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Safety Risk Analysis of Unmanned Aircraft Systems Integration Into the National Airspace System: Phase 2

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16. Abstract

This report describes Phase 2 of the continued development of a system-level hazard taxonomy for Unmanned Aircraft Systems (UAS). The taxonomy is termed the Hazard Classification and Analysis System (HCAS) and was developed by researchers at Rutgers University during Phase 1 through a cooperative agreement with the Federal Aviation Administration (FAA). It was particularly emphasized that this study should remain focused at the system level and not become operational in perspective. The Rutgers University Phase 1 approach was based on the FAA regulatory perspective (i.e., Title 14 Code of Federal Regulations chapters on Aircraft, Airmen, Certification/Airworthiness, Flight Operations, etc.). Such an approach uniquely distinguishes the HCAS taxonomy from all other UAS hazard analyses being performed by the Department of Defense, the RTCA-Special Committee 203, etc. The Phase 1 research goal was to develop a generalized taxonomy of system-level UAS hazards that would have broad applicability across FAA part types. This report describes Phase 2's enhanced developmental steps leading to the refined HCAS taxonomy.

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LIST OF ACRONYMS

BN	Bayesian Networks
CFR	Code of Federal Regulations
CPD	Conditional probability distribution
DAG	Directed acyclic graph
DoD	Department of Defense
FAA	Federal Aviation Administration
HALE	High-altitude long endurance
HBN	Hybrid Bayesian Networks
HCAS	Hazard Classification and Analysis System
NAS	National Airspace System
NASA	National Aeronautics and Space Administration
SC	Special Committee
SMS	Safety Management System
SRM	Safety Risk Management
UAS	Unmanned Aircraft System
UAV	Unmanned aerial vehicle

EXECUTIVE SUMMARY

The National Airspace System (NAS) in the United States is increasingly becoming a complex array of commercial and general aviation aircraft, very light jets, unmanned aircraft systems, reusable launch vehicles, rotorcraft, airports, air traffic control, weather services, and maintenance operations, among others. This increased system complexity necessitates the application of systematic safety risk analysis methods to understand and eliminate, where possible, or reduce and/or mitigate risk factors.

As such, the Rutgers University Phase 1 Unmanned Aircraft Systems (UAS) research objectives may be summarized as:

- the identification, categorization, and evaluation of potential system-level hazards of UAS operations in the NAS.

- the coordination of hazard identification and subsequent analysis with Federal Aviation Administration (FAA) offices.

- a focus on civil (i.e., public) applications.

This Phase 2 report describes the continued development of and enhancements to a system-level hazard taxonomy for UAS. The taxonomy is termed the Hazard Classification and Analysis System (HCAS) and was developed by researchers at Rutgers University (hereinafter referred to as Rutgers) during Phase 1 in consultation with the FAA. This report emphasizes focus at the system level and is not operational in perspective. The research goal was to develop a generalized taxonomy of system-level UAS hazards that would have broad applicability across FAA part types. The intent was that the Phase 1 study would lead to general research recommendations and guidelines in high-level support of the FAA's UAS Program Office (AIR 160). Moreover, it should be emphasized that the Rutgers Phase 1 approach was based on the FAA regulatory perspective (i.e., Title 14 Code of Federal Regulations chapters on Aircraft, Airmen, Certification/Airworthiness, Flight Operations, etc.). Such an approach uniquely distinguishes the HCAS taxonomy from all other UAS hazard analyses being performed by the Department of Defense, the RTCA Special Committee 203, etc.

The three primary Rutgers Phase 2 research tasks involved:

- Building upon and further evaluating the UAS hazard taxonomy developed in Phase 1.

- Decomposing the hazards in the proposed UAS taxonomy into a framework of causal factors.

- For notional UAS scenarios, creating influence diagrams to facilitate eventual risk modeling.

This Phase 2 report describes in detail the integrated approach that was used to enhance the development of the HCAS taxonomy. This approach was based on system safety/risk analysis principles and decision analytic methods for hazard categorization/prioritization blended with inductive reasoning from hypothesized UAS scenarios to establish a system-level framework to eventually assess the risks of emergent aeronautical operations into the NAS. The HCAS or "cube" model includes the four primary hazard sources or "cubes" of Airmen, Operations, UAS, and Environment and their corresponding subelements.

The major research conclusions from the Rutgers Phase 2 study include the following:

- The refined HCAS taxonomy is an effective way to capture the four major system-level sources of hazards and ensure that the interdependencies among hazards are modeled.

- The HCAS is essentially independent of any particular scenario set and could be easily changed to any UAS data set, preserving the integrity of the hazard identification process.

- The HCAS taxonomy was reviewed by FAA William J. Hughes Technical Center analysts and industry subject matter experts and was presented at the *26th International Congress of the Aeronautical Sciences* in Alaska.

The primary research recommendations of the Rutgers Phase 2 study are to

- continue to build and further evaluate the UAS hazard taxonomy refined in Phase 2.

- construct a reference manual for the HCAS.

- strengthen the sensitivity analyses of the risk modeling phase, explore formal methods and algorithms for uncertainty analysis.

- construct a reference manual for the HCAS causal factors.

- further develop the UAS influence diagrams for selected UAS hazards.

- map existing mitigations to the UAS hazards/causal factors for a gap analysis.

- critique the proposed system-level influence modeling approach for relevancy and accuracy using actual test cases from industry and government groups to create prototypical-applicant processes.

- investigate the use of text mining tools to review possible outcomes of UAS integration into the NAS to reinforce the HCAS taxonomy elements and to possibly develop new elements.

- construct a prototype UAS safety database consistent with the refined UAS hazard taxonomy.

1. INTRODUCTION.

1.1 PURPOSE.

This study was performed in response to a research need communicated by Dr. Xiaogong Lee from the Federal Aviation Administration (FAA) Research and Development Office, Airport and Aircraft Safety Group. The initial guidance from Dr. Lee advised the Rutgers University (hereinafter referred to as Rutgers) research team, led by Principal Investigator, Dr. James T. Luxhøj, to perform a system-level assessment that characterized Unmanned Aircraft System (UAS) hazards and risks. It was particularly emphasized that this study should remain focused at the system level and not become operational in perspective. The research goal was to develop a generalized taxonomy of system-level UAS hazards that would have broad applicability across FAA part types. The intent was that the Phase 1 study would lead to general research recommendations and guidelines in high-level support of the FAA UAS Program Office. Thus, the Rutgers Phase 1 objectives were

- the identification, categorization, and evaluation of potential system-level hazards of UAS operations in the NAS.
- the coordination of hazard identification and subsequent analysis with FAA offices.
- the focus on civil (i.e., public) applications.

It should be emphasized that the resulting hazard taxonomy developed by the Rutgers Phase 1 research approach was based on the FAA regulatory perspective (i.e., Title 14 Code of Federal Regulations (CFR) chapters on Aircraft, Airmen, Certification/Airworthiness, Flight Operations, etc.). Such an approach uniquely distinguishes the developed taxonomy from all other UAS hazard analyses being performed by the Department of Defense (DoD), the RTCA Special Committee (SC) 203, etc.

This Phase 2 report describes the continued development of the system-level hazard taxonomy for UAS.

The three primary Rutgers Phase 2 research tasks involved

- building upon and further evaluating the UAS hazard taxonomy developed in Phase 1.
- decomposing the hazards in the proposed UAS taxonomy into a framework of causal factors.
- for notional UAS scenarios, creating influence diagrams to facilitate eventual risk modeling.

1.2 BACKGROUND.

The National Airspace System (NAS) in the United States is increasingly becoming a complex array of commercial and general aviation aircraft, unmanned aircraft systems, reusable launch vehicles, rotorcraft, airports, air traffic control, weather services, and maintenance operations, among others. This increased system complexity necessitates the application of systematic safety risk analysis methods to understand and eliminate (where possible), reduce, and mitigate risk factors. The FAA mission is to ensure the safe and efficient use of the navigable airspace in the United States; to regulate air commerce in such a manner as to best promote its development and safety; to promote a common system of air traffic and navigation for both military and civil aircraft; and to promote, encourage, and develop civil aeronautics. As such, a safety risk analysis of UAS integration into the NAS is highly aligned with the FAA mission statement.

A UAS is defined as being comprised of the

> "…manufactured integrated system including the architecture, operations, procedures, and functions to support the Unmanned Aerial Vehicle (UAV), ground control, and command, communication, and control (C3) data links. The vehicle is comprised of airframe, mechanical, propulsion, and avionic subsystems. Ground control includes the pilot interface and support efforts: flight planning, maintenance, preparation and procedures. The C3 interface includes the data link between the vehicle or other vehicles and ground control. There is also communications between the vehicle and satellites concerning Global Positioning System (GPS)." (Allocco, 2006, p. 10).

UAS applications are quite diverse. Applications include remote sensing, such as power line or pipeline monitoring, mapping, meteorology, geology, atmospheric monitoring, and agriculture. A UAS may also be used in security operations for threat detection, tracking, security monitoring, and possible mitigation (i.e., weapon disposal). Public safety applications include accessing hazardous areas, hazardous sites, firefighting, enforcement, search and rescue, contingency, disaster response, communication relay, visual recording, and evaluation and mitigation delivery. Commercial applications include weather monitoring and sensing, cargo transport, advertising, and broadcasting. Military applications involve remote weapon deployment, battlefield management, monitoring, target identification, detection, and communication. Research and development applications include high-altitude research, human factors research, flight endurance, fuel consumption, atmospheric monitoring and measurement, advanced flight dynamics, radiation monitoring, and materials science testing (Allocco, 2006, p. 12).

Sponsored by the National Aeronautics and Space Administration (NASA) and the industry, with participation by the FAA and the DoD, Access 5 was a national project to introduce high-altitude long endurance (HALE) UAS for routine flights in the NAS. The stated goal of Access 5 was to foster the development of a robust civil and commercial market for HALE UAS. Thus, there is a national effort to promote the routine use of UAS applications in the NAS, thereby strengthening the need for a systematic approach to modeling the risks associated with the added complexity to the NAS. However, routine UAS operations in the NAS pose potentially new or different hazards and risks. The research need is to perform system safety risk analyses that characterize UAS hazards and risks with specific recommendations for safe operations in the NAS with guidelines for the eventual certification process.

The Rutgers Phase 1 and Phase 2 safety risk analysis study focused on civil (i.e., public) applications of UAS integration into the NAS.

As presented in figure 1, the Rutgers research team followed a systematic, multistep approach in the performance of this UAS study. To initiate the research, the Rutgers team reviewed a number of UAS-related documents. (Representative documents are listed in section 1.3.) In particular, the RTCA SC-203, Guidance Material and Considerations for Unmanned Aircraft Systems (DO-304), Detect, Sense and Avoid Safety Metrics; and Guidelines for Approval of the Provision and Use of Air Traffic Services Supported by Data Communications (DO-264) were reviewed. The suggested RTCA SC-203 tripod model of NAS segments was studied and was found to have an operational perspective that, while important, did not meet the Rutgers research objective of developing a system-level framework for characterizing UAS hazards. In addition, the Rutgers research team was requested to position its research with respect to the DO-264 methodology, which is shown in figure 2. Fundamentally, the Rutgers research team followed the Safety Risk Management (SRM) process, as depicted in figure 3, that is consistent with guidelines included in Bahr (1997) as well as the FAA System Safety Handbook (2007). Note that the RTCA SC-203 tripod model (see section 1.3) differs from the FAA SRM process.

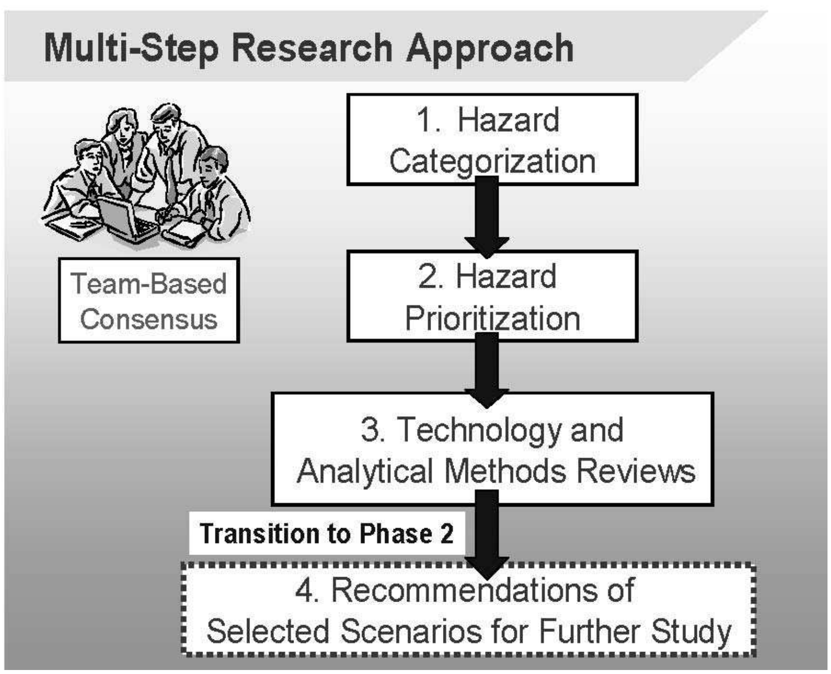


Figure 1. Rutgers Phase 1 and Phase 2 Multistep Research Approach

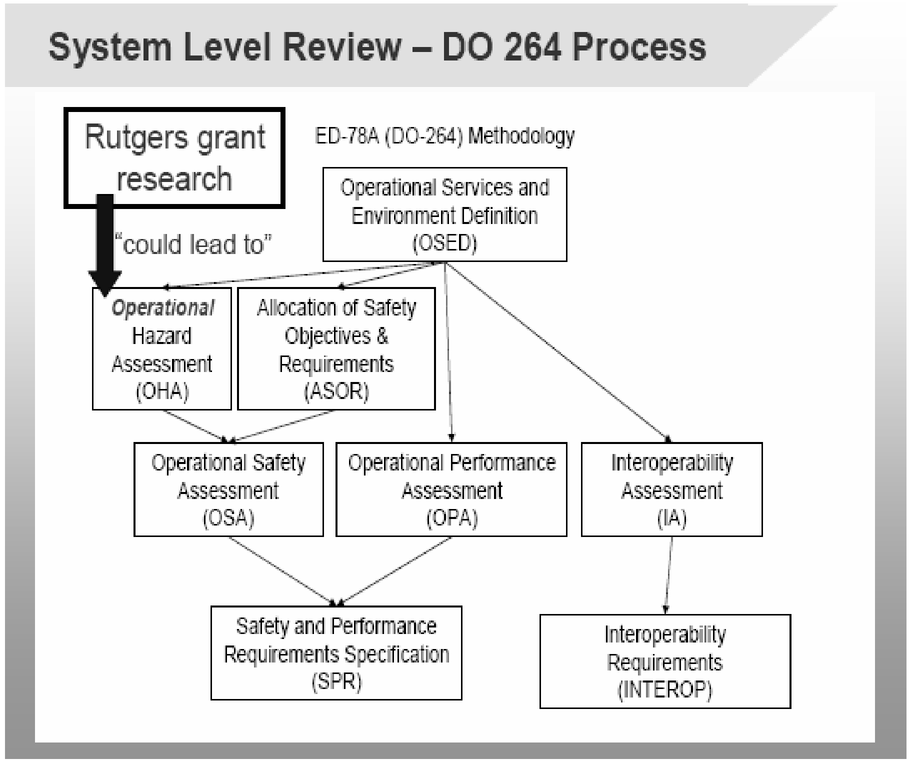


Figure 2. Positioning of Rutgers Phase 1 and Phase 2 Research With the DO-264 Process

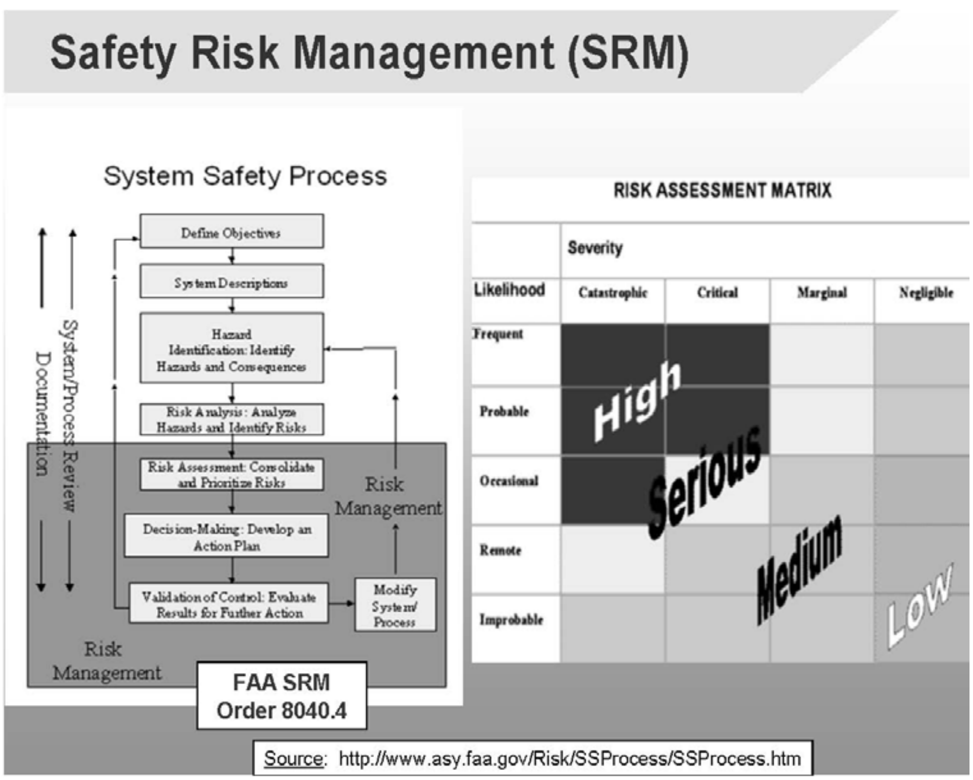


Figure 3. The SRM Process

Thus, the multistep research approach manifested into a more detailed, "bottom-up" systematic study, as shown in figure 4. The identification of UAS system-level hazards was primarily based upon a review of 208 hypothesized UAS scenarios (see Allocco, 2006). This led to the development of a new taxonomy unique to the UAS domain. Based on this taxonomy, an implicit prioritization of UAS hazards was accomplished and is further described in the Rutgers Phase 1 report. As indicated in figure 4, the Phase 1 research hazard analysis formed the basis for subsequent risk analysis in the Phase 2 study. Additionally, the UAS system-safety Phase 1 and Phase 2 study contributes, to some extent, to the overall development of a component of the higher-order, much larger-scale Safety Management System (SMS) research that is underway.

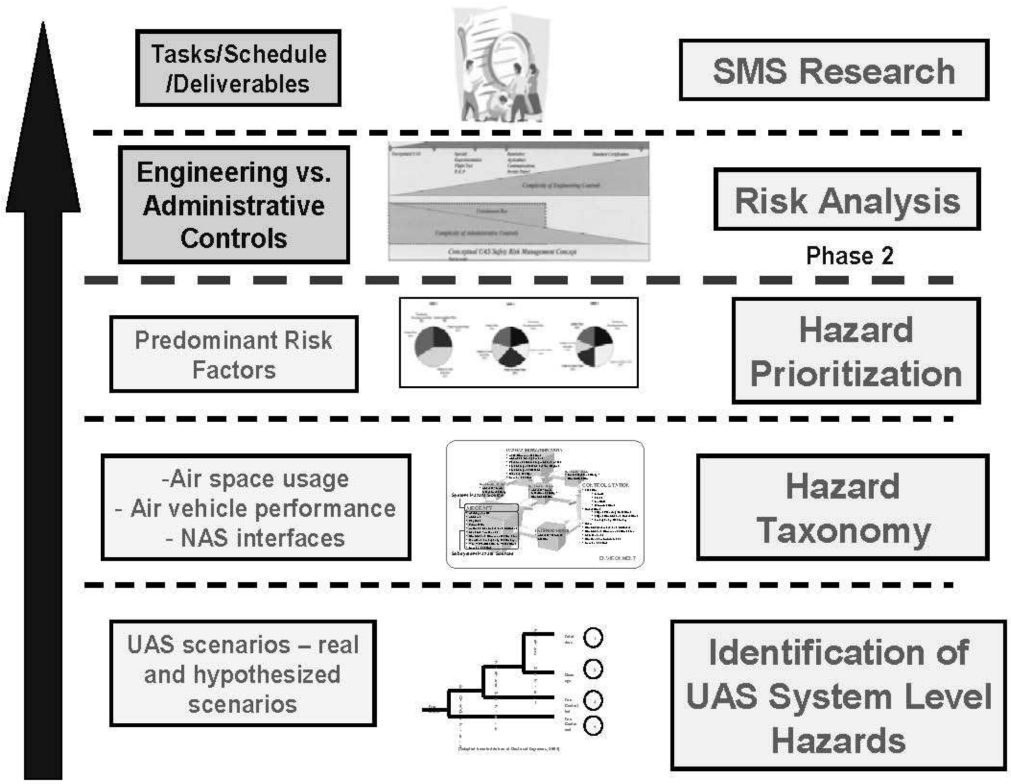


Figure 4. Phase 1 and Phase 2 Bottom-Up Approach

1.3 REPRESENTATIVE SOURCE MATERIAL.

The following documents relate directly to the issues addressed herein and were used as background material.

- RTCA SC-203, Guidance Material and Considerations for Unmanned Aircraft Systems
- RTCA DO-264, Guidelines for Approval of the Provision and Use of Air Traffic Services Supported by Data Communications
- RTCA SC-203, Detect, Sense and Avoid Safety Metrics

- Advisory Circular (AC) 91-57 (Revised), Model UAV Operating Standards

- M. Allocco, UAS System-Level Preliminary Hazard Analysis report (2006)

- Ronald E. Wiebel and R. John Hansman (2005), "Safety Considerations for Operation of Unmanned Aerial Vehicles in the National Airspace System," Report No. ICAT-2005-1, MIT, International Center for Air Transportation, Cambridge, Massachusetts, March.

- K.J. Hayhurst, J.M. Maddalon, R.S. Miner, M.P. DeEalt, and G.F. McCormick (2006), "Unmanned Aircraft Hazards and Their Implications for Regulation" *25th Digital Avionics Systems Conference*, October 15, pp. 5B1-1 to 5B1-12.

- K.W. Williams (2004) "A Summary of Unmanned Aircraft Accident/Incident Data: Human Factors Implications," Report DOT/FAA/AM-94/24, FAA Civil Aerospace Medical Institute, Oklahoma City, OK, December.

- R. Anoll (2006), "Safety Checklist," FAA, Unmanned Aircraft System (UAS), Program office, Washington, DC, December.

In addition to these documents, other documents and research papers that were reviewed are listed in section 6.

2. DISCUSSION.

The Rutgers Phase 1 final report describes the methodology used to develop the system-level taxonomy of UAS hazards. This section reports on the enhancements made to the taxonomy during the Phase 2 research.

2.1 METHODOLOGY.

Before proceeding with describing the methodology used in UAS hazard categorization, it is important to establish some basic terminology. For purposes of the Rutgers Phase 1 and Phase 2 research, the following definition of a hazard is used:

> Hazard: A hazard is a state or set of conditions of a system that, together with other conditions in the environment of the system, may lead to an unsafe event. (Adapted from Leveson, 1995)

Also, it is important to understand the relationship between hazard, risk, and mishap, as depicted in figure 5. Ericson (2005) describes a hazard triangle, as shown in figure 5, that includes the hazardous element, initiating mechanism, and the target/threat. This notion of a hazard triangle influenced the Rutgers research team to think of hazard sources. It should be noted that figure 5 is a simplification and that mishap causation is not as linear as the figure suggests, as there most likely will be multiple hazards acting in a nonlinear causative fashion. A mishap outcome that has occurred may be addressed by using the model to show the events that led to it. The fact that a hazard (including hazardous elements, initiating mechanisms, and targets/threats) can be identified and the associated risk can be described, lends to circumstances that rarely result in a mishap occurrence. The UAS hazard identification step involved identifying the components of the UAS and its NAS integration, treating the components as potential sources of system-level hazards, and decomposing the system further into its subcomponents.

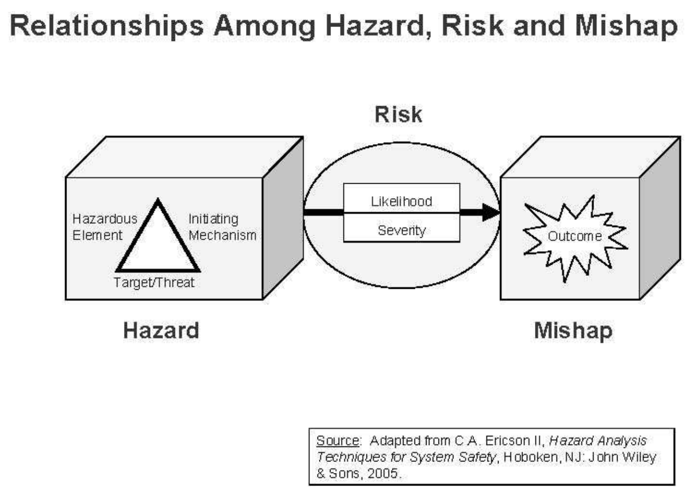


Figure 5. Relationship Among Hazard, Risk, and Mishap

2.2 HAZARD CLASSIFICATION AND ANALSYIS SYSTEM.

The system-level hazard taxonomy developed for unmanned aircraft in this research is termed the Hazard Classification and Analysis System (HCAS). Brief descriptions of both the original and revised versions are provided below.

2.2.1 Phase 1 HCAS Final Version.

The final Phase 1 version of the HCAS is presented in the Rutgers Phase 1 technical report (Luxhøj, 2009), as well as Oztekin, et al. (2007), and is shown in figure 6. The idea was to provide a structured framework to identify and classify or to categorize both system and subsystem hazard sources for UAS operations. The final Phase 1 version of HCAS identified the four system-level hazard sources of Airmen, Operations and NAS Interconnectivity, Unmanned Aircraft Systems, and Environment. It was verified from an analysis of 208 hypothesized UAS scenarios as well as some real UAS mishaps. The details are provided in Luxhøj (2009). Once the hazards for a given scenario set are categorized, an implicit prioritization of the hazards may be obtained by recomputing frequency counts as percentages, as shown in figure 7. Such an approach provides a possible structured means to systematically weight the hazards.

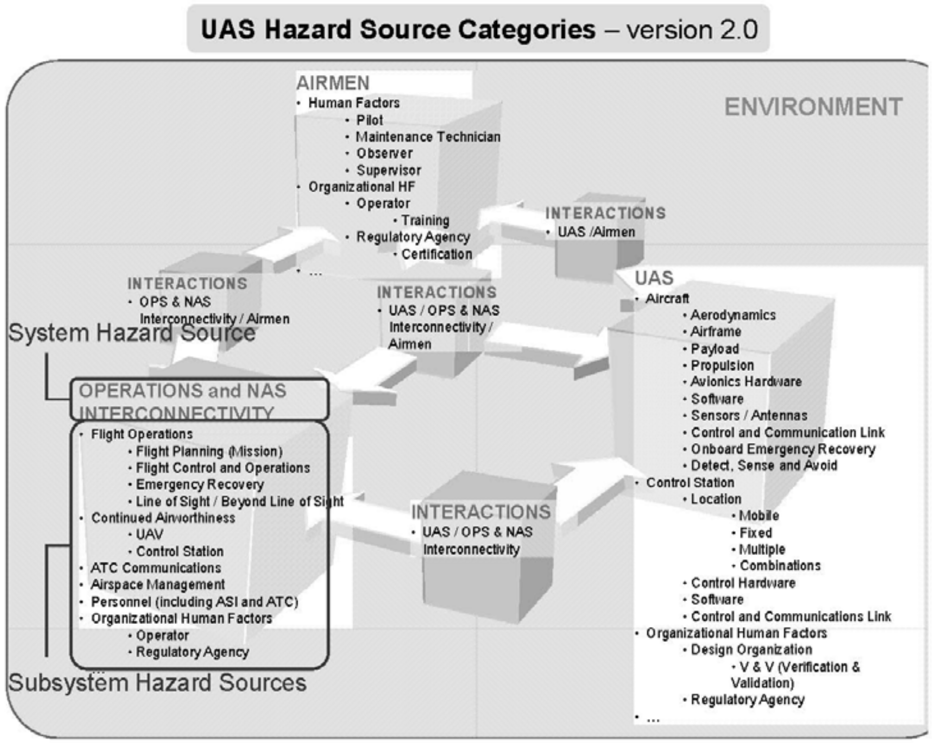


Figure 6. Final Phase 1 HCAS Taxonomy

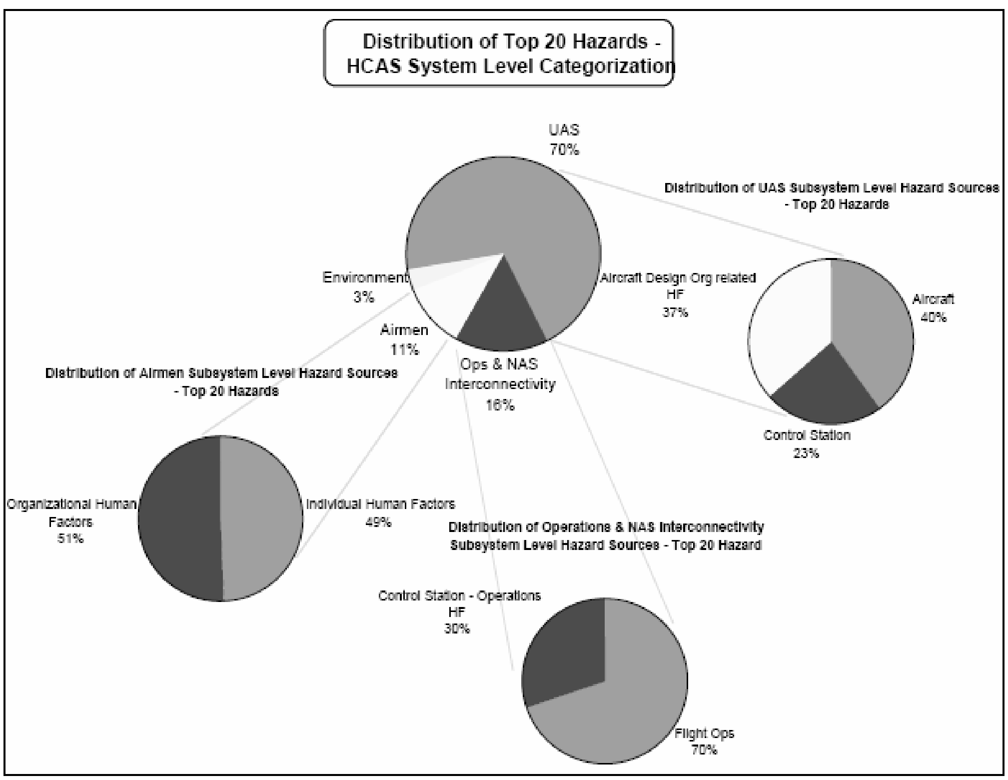
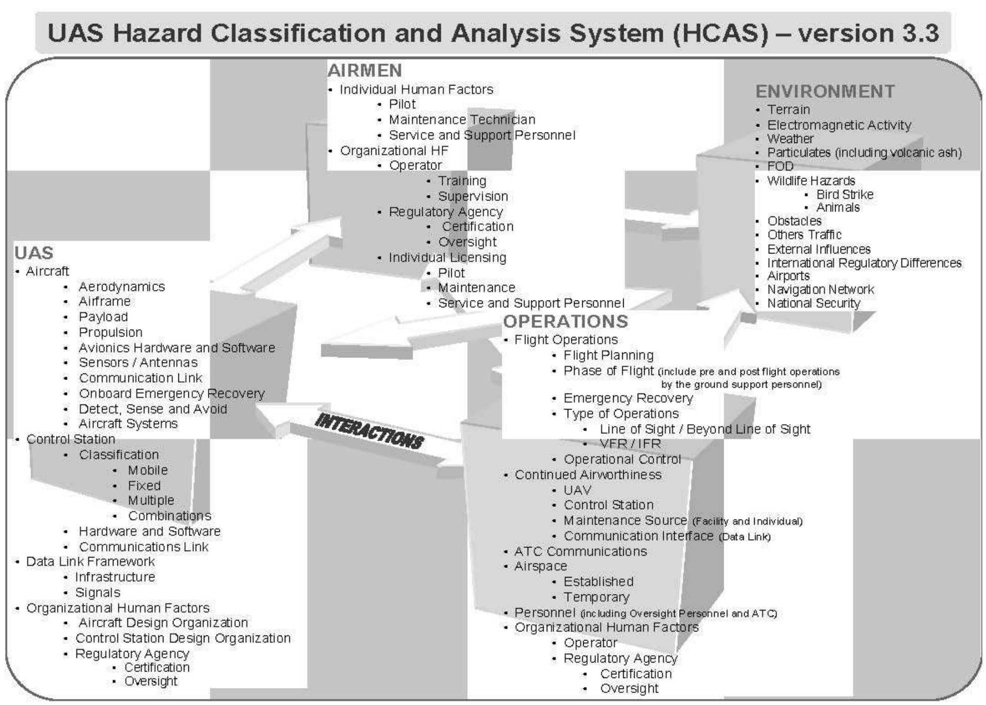


Figure 7. Distribution of Hazards for a Given HCAS Scenario Set

2.2.2 Phase 2 HCAS Final Version.

A review and critique of the original HCAS version by industry subject matter experts indicated a need to have the taxonomy become more aligned with FAA regulations, in particular, the 14 CFR chapters on Aircraft, Airmen, Certification/Airworthiness, Flight Operations, etc., as well as the Unmanned Aircraft System Operations in the U.S. National Airspace System—Interim Operational Approval Guidance (2005). Such an approach uniquely distinguishes the HCAS taxonomy from all other UAS hazard analyses being performed by the DoD, the RTCA SC-203, etc. The Rutgers Phase 1 and Phase 2 research goal was to develop a generalized taxonomy of system-level UAS hazards that would have broad applicability across FAA part types.

The revised Phase 2 version of the HCAS taxonomy (version 3.3) is shown in figure 8. A numbered outline form of the HCAS taxonomy (version 3.3) is provided in appendix A. Some of the significant changes include embedding the Control Station system source under the original Aircraft system source, renamed UAS. A fourth cube, termed Environment, was added to the revised version and numerous subsystem hazard sources added. A detailed review of the HCAS taxonomy by industry subject matter experts improved the taxonomy by making it more closely aligned with the existing 14 CFR chapters. The expertise of the subject matter experts proved quite valuable in providing additional detail for the Environment hazard system source.



FOD = Foreign object damage
VFR/IFR = Visual Flight Rules/Instrument Flight Rules
ATC = Air traffic control

Figure 8. Phase 2 HCAS Taxonomy

3. THE HCAS CAUSAL FACTORS.

This section outlines the approach used to translate the HCAS taxonomy into causal factors that may be used to graphically represent notional UAS outcomes.

3.1 GRAPHICAL ASSOCIATIVE MODELING APPROACH.

Since civil UAS operations are relatively new and emergent, databases of mishaps are not readily available. In the Rutgers Phase 2 research, the proposed UAS hazard taxonomy depicted in figure 8 was transformed into influence diagrams, as shown in figure 9, for hypothetical or notional UAS outcome scenarios. These influence diagrams are intended to display the causal factors associated with the hazards and their interactions. A high-level, notional framework depicting the interactions among the HCAS system sources is shown in figure 10. The HCAS system sources may then be decomposed into their subsystem hazard sources, as shown in figure 11. The use of modifiers placed on the HCAS taxonomy elements, such as “inappropriate” and “inadequate,” can be used to create the causal factor diagram as shown for an exemplary scenario.

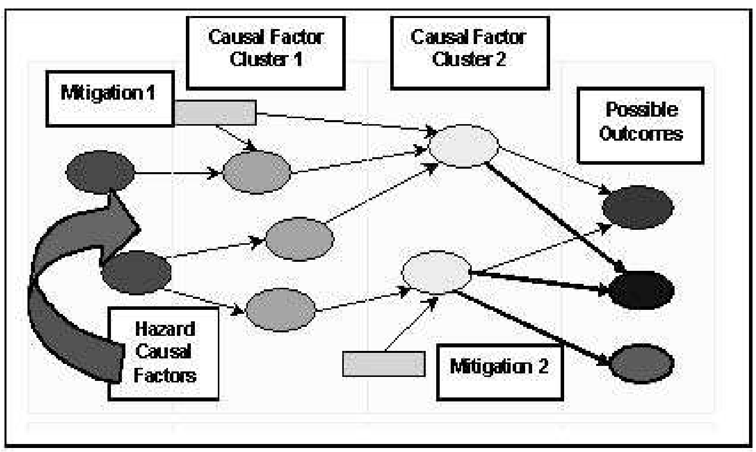


Figure 9. Conceptual UAS Hazard Influence Diagram

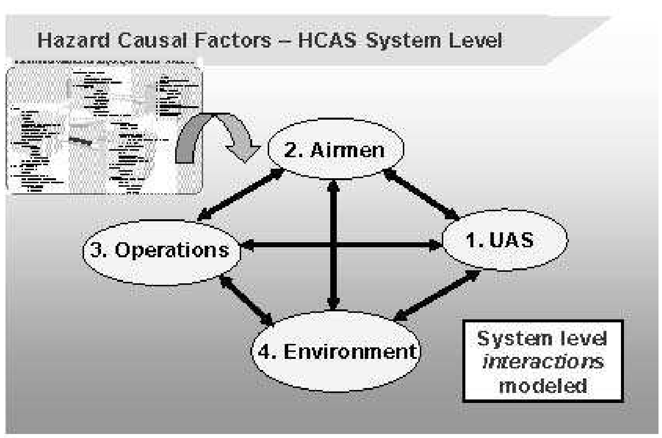


Figure 10. Notional HCAS Causal Factor Framework

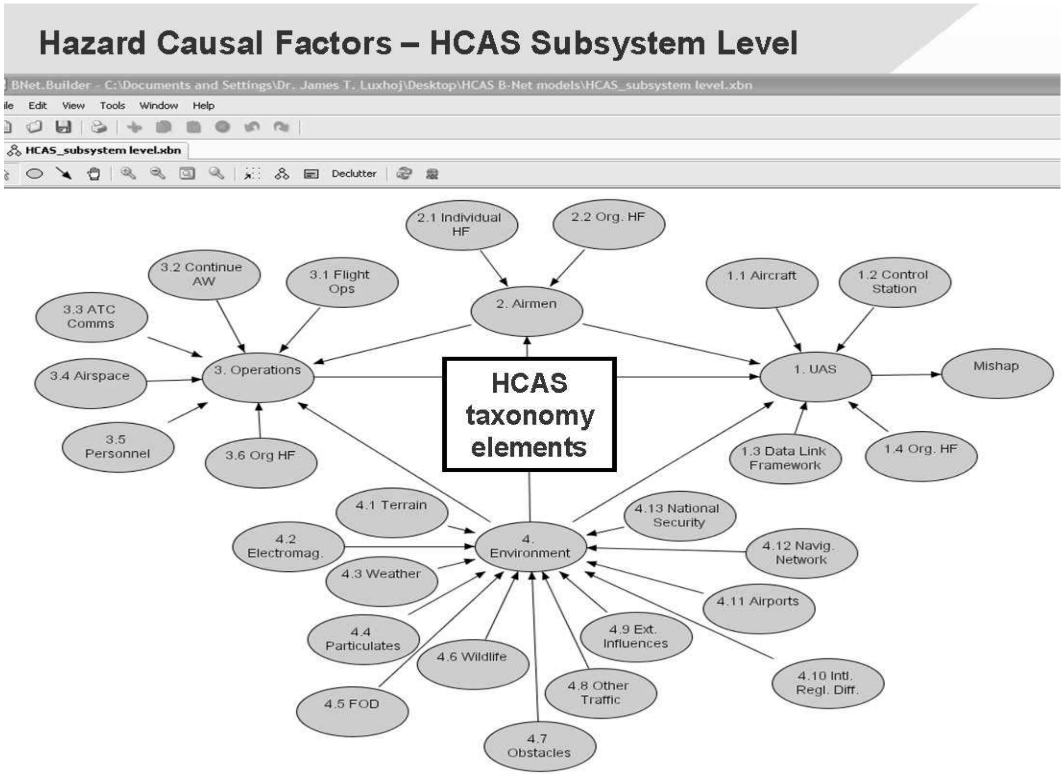


Figure 11. Numbered HCAS Taxonomy Elements

For example, suppose that a hypothesized UAS outcome scenario involves a UAS collision with terrain and loss of the vehicle. As figure 12 shows, an incident analysis of the hypothesized scenario reveals the existence of strong wind conditions, thus, the environment HCAS, numbered element 4.2, is added. An explanation of the numbered elements is provided in appendix A. An analysis of the scenario further reveals that in switching control from one ground control station to the other due to a lock up, the UAS data links were lost. Further analysis of upstream causal factors indicated that due to deficient pilot training, the UAS fuel valve was inadvertently shut off, leading to a loss of engine power. Additional incident analysis noted that checklist procedures were not followed in switching control from one ground control station to the other and some concerns about maintenance procedures may have contributed to the lock up. Figure 12 graphically portrays how an influence diagram could be constructed using the corresponding HCAS taxonomy elements to depict possible causation. This type of causal diagramming approach is presented in Luxhøj (2003 and 2005a and 2005b) and in Ale, et al. (2005).

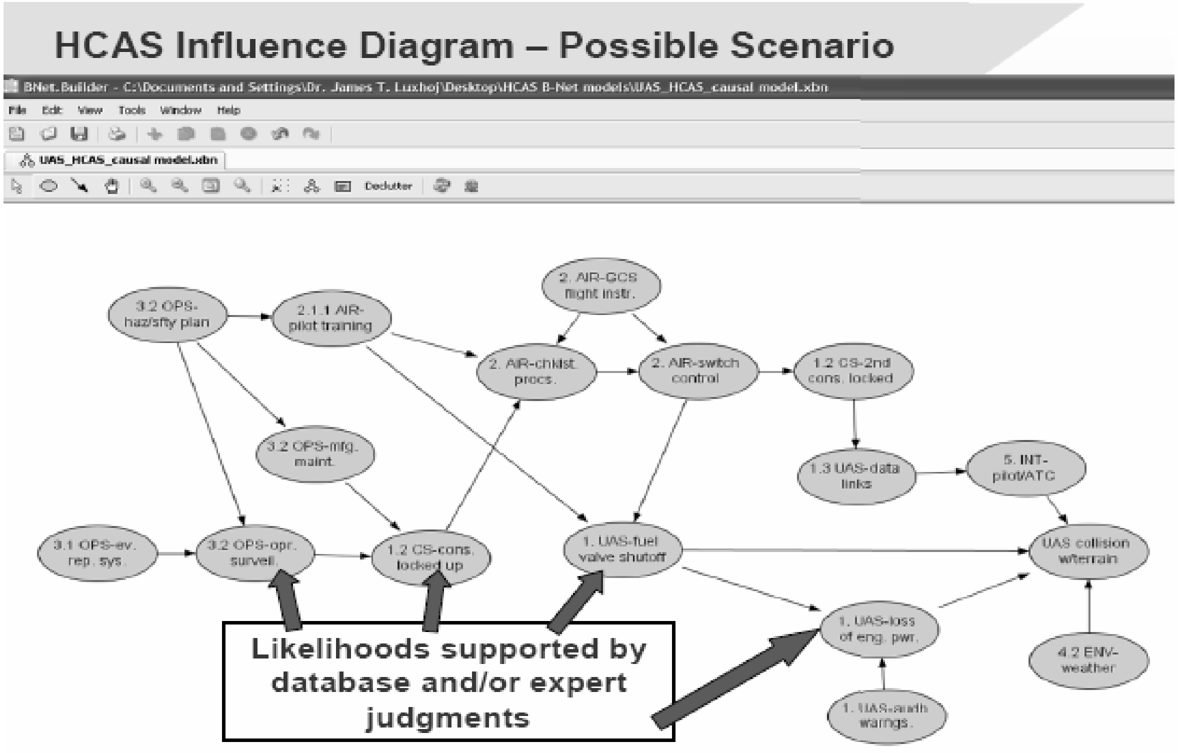


Figure 12. Notional UAS Outcome Scenario Characterized Using an Influence Diagram

Uncertainties will exist in likelihood and severity assessments and the impact of these uncertainties on UAS scenario risk evaluations need to be systematically explored. Future Rutgers research tasks will lead to the development of new analytical methods and corresponding prototype software tools for assessing the uncertainties associated with the construction of the influence diagrams of hazard causal factors for selected UAS scenarios. These tasks will lead to more robust and defensible risk modeling and facilitate exploration of the sensitivities and impacts of both single- and multifactor perturbations on the risk values.

3.2 HYBRID RISK MODELING METHODOLOGY.

The Rutgers Phase 2 research also explored using the influence diagramming methodology for risk modeling of mixed random variables used in the analysis of a possible outcome of UAS integration into the NAS.

Figure 13(a) shows a cluster of continuous and discrete variables. The variables Airspeed (measured in knots) and Loss of Engine Power (represented by a percentage) are continuous entities. The variables Data Link and Airspeed Indicator, represented by mutually exclusive states such as "up or down" and "operational" or "not operational," respectively, are discrete in their nature. This section introduces the concept of an inferencing methodology for hybrid complex systems where the continuous variables are transformed into Fuzzy discrete variables, whose states are represented by Fuzzy Sets. An example of such a transformation is illustrated in figure 13(b). Next, this hybrid inferencing idea, which incorporates Fuzzy Set theory and Bayesian Network (BN), is outlined.

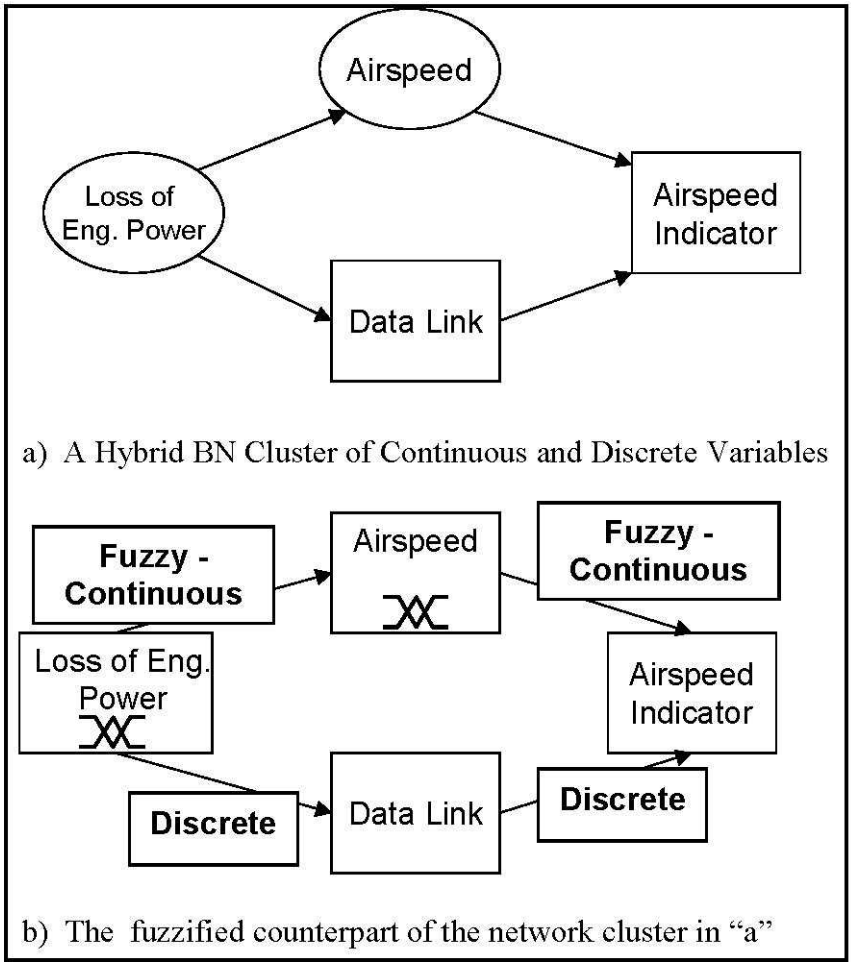


Figure 13. A Sample Cluster of a Hybrid Bayesian Network and its Fuzzified Counterpart

Taxonomy development that is specific to a contextual domain, such as UAS, dramatically increases the analyst's understanding of the system to be modeled. However, without the appropriate theoretical tools supporting the proper modeling approach, this contextual knowledge in the form of the taxonomy does not guarantee a realistic representation of the problem domain. This section introduces the conceptual basis of a hybrid risk modeling approach that best suits the rather unique features of the UAS contextual domain.

Modeling complex systems is a very broad area of research where, more often than not, a multidisciplinary approach is needed to achieve a meaningful representation of the subject matter. The analytical methods employed along the process remain as much art as science, especially if the subject matter is safety and risk analysis of a complex system.

One aspect that particularly increases the complexity of modeling many real-world systems is the fact that they naturally include both discrete and continuous variables. It can be further argued that because of the hybrid nature of real-world systems, many of them can best be modeled as hybrid stochastic processes, i.e., stochastic processes that contain both discrete and continuous variables. Due to their hybrid nature, they can be used in a wide variety of problem domains, such as fault diagnostics of complex machinery, pattern recognition, and risk analysis of complex systems. Although the problem domains are different, the task asked of the model is to perform probabilistic inference, such as to determine the probability of system failure given the malfunction of certain components of the machinery, to calculate the probability that a certain word is pronounced given the readings by the microphone, and to determine the likelihood that a mishap occurs given a set of precursors.

Within this context, to perform these tasks, an intelligent agent should be able to perform reasoning under uncertainty. As the most complex of intelligent agents, humans certainly can perform a complex reasoning task given little or no information regarding the situation they are in. The ultimate goal of a designer of an intelligent system is to mimic the human reasoning process under uncertainty and enhance it with the help of the infallible memory and unrivaled computational skills of computers.

The method of choice by the engineering and academic communities to deal with uncertainty in real-world applications is probability theory. Probability theory is a well-established area of study with an extensive historical background of successfully understanding randomness in natural phenomena. However, its application as a tool to model uncertainty in complex real-world systems is quite recent. In particular, its use as a modeling tool started with BN in the late 1980s following the introduction of the concept by Pearl (1988). To be concise, BNs are directed acyclic graphs (DAG) that have the analogous form of an influence diagram. However, in a DAG, a probability distribution is attached to each element in the graphical structure. The DAG of a BN is composed of nodes representing the variables in the domain of interest and directed links representing the conditional relations among the variables. Furthermore, each node is denoted by a conditional probability distribution (CPD) imposed by its parentage.

As popular tools for modeling uncertainty, models based on BNs are used in a variety of complex problem domains, such as troubleshooting for computer operating systems, junk e-mail filtering, medical diagnosis, and safety risk assessment in aviation. There are two aspects of using BNs to model uncertainty in complex systems: (1) the representation of the problem domain and (2) the inferencing within the resulting graphical structure. As expected, the majority of the research on BNs focused on solving the inferencing problem. The research on the inferencing aspect can be further divided into two subcategories: inferencing in discrete-only BNs and inferencing for hybrid BNs, which include both discrete and continuous variables.

The problem of inferencing in discrete BNs is fairly well understood and an overwhelming majority of existing studies either are based solely or focus mainly on discrete BNs. After the introduction of BNs by Pearl (1988), Lauritzen and Spiegelhalter (1988) proposed an exact inferencing algorithm for discrete BNs. By exact inferencing, it is meant that the inferencing algorithm results in exact answers to the probabilistic query, given the graphical structure and CPDs of the BN. By now, there are a few exact inferencing algorithms for discrete BNs; and furthermore, there is a good understanding of the computational complexity of exact inferencing and how it relates to the graphical structure of the BN. Particularly, the existing exact inferencing algorithms can be very efficient for small, discrete BNs.

Notwithstanding its accumulated knowledge on exact inferencing and wide acceptance on various problem domains, discrete BNs are not always adequate, since many real-world systems are not entirely composed of discrete variables. For example, consider the complex problem of assessing the safety risk associated with operating UAS in the airspace over a populated area. A BN model of the system may include flight hours, altitude, speed, and fuel onboard as model variables, none of which could easily be represented by discretization without sacrificing some of the representative power of the network. However, when employing BNs, crude discretization of continuous variables is commonly used to perform exact inferencing on the system model.

The need for discretization of continuous variables especially in BNs where the lack of hard data forces the analysts to resort to expert judgment to quantify the model is understood. It is quite hard, if not impossible, to generate continuous conditional distributions when the distributions are required to be constructed by subject matter expert input only. However, using simple discretization of a problem domain to be able to perform exact inferencing is equivalent to approximate reasoning and, in most cases, leads to unreliable results. Consider the variable airspeed, which is inherently a continuous entity. Now, for the sake of computational simplicity and exact inferencing, the modeler may choose to treat it as a discrete variable with three mutually exclusive states: slow, medium, and fast. Further assume that the crisp boundary between states slow and medium is defined by "less than or equal to" 80 knots and "greater than" 80 knots and the sensor readings on the UAS indicate that it is cruising at 85 knots. According to the predetermined, mutually exclusive, three-state discretization scheme, this is a medium airspeed and the exact inferencing should be performed accordingly. However, one could argue that even though the states slow and medium are different, the actual observation about the airspeed is so close to the crisp boundary separating them that any inferencing using this discretization scheme is fundamentally flawed to produce meaningful results.

3.3 HYBRID BAYESIAN NETWORKS.

Hybrid Bayesian Networks (HBN), which include both continuous and discrete variables, are a generalization on discrete-only BNs. HBNs are inherently more suitable for modeling complex systems (such as visual target tracking, as in "see and avoid" type of applications where the variables defining location of the target and its speed are inherently continuous, and speech recognition, where the bits and pieces of processed audio signals are often continuous).

However, HBNs, as the generalization of discrete BNs, have their own shortcomings that arise when attempts are made to perform exact inferencing on them. Exact inferencing on general HBNs imposes restrictions on the network structure of the HBN. The state-of-the-art exact inferencing algorithm for HBNs, the Lauritzen (1992) algorithm, requires that the network satisfies the constraint that no continuous variables have discrete children. As expected, this restriction places a considerable burden on the generalization claim of the HBNs. Here, an approach is proposed that, using Fuzzy Set theory, builds on the Lauritzen algorithm to generate a hybrid exact inferencing algorithm for general HBNs.

Fuzzy Set theory, introduced by Zadeh (1965), proposes a framework to deal with a poorly defined concept in a coherent and structured way. Examples of poorly defined concepts suitable for the application of Fuzzy logic are semantic variables, such as heavy workload, inadequate training, fast, slow, tall, and short. Within the context of the current research, fuzzy sets present two important features worthwhile for further exploration:

- Fuzzy sets provide a complete set of tools to partition continuous domains into overlapping membership regions, which result in a much more realistic discretization of the continuous domain in question.

- Uncertainty regarding any empirical observation can be represented as a fuzzy measure.

Previously, it was stated that BNs are tools to model uncertainty in the form of a probability distribution imposed by a DAG representing the domain of interest. Hence, BNs only address the uncertainty in the form of randomness about a problem domain. However, uncertainty in a typical real-world application has three dimensions: vagueness, ambiguity, and randomness (Ross, 1995). BNs, being solidly anchored to probability theory, only address one of these dimensions, namely randomness. For instance, consider that there is ambiguity regarding the observed evidence associated with some variable in a given BN.

It is believed that Fuzzy Set theory offers a comprehensive structure to introduce the ambiguity dimension of uncertainty to the existing framework of classical BNs and within this context, the development of a complete formalism that combines Fuzzy Sets and BNs for reasoning about complex problems, such as modeling the safety risk in UAS applications, is currently being researched.

4. CONCLUSIONS.

In this Phase 2 report, a system-level structured process for identifying, categorizing, and modeling hazards for unmanned aircraft operations is presented. Termed the Hazard Classification and Analysis System (HCAS), the taxonomy comprises a core of four cubes representing system and subsystem hazard sources. Hazards are not causal factors, so a notional method is also presented that relies upon influence diagrams to depict the interactions of causal factors in unmanned aircraft mishaps. These influence diagrams may then be used to facilitate subsequent risk analysis for a complex system. This report outlines the concept of a hybrid fuzzy-Bayesian approach that is being developed to handle both discrete and continuous variables when randomness and vagueness may co-exist in the safety risk analysis. Future research involves more mathematical development of the hybrid methodology and applications to the unmanned aircraft contextual domain.

4.1 PHASE 2 CONCLUSIONS.

As a result of the completion of the Phase 1 and Phase 2 Unmanned Aircraft System (UAS) safety risk research project, the following conclusions are surmised:

- It is possible to develop a system-level hazard taxonomy for UAS integration into the National Airspace System. The refined Phase 2 HCAS taxonomy is novel and presents a robust and resilient way to not only capture the four major system-level sources of hazards (i.e., Airmen, Operations, UAS, and Environment), but also to serve as a tool for ensuring that the interdependencies among hazards are modeled. A regulatory perspective based on the Federal Aviation Administration (FAA) Title 14 Code of Federal Regulations (CFR) chapters provided a strong foundation for building such a hazard classification and analysis framework for unmanned aircraft.

- While the HCAS was verified using a certain scenario set, it is concluded that the HCAS is essentially independent of any particular scenario set and could be easily updated given access to any UAS data set using the systematic process mapping strategy outlined in this report. de Jong, et al. (2007), present an approach to pushing the boundary between imaginable and unimaginable hazards that keeps the performance of the hazard identification process separate from the hazard analysis and hazard mitigation processes. A future research task could involve the use of the de Jong, et al. method to see what impact, if any, the use of their suggested methods would have on UAS hazard identification.

- Additional vetting of the HCAS taxonomy occurred during Phase 2 by representatives of the FAA William J. Hughes Technical Center analysts, by industry subject matter experts, and by a presentation at the 26th International Congress of the Aeronautical Sciences held in Alaska. It is suggested that additional industry reviews of the HCAS taxonomy be performed. This will ensure that a robust, resilient system framework has indeed been developed for UAS system-level hazard identification and prioritization.

4.2 PHASE 2 RESEARCH RECOMMENDATIONS.

This longer-term UAS safety risk research involves the modeling of risks and the eventual evaluation of possible mitigations. In particular, the proposed research plan suggests building around the Rutgers research team's Phase 1 and Phase 2 research accomplishments. It is envisioned that the following tasks will form a multiyear, multitask research program. The proposed research tasks are briefly described below:

- Build upon and further evaluate the UAS hazard taxonomy developed in Phase 1 and Phase 2—In Phase 1 and Phase 2, the Rutgers research team developed and refined a proposed UAS hazard taxonomy. However, as in any quality research development, additional suggestions from the UAS community will most likely develop after further reflection and critique. For example, operational dimensions, including phase of flight, airspace category, and UAS type, need to be explored to assess what, if any, additional hazards may be contributed by these dimensions to the proposed taxonomy. Such an evaluation will ensure that a robust, system-level taxonomy results. In addition, the proposed taxonomy needs to be further compared with a regulatory perspective to assess its correspondence with this viewpoint. Such a correspondence analysis may lead to some renaming of the hazards and, to some extent, some minor restructuring of the taxonomy. Additional discussion of UAS hazards and their implications for regulation is presented in Hayhurst, et al. (2006) and Mercaldi, et al. (2006).

- Construct a reference manual for the HCAS—In Phase 1 and Phase 2, the Rutgers research team developed the proposed UAS hazard taxonomy. This taxonomy HCAS would benefit the user community by having a fully documented reference manual. The output from this task will be an HCAS reference manual in hyperlinked format that fully defines each of the system and subsystem hazard sources and provides examples of such from the UAS contextual domain.

- Decompose the hazards in the proposed UAS taxonomy into a framework of causal factors—Hazards are not causal factors. The decomposition of hazards into their constituent causal factors is another, separate research task. The causes of the hazards, such as failure modes, operator and software errors, and design flaws, need to be identified. To eventually determine the mishap risk and the hazard mitigations, the detailed root causes of the hazards must be identified to the fullest extent possible. The research should investigate and develop a framework of causal factors consistent with the proposed system and subsystem hazard sources in the UAS hazard taxonomy.

- Create influence diagrams to facilitate eventual risk modeling for selected UAS—Influence diagrams graphically portray the complex interrelationships among the various hazard causal factors (i.e., variables) in the mishap chain. Influence diagrams may be used to support a system-level safety risk analysis of representative UAS operations by creating hazard "clusters" consistent with the developed UAS hazard taxonomy. These influence diagrams may be used to motivate discussion of UAS hazard causal factors and especially focus on depicting the complex interrelationships among these factors. The resulting influence diagrams will serve as essential starting points for a more intensive study subsequent to the research involving the construction of detailed analytical risk models. Eventual risk modeling will involve likelihood and severity assessments using data where available and complementary subject matter expertise.

- Strengthen the sensitivity analyses of the risk modeling phase by exploring formal methods and algorithms for uncertainty analysis—Since UAS operations are relatively new and emergent, databases of mishaps may not be readily available. It is recommended that the proposed UAS hazard taxonomy be transformed into influence diagrams for select UAS mishap scenarios. These influence diagrams will display specific hazard causal factors and their interactions. However, uncertainties will exist in likelihood and severity assessments, and the impact of these uncertainties on UAS scenario risk evaluations need to be systematically explored. For example, Bareither and Luxhøj (2007) present an application of uncertainty and sensitivity analysis using BBNs in safety risk assessments. This research task will lead to the development of new analytical methods and corresponding prototype software tools for assessing the uncertainties associated with the construction of the influence diagrams of hazard causal factors for selected UAS scenarios. Such a research task will lead to more robust and defensible risk modeling and will facilitate the exploration of the sensitivities and impacts of both single- and multifactor perturbations on the risk values. Methods to graphically portray these uncertainties will be developed. Such research will be on the forefront of analytical modeling of complex situations characterized by lack of clarity, uncertainty, ambiguity, high risk, and limited understanding, leading to the development of engineering and administrative solutions.

- Construct a reference manual for the HCAS causal factors—It is suggested that the causal factors underlying the system and subsystem hazard sources be identified and categorized. The new HCAS reference manual should be appended to include detailed descriptions and examples of UAS hazard causal factors.

- Expand the development of the UAS influence diagrams for selected UAS hazards. Influence diagrams can be constructed to depict the complex interactions of UAS hazard causal factors—These influence diagrams may be used to support a system-level safety risk analysis of representative UAS operations by creating hazard clusters consistent with the developed UAS hazard taxonomy. Development of these influence diagrams includes obtaining likelihood and severity assessments for the causal factors. These assessments should be obtained using a complementary approach of knowledge elicitations from subject matter experts and mishap data if available.

- Map existing mitigations to the UAS hazards/causal factors and development of a gap analysis—Once the UAS hazards and their concomitant causal factors are identified, a mitigation matrix can be created that maps existing administrative and engineering mitigations against the hazards and causal factors. Mapping eventually leads to a gap analysis that identifies opportunities to develop new mitigations and can assist in the development of a mitigation portfolio. For example, some mitigation options include eliminating the hazard, reducing the hazard's occurrence, reducing the likelihood that the hazard leads to the consequence, and reducing the consequence severity.

- Critique the proposed system-level influence modeling approach for relevancy and accuracy using actual test cases from industry and government groups to create prototypical applicant processes—A critique will promote understanding of the limitations and uncertainties of the system-level analyses and will assist in creating prototypical applicant processes. For purposes of this research task, advice will be sought from the FAA regarding possible actual case studies of UAS operations that may be useful in supporting system-level risk analyses.

- Use text mining tools to review UAS scenarios to reinforce the HCAS taxonomy elements and to possibly develop new elements—Currently, the reading of scenarios and mapping of keywords into the HCAS taxonomy elements is a manual process conducted by an experienced analyst. The use of text mining tools should be investigated as a possible support tool in this mapping process. If the tools show results that are consistent with the analyst's interpretation within an acceptable error level, then the text mining tools could serve as a substitute for this time-intensive manual process.

- Construct a prototype UAS safety database consistent with the refined UAS hazard taxonomy—Further development and refinement of the proposed UAS taxonomy of hazards with causal factors could be used to create the framework for a prototype UAS safety database. This research task will lead to the creation of a prototype software shell consistent with the UAS hazard taxonomy.

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APPENDIX A—HAZARD CLASSIFICATION AND ANALYSIS SYSTEM TAXONOMY OUTLINE (VERSION 3.3)

1. **UAS (Systems Level)**
    - 1.1. **Aircraft (Subsystems Level)**
        - 1.1.1. Aerodynamics
        - 1.1.2. Airframe
        - 1.1.3. Payload
        - 1.1.4. Propulsion
        - 1.1.5. Avionics Hardware and Software
        - 1.1.6. Sensors / Antennas
        - 1.1.7. Communication Link
        - 1.1.8. Onboard Emergency Recovery
        - 1.1.9. Detect, Sense and Avoid
        - 1.1.10. Aircraft Systems
    - 1.2. **Control Station**
        - 1.2.1. Classification
            - 1.2.1.1. Mobile
            - 1.2.1.2. Fixed
            - 1.2.1.3. Multiple
            - 1.2.1.4. Combinations
        - 1.2.2. Hardware and Software
        - 1.2.3. Communications Link
    - 1.3. **Data Link Framework**
        - 1.3.1. Infrastructure
        - 1.3.2. Signals
    - 1.4. **Organizational Human Factors**
        - 1.4.1. Aircraft Design Organization
        - 1.4.2. Control Station Design Organization
        - 1.4.3. Regulatory Agency
            - 1.4.3.1. Certification
            - 1.4.3.2. Oversight

2. **AIRMEN**
    - 2.1. **Individual Human Factors (HF)**
        - 2.1.1. Pilot
        - 2.1.2. Maintenance Technician
        - 2.1.3. Service and Support Personnel
    - 2.2. **Organizational HF**
        - 2.2.1. Operator
            - 2.2.1.1. Training
            - 2.2.1.2. Supervision
        - 2.2.2. Regulatory Agency
            - 2.2.2.1. Certification
            - 2.2.2.2. Oversight

2.2.3. Individual Licensing
2.2.3.1. Pilot
2.2.3.2. Maintenance
2.2.3.3. Service and Support Personnel

3. OPERATIONS
3.1. Flight Operations
3.1.1. Flight Planning
3.1.2. Phases of Flight (include pre and post flight operations by the ground support personnel)
3.1.3. Emergency Procedures
3.1.4. Type of Operations
3.1.4.1. Line of Sight / Beyond Line of Sight
3.1.4.2. VFR / IFR
3.1.5. Operational Control
3.2. Continued Airworthiness
3.2.1. UAV
3.2.2. Control Station
3.2.3. Maintenance Source (Facility and Individual)
3.2.4. Communication Interface (Data Link)
3.3. ATC Communications
3.4. Airspace
3.4.1. Established
3.4.2. Temporary
3.5. Personnel (including Oversight Personnel and ATC)
3.6. Organizational Human Factors
3.6.1. Operator
3.6.2. Regulatory Agency
3.6.2.1. Certification
3.6.2.2. Oversight

4. ENVIRONMENT

- **4.1. Terrain**
- **4.2. Electromagnetic Activity**
- **4.3. Weather**
- **4.4. Particulates (including Volcanic Ash)**
- **4.5. Foreign Object Damage**
- **4.6. Wild Life Hazards**
  - 4.6.1. Bird Strike
  - 4.6.2. Animals
- **4.7. Obstacles**
- **4.8. Other Traffic**
- **4.9. External Influences** (Social, Political)
- **4.10. International Regulatory Differences**
- **4.11. Airports**
- **4.12. Navigation Network** (ground- and space-based infrastructure and signals)
- **4.13. National Security**

5. INTERACTIONS

- **5.1. UAS / Environment**
- **5.2. Operations / Environment** (includes NAS interconnectivity)
- **5.3. Airmen / Environment**
- **5.4. UAS / Operations / Environment**
- **5.5. UAS / Airmen / Environment**
- **5.6. Operations / Airmen / Environment**
- **5.7. UAS / Operations / Airmen / Environment**