach

EVENT92

r=0

Other cause

EVENT93

r=0

Skill-based error

GATE210

Pilot fails to recognize aircraft state

EVENT112

r=0

Pilot fails to recognize aircraft state

EVENT113

r=0

Other skill-based error

EVENT114

r=0
ATC fails to accommodate

Unrealistic expectation of UAS pilot

Issuance of instruction conflicting with COA

Page 88

Page 89

Unrealistic expectation of UAS pilot

Perceptual error

Skill-based error

EVENT176

r=0

EVENT177

r=0
Issuance of instruction conflicting with COA

Perceptual error
EVENT178
r=0

Skill-based error
EVENT179
r=0

Signal interference

Radio control interference
EVENT168
r=0

Navigation signal interference
EVENT169
r=0
Decision error

Bad judgement of weather conditions

Unrealistic expectation of aircraft performance capability

Other decision error

Perceptual error

Incomplete/outdated weather information

Other perceptual error

EVENT153
EVENT154
EVENT160
EVENT155
EVENT156
Unintentional flight into clouds

GATE238

Perceptual error

GATE239

Undiagnosed maintenance condition

EVENT5

r=0

Other perceptual error

EVENT6

r=0
Skill-based error

EVENT62
Pilot lacks sufficient understanding of control interface

r=0

EVENT63
Other skill-based error

r=0

Perceptual error

EVENT64
Pilot experiences control disorientation

r=0

EVENT65
Other perceptual error

r=0
Skill-based error

GATE255

Pilot lacks sufficient understanding of control interface

EVENT66

Other skill-based error

EVENT67

Perceptual error

GATE256

Unexpected aircraft performance

EVENT68

Other perceptual error

EVENT69
Pilot skipped in favor of other tasks due to heavy workload

EVENT3

r=0

Pilot neglected to perform

EVENT4

r=0

Skipped steps

GATE293

r=0

Pilot skipped in favor of other tasks due to heavy workload

EVENT9

r=0

Other cause

EVENT10

r=0
Skill-based error

GATE296

- Aircraft controls have been configured incorrectly
  - EVENT76
  - r=0

- Pilot lacks sufficient understanding of control interface
  - EVENT77
  - r=0

- Pilot commits an accidental control error
  - GATE297

- Other skill-based error
  - EVENT87
  - r=0

Page 110
Pilot commits an accidental control error

EVENT78
Accidental shutoff of stability/altitude/location hold system
r=0

EVENT79
Other control error
r=0
Perceptual error

GATE298

EVENT80
Pilot experiences disorientation of controls
r=0

EVENT81
Unexpected aircraft performance due to weather/environment
r=0

EVENT88
Other perceptual error
r=0
Skill-based error

GATE299

Aircraft controls have been configured incorrectly
EVENT82 r=0

Pilot lacks sufficient understanding of control interface
EVENT83 r=0

Pilot commits an accidental control error
GATE300

Other skill-based error
EVENT89 r=0

Page 113
Pilot commits an accidental control error

Accidental shutoff of stability/altitude/location hold system

EVENT 84
r=0

Other control error

EVENT 85
r=0
APPENDIX C: FAULT TREE ANALYSIS: ICAO AVIATION

OCCURRENCE 1: SYSTEM/COMPONENT FAILURE OR MALFUNCTION

(NON-POWERPLANT) (SCF-NP)

Note: The following paginated fault tree contains page numbers to tie the pages together. Additionally, the fault tree subset figures have been captioned with figure numbers. The page numbers within the fault tree correspond to the captioned figure numbers, as opposed to the appendix pages. All event probabilities are set to 0 to reflect the qualitative nature of the tree. The fault tree graphics presented in this appendix were created using Isograph FaultTree+ 11.2.
Downlink failure

GATE16

Uplink failure

GATE17

Maintenance error

GATE59

Other

EVENT58

Page 52

r=0
Downlink failure

GATE18

Maintenance error

GATE61

Other

EVENT57

r=0

Page 53

Uplink failure

GATE19

C19

C20
Electrical failure

Total loss of link
Battery failure
Alternator failure
Circuit failure

Loss of communication

Page 36
Page 37
Page 38
Page 48
Loss of control

Loss of navigation

Control failure
Control failure

Communication failure

Airframe component failure
Altimeter failure

Other

Pitot-static failure

EVENT6

r=0

Page 54

Airspeed indicator failure (non-GPS)

Other failure

Pitot-static failure

EVENT8

r=0

Page 55
Situational awareness-type failure

Display failure
EVENT9
r=0

Map display failure
EVENT10
r=0

Maintenance error

Skill-based error
EVENT49
r=0

Decision error
EVENT50
r=0

Perceptual error
EVENT51
r=0
Aircraft diagnostics

Other

Maintenance error

Skill-based error
Decision error
Perceptual error

EVENT25
EVENT26
EVENT27

r=0
r=0
r=0
Pitot tube cover was not removed before flight

GATE75

EVENT65 Skill-based error
r=0

EVENT66 Decision error
r=0

EVENT67 Perceptual error
r=0
APPENDIX D: FAULT TREE ANALYSIS: ICAO AVIATION

OCCURRENCE 2: AIRPROX/TCAS ALERT/LOSS OF

SEPARATION/NEAR MIDAIR COLLISIONS/MIDAIR COLLISIONS

(MAC)

Note: The following paginated fault tree contains page numbers to tie the pages together. Additionally, the fault tree subset figures have been captioned with figure numbers. The page numbers within the fault tree correspond to the captioned figure numbers, as opposed to the appendix pages. All event probabilities are set to 0 to reflect the qualitative nature of the tree. The fault tree graphics presented in this appendix were created using Isograph FaultTree+ 11.2.
Loss of Separation

GATE3

Failure of self separation
GATE8
Page 9

Failure of ATC managed separation
GATE9
Page 10

Airspace incursion
GATE41
Page 20

Onboard alert issued to manned aircraft
GATE4

D4

D5
No onboard alert issued to manned aircraft

GATE5

Onboard alert issued to manned aircraft

GATE6

No onboard alert issued to manned aircraft

GATE7
Failure of self separation

GATE8

Pilot of UAS failed to recognize threat
GATE10
Page 11

UAS pilot recognized threat but did not mitigate risk
GATE11
Page 12

Loss of separation with life
GATE52
Page 25

Loss of control of aircraft
GATE56
Page 27

Note Gate 10: Skill-based error
Failure of ATC managed separation

GATE9

Decision error  Perceptual error  System error  Skill-based error

GATE12  GATE13  GATE44  GATE96

Page 13  Page 14  Page 22  Page 39
Pilot of UAS failed to recognize threat

GATE10

Pilot inattention
Observer/flight crew inattention
Insufficient understanding of right of way rules
Insufficient understanding of separation rules/definitions

EVENT3
EVENT4
EVENT5
EVENT6

r=0
r=0
r=0
r=0

Note Gate 10: Skill-based error

D11
UAS pilot recognized threat but did not mitigate risk

- Increased reaction time
  - GATE22
- Other aircraft made insufficient avoidance maneuver
  - GATE35
- Other aircraft did not see need to self-separate
  - GATE40
- Skill-based error
  - GATE88
- Perceptual error
  - GATE90
- Other aircraft made inappropriate avoidance maneuver
  - EVENT14

r=0
Decision error

GATE12

- ATC unaware of UAS operations no information
- Other decision error
- Insufficient separation buffer for UAS traffic
- Insufficient UAS coordination with ATC

EVENT27
EVENT31
EVENT34

GATE95

Page 38
Perceptual error

GATE13

UAS failed to adhere to instruction
Other perceptual error

EVENT32
r=0

EVENT33
r=0

Increased reaction time

GATE22

Skill-based error
Perceptual error
System error

GATE85
GATE86
GATE87
Other aircraft made insufficient avoidance maneuver

GATE35

12

Incorrect perceived distance to impact

GATE37

Insufficient reaction time

GATE39

Page 17

Page 18

Incorrect perceived distance to impact

GATE37

D16

D17
Insufficient reaction time

Other aircraft did not see need to self-separate

Aircraft did not recognize conflict as UAS

Other

GATE39

GATE40

GATE45

GATE46

Page 23

Page 24
Airspace incursion

GATE41

Pilot enters unauthorized airspace

GATE42

Other aircraft enters unauthorized airspace

EVENT42

Page 21

r=0
System error

GATE44

Loss of ATC communication with pilot
EVENT37 r=0

Other System error
EVENT38 r=0

Unexpected UAS path due to loss of control
EVENT39 r=0

Aircraft did not recognize conflict as UAS
GATE45

D22

D23
Loss of separation with life

Loss of control of the aircraft

Skill-based error

Page 26

Page 37
Loss of control of the aircraft

GATE55

Loss of control of aircraft

GATE56

9

EVENT24
Lost link

EVENT25
Loss of power in ground station

EVENT26
Unexpected system reset

r=0

r=0

r=0
System error

GATE87

Link latency

Other system error

EVENT10

EVENT11

r=0

r=0
Skill-based error

GATE88

Pilot did not assume control of aircraft in autopilot mode

EVENT13

r=0

Page 32

GATE89

Pilot made inappropriate avoidance maneuver

GATE93

Pilot made insufficient avoidance maneuver

Page 36
Pilot made inappropriate avoidance maneuver

GATE89

31

EVENT15
Insufficient understanding of right of way rules
r=0

EVENT16
Accidental control input
r=0

EVENT59
Other skill-based error
r=0
Perceptual error

GATE90

Pilot made insufficient avoidance maneuver

GATE91

Other perceptual error

GATE92

Page 34

Page 35
Pilot made insufficient avoidance maneuver

Incorrect perceived distance to impact

EVENT19

r=0

Insufficient aircraft performance

EVENT20

r=0

Other perceptual error

GATE92
Pilot made insufficient avoidance maneuver

GATE93

Insufficient reaction time
EVENT17
r=0

Other skill-based error
EVENT18
r=0

Insufficient training
EVENT21
r=0
Skill-based error

GATE94

Failure of flight crew to clear area
EVENT22 r=0

Failure of flight crew to enforce area of operation
EVENT23 r=0

Other skill-based error
EVENT60 r=0

Insufficient UAS coordination with ATC
GATE95

UAS not in contact with ATC
EVENT35 r=0

No lost link procedure on file
EVENT36 r=0
System error

GATE97

Failure of geofencing feature/altitude hold
EVENT43
r=0

Unexpected path of UAS due to loss of control
EVENT44
r=0

Other system error
EVENT53
r=0
Unexpected path under pilot control

GATE 100

41

Pilot inattention

EVENT 50

r=0

Pilot fails to adhere to clearance

GATE 103

Page 45
Unexpected path of UAS due to loss of control

GATE101

Preprogrammed mission conflicts with lost link procedure provided

EVENT47

r=0

No lost link procedure provided to ATC

EVENT48

r=0
Perceptual error

GATE102

Pilot fails to adhere to clearance

Other perceptual error

EVENT45

r=0

EVENT46

r=0
APPENDIX E: FAULT TREE ANALYSIS: ICAO AVIATION

OCCURRENCE 3: NAVIGATION ERRORS (NAV)

Note: The following paginated fault tree contains page numbers to tie the pages together. Additionally, the fault tree subset figures have been captioned with figure numbers. The page numbers within the fault tree correspond to the captioned figure numbers, as opposed to the appendix pages. All event probabilities are set to 0 to reflect the qualitative nature of the tree. The fault tree graphics presented in this appendix were created using Isograph FaultTree+ 11.2.
Note Gate 22: Skill-based error
Note Gate 47: Skill-based error
Note Gate 55: Perceptual error
In-Flight Navigation Error

Airspace Incursion

Failure to Follow ATC Instruction

Lateral Airspace Incursion

Vertical Airspace Incursion

Page 4

Page 5

Page 6

Page 7
Note Event 77: Decision error

GATE4: Failure to Follow ATC Instruction
- GATE19: ATC Instruction Unclear to Pilot
  - GATE12: Page 12
- GATE31: Difficulty Holding Attitude or Heading
- GATE84: Skill-based error
- EVENT77: ATC Instruction conflicted with approved COA operation
  - $r=0$

GATE5: Lateral Airspace Incursion
- GATE9: Navigation Error Under Autopilot Control
  - GATE8: Page 8
- GATE17: Navigation Error Under Pilot Control
  - GATE10: Page 10
Navigation Error Under Autopilot Control

System error

Skill-based error

EVENT20: Perceptual error

Note Event 20: Perceptual error
Navigation Error Under Pilot Control

Perceptual error
Skill-based error
Decision error

ATC Instruction Unclear to Pilot

Skill-based error
Decision error
ATC Instruction Unclear to Pilot

GATE20

Skill-based error

GATE59
Page 20

Decision error

GATE60
Page 21

Insufficient communication with ATC

GATE22

Operator did not engage in ATC coordination procedure

EVENT49
r=0

Operator engaged only partially in ATC coordination procedure

EVENT50
r=0

Other skill-based error

EVENT51
r=0

Note Gate 22: Skill-based error
Taxiway/Ramp Incursion

GATE47

Entered secure taxiway area without instruction

Entered closed taxiway area

EVENT12

r=0

EVENT13

r=0

Note Gate 47: Skill-based error

Runway Incursion/Excursion

GATE48

Skill-based error

Perceptual error: pilot situational awareness

GATE61

Page 22

GATE62

Page 23
Insufficient reaction time

GATE55

Pilot distraction

EVENT9
r=0

Increased reaction time due to link latency

EVENT10
r=0

Insufficient situational awareness of pilot

EVENT11
r=0

Note Gate 55: Perceptual error

---

Insufficient reaction time

GATE58

Pilot distraction

EVENT41
r=0

Skill-based error

GATE91
Page 43

Perceptual error

GATE92
Page 44
Skill-based error

Entered closed runway
Entered secure runway without instruction

Perceptual error: pilot situational awareness

Entered closed runway
Entered secure runway without instruction
Entered secure runway without instruction

GATE68

System error

GATE69

Improper preprogrammed route

EVENT17

EVENT52

Other

r=0

r=0
No preprogrammed route has been supplied to ATC

EVENT19

Preprogrammed route is in conflict with ATC lost link route

EVENT18

Improper preprogrammed route

EVENT17

Insufficient coordination with ATC

EVENT55

Pilot experiences control disorientation

Page 31
Insufficient coordination with ATC

EVENT53: Operator did not engage in ATC coordination procedure
r=0

EVENT54: Operator engaged only partially in ATC coordination procedure
r=0

E31
Skill-based error

GATE75

EVENT19: No preprogrammed route has been supplied to ATC; r=0
EVENT18: Preprogrammed route is in conflict with ATC lost link route; r=0
EVENT17: Improper preprogrammed route; r=0
EVENT80: Other skill-based error; r=0

Perceptual error

GATE76

EVENT56: Unexpected aircraft performance; r=0
EVENT57: Pilot experiences control disorientation; r=0
EVENT79: Other perceptual error; r=0
Unrealistic expectations from the system

EVENT58: Unrealistic lateral positioning tolerances for operation, $r=0$

EVENT59: Other unrealistic expectation, $r=0$

Insufficient coordination with ATC

EVENT62: Operator did not engage in ATC coordination procedure, $r=0$

EVENT63: Operator engaged only partially in ATC coordination procedure, $r=0$