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An Integrated Approach to Evaluating Risk Mitigation Measures for UAV Operational Concepts in the NAS

Roland E. Weibel[*] and R. John Hansman, Jr.[†]
Massachusetts Institute of Technology, Cambridge, MA, 02139

An integrated approach is outlined in this paper to evaluate risks posed by operating Unmanned Aerial Vehicles in the National Airspace System. The approach supports the systematic evaluation of potential risk mitigation measures recognizing key issues in creation of regulatory and safety policy, including public perception and UAV market forces. Risk mitigation measures are examined for two example concepts of operation: High Altitude Long Endurance UAV and small, local UAV operations. Primary hazards of ground impact and midair collision are considered. The examples illustrate three major areas of risk mitigation: exposure, recovery, and effects mitigation. The different mitigation possibilities raise key issues on how to determine appropriate UAV policies to ensure that an acceptable level of safety is achieved.

I. Introduction

Unmanned Aerial Vehicles (UAVs) are emerging as a new class of aircraft to be operated in the National Airspace System (NAS). This emergence is driven by the success of several previous flights operated under Certificates of Authorization and strong demand for a variety of applications. While there are currently no regulations in place to allow the routine operation of UAVs in the NAS, there is a significant effort underway to enable routine operations of UAVs in civil airspace in the U.S. and abroad. Several individual UAVs are undergoing review for experimental certification by the FAA[1]. Safety is a fundamental requirement for operation in the NAS, and is a key concern in evaluating potential NAS operations. A prior analysis of ground and midair collision risk found most UAV operations would not meet target levels of safety without incorporation of mitigation[2]. A variety of mitigation measures are under consideration to reduce risk levels to FAA target levels of safety, including operating restrictions, specific technologies, or design and reliability requirements. There is a need to evaluate the effectiveness of different mitigation at reducing the risk of accidents, and understand at what points in the causal chain risk can be mitigated.

The purpose of this paper is to outline an approach to evaluating risk mitigation measures that integrates both safety policy considerations and the effectiveness of risk mitigation measures. It is important to note that mitigation that is appropriate for one class of UAVs may not be appropriate for all classes. Therefore there is a need to examine how UAV policies may vary for different concepts of operation. To investigate this broad range, mitigation considerations will be discussed for examples from two different categories: High Altitude, Long Endurance UAVs[5], and a low altitude, small UAV concept likely to be used by local law enforcement officials. In addition to the basic risk analysis, there are several other factors that need to be considered in support of UAV policy, such as the influence of public perception on safety requirements, the cost of implementation of mitigation measures, and functional requirements of NAS interfaces on the operation of UAVs.

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[*] Ph.D. Candidate, Department of Aeronautics & Astronautics, 77 Massachusetts Ave, Room 17-110, AIAA Student Member.
[†] Professor, Department of Aeronautics & Astronautics and Engineering Systems Division, 77 Massachusetts Ave, Room 33-303, AIAA Fellow.

II. The Unmanned Aerial System

A. System Description

A generic, systems-level representation of an Unmanned Aerial System and the operational interfaces with elements of the National Airspace System (ANS) and associated support services is shown in Figure 1. The combination of an air vehicle and associated command and control architecture, including the ground station, is referred to as an Unmanned Aerial System (UAS). With respect to safety, there is a key distinction between internal interfaces within the UAS and the external interfaces to other systems or services. Figure 1 shows the boundary of the various relevant systems denoted by dashed lines and associated interfaces between components, denoted by black rectangles. The UAS operates within the NAS, interacting with other NAS components and services in different phases of operation and through different interfaces. Support services such as company operations and dispatch and maintenance also interface with the UAS, and influence the safety of the system. Finally, there are interfaces internal to the UAS, between UAS air and ground components and human operators. While human control is shown in the ground station, it is possible that future UAV flights will be flown autonomously, if sufficient performance and safety objectives can be met by the onboard systems.

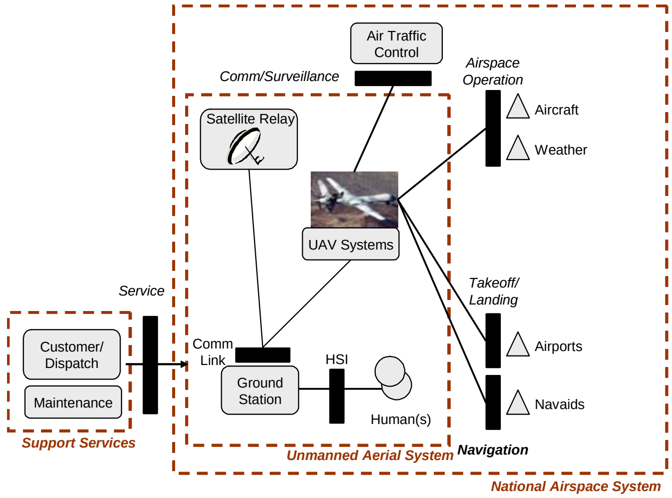

Figure 1: Interfaces between the UAS and NAS

Functional and safety requirements in interfacing with the NAS are generally rigid. There is more functional and operational flexibility within different UAS configurations. Therefore, in the current system, it is easier to impose requirements on the UAS to have equivalent interactions with the NAS as manned aircraft than to change NAS procedures or requirements to accommodate a UAS. However, integrating UAS into the NAS may require some changes in NAS procedures.

B. Concepts of Operation

Recognizing that there is functional and architectural flexibility within the UAS system boundaries shown in Figure 1, a *concept of operation* is typically used to describe a specific UAS system. The concept of operation describes the types of missions which will be performed, the technologies to be used for vehicle control and collision avoidance, the distribution of authority between the human operator and onboard systems, and the control and communications architecture for the vehicle. The concept of operation description will be used as a baseline when examining the safety implications of UAS/NAS integration. As there is a broad range of potential system configurations, it is expected that both the safety implications and the corresponding safety policies will vary widely among the spectrum of UAS concepts of operation.

III. UAS Safety Policy

A. Policy Process

The key question in the introduction of UAVs into the existing national airspace system is how to generate new policies to ensure that safety and functionality goals are achieved. This policy dynamic is illustrated in Figure 2, with emphasis placed on the dynamics of UAS operation within the existing NAS environment. There is a current set of existing procedures, policies, and infrastructure which has evolved to support safe operation of manned aircraft. The emergence of UAS operations drives the need to generate policies to ensure that functionality and safety requirements are met. The policy generation process is driven by public perception of UAS operations, as well an analysis of the required policies to ensure safe operation of Unmanned Aerial Systems in the NAS, which the risk assessment approach introduced in this paper will partially address. There is a set of policies which are applicable to this new class of aircraft, as well as new policies that must be created.

B. Safety Requirements

Of primary importance for this analysis is the impact of the UAS concept of operation on the safety of the system. Ensuring and enhancing safety of the air transportation system is the primary mandate given to the FAA and is a fundamental standard in the integration of new technologies into the NAS. While the FAA is primarily charged with the safety of the system in creating regulations and policy, there is also a burden on manufacturers and operators of UAS systems. The UAS must be designed and analyzed to meet FAA system safety requirements.

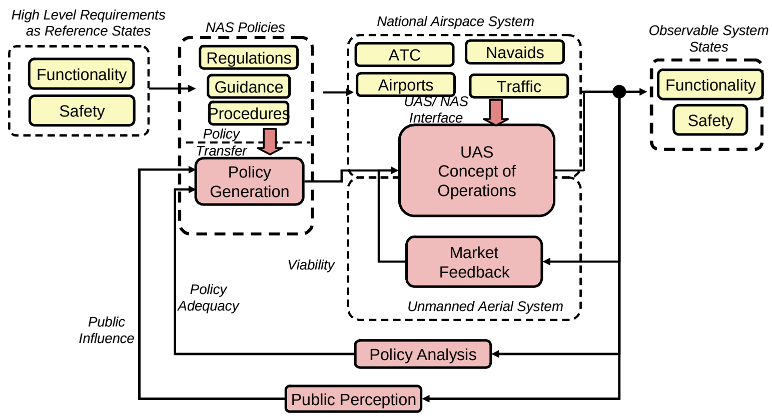

Figure 2: UAS Policy Creation Dynamic

Safety in the current system is assured through certification and training requirements, operating rules, maintenance, and air traffic control services, which are governed by several NAS policies, as shown in Figure 2. The difficulty in evaluating potential UAS safety policies is that the new technology presents several unique issues in NAS operation. The integration of UAS into the NAS has impacts on a variety of FAA organizations including air traffic operations, flight standards, aircraft, and aircrew certification for an entirely new class of aircraft. The impact on NAS safety through collision avoidance capability and the airworthiness certification of an aircraft without occupants present new challenges.

C. Public Perception

There is a need to examine the influence of public perception on the determination of UAS policy. Public perception has had a strong influence on the development and deployment of previous technologies, such as nuclear power. The current public reaction to UAS operations is unknown, as the current operational experience in civil airspace has been limited (although preliminary indications are that the public appreciates the use of UAVs for public safety, security, and rescue operations). The anticipation of negative reaction to a major UAV accident has been a key source of a precautionary approach to current UAS/NAS policymaking. It is therefore essential to understand the fundamental influences of UAS operation on public perception of risk and the corresponding influence on UAS policy. Previous research suggests that public perception of technological risks does not depend heavily on the actual risk, but depends largely on the perceived benefits of the technology, opinion of the technology and other factors that are not generally termed as rational[3]. The public perception dynamic also presents several key issues on risk communication, or how to inform both the general public and users of the system that key risks have been considered and mitigated.

D. Market Forces

UAS concepts of operation are also subject to external market forces. The market feedback governs what concepts of operation are economically viable, i.e. what missions can be performed profitably. Market forces also drive safety aspects of the concept of operation, through legal liability and insurance requirements. The implementation of different mitigation measures has associated costs in several dimensions. Both up-front and recurring capital costs can be incurred to implement mitigation measures. Initial costs include research and development, compliance with regulations, and acquisition of systems. Recurring costs can arise from personnel training and staffing, or operation of systems. There is also a cost to mission associated with a loss of mission capability in terms of loss of payload space, operating restrictions, or a loss of a market. Therefore, policies enacted also constrain the viability of different UAS concepts of operation through several financial mechanisms.

IV. Evaluation of Mitigation Measures

This section outlines the general approach taken to analyze risk mitigation measures. The systems-level risk analysis approach is shown in Figure 3. In the approach, a UAS operational concept outlines the general functional goal of the UAS operations, along with specific functional attributes, such as expected mission profile, control architecture, and vehicle to be used. Risk mitigation measures incorporated into the operational concept are examined for their influence on the occurrence of a set of general systems-level hazards through contributory hazards or influences of the operational environment. The mitigation measures can also influence the risk of adverse outcomes after the occurrence of a hazardous state. These mitigation effects are modeled through the mitigation event tree. The end result is an overall level of risk posed by the concept of operation.

The safety analysis process is iterative. The risk levels posed by a set of mitigation measures and an operational concept are compared to requirements on target levels of safety to determine the requirements additional mitigation approaches in the concept of operation. This requirements generation process addresses the key policy issues outlined in the previous section. The risk assessment process in this section lays the foundation for discussion of mitigation approaches for two example concepts of operation: High Altitude, Long Endurance (HALE) UAS, and a small UAS used for local missions, discussed in the following sections.

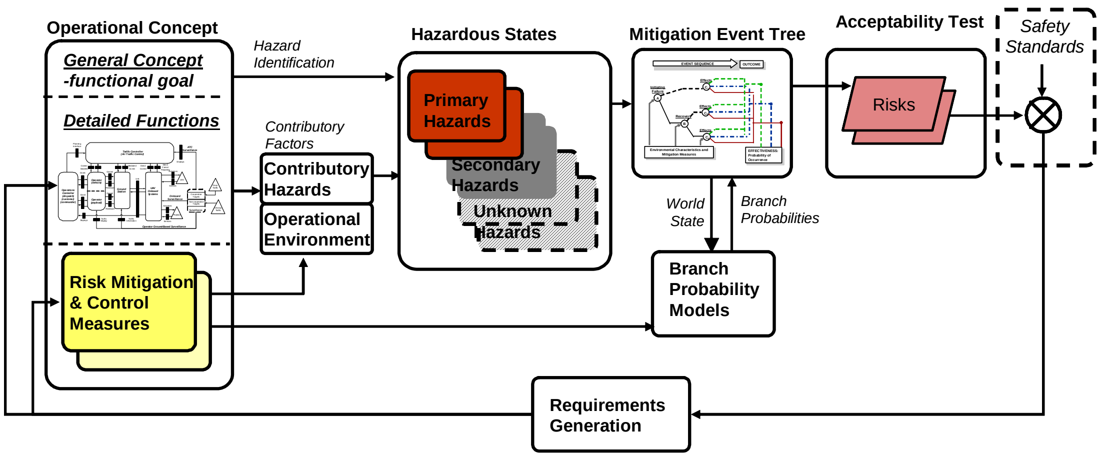

Figure 3: Integrated Risk Analysis Framework

A. Hazardous States

To add structure to analysis of risks in potential designs, risks are defined related to individual hazards, where a hazard is defined as a state of the system that could potentially result in an accident. The definition can be interpreted in many different ways at varying levels within a system. The FAA system safety handbook differentiates between initiating hazards, contributory hazards, and critical events (or primary hazards)[4].

Noting the potential ambiguity in definition of a hazard, it is important to define what are considered to be hazardous states for the purposes of analysis. For this paper, hazardous states are defined as the general categories in which harm to persons or property can occur. The identified primary and secondary hazardous states for UAS operation are shown in Table 1. This allows for the separation of primary hazards, which are expected to be critical system design drivers, and the most likely to require mitigation. The two primary potential contributors to loss of life in UAS operation are ground impact and collision with another aircraft. There are other secondary hazards, such as environmental contamination, injuries to ground personnel in operating the aircraft, and property damage associated with UAS accidents. The secondary hazards are important to control, but typically have lower target levels of safety associated with them, and are therefore not as critical in designing mitigation. There is also a set of unknown hazards that may not have yet been identified in the analysis, denoted as *other hazards* in Table 1.

Table 1: Identified Hazardous States

Primary Hazards
-Potential midair collision
-Potential ground impact
Secondary Hazards
-Potential harm to operators, ground crew
-Potential environmental contamination
-Potential loss of aircraft part or debris
Other Hazards

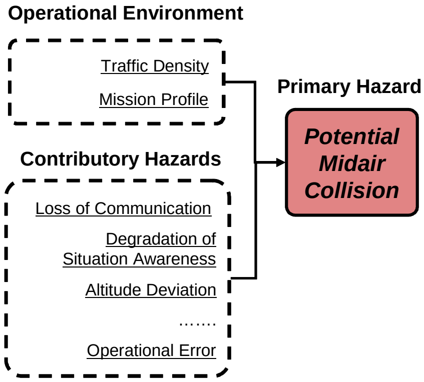

Figure 4: Influence of Contributory Hazards and Operation Environment on the Midair Collision Hazard

An example of both contributory hazards and environmental factors related to a potential midair collision is shown in Figure 4. The analysis of contributory hazards and failure modes is typically performed in the context of a well-defined system, to determine detailed safety requirements by function. When examining the likelihood of hazard occurrence for a general operational concept, the operational environment is expected to be the dominant driver of the rate of occurrence of primary hazards, as a detailed functional description of the concept of operation has not yet been formulated.

B. Mitigation Evaluation

A variety of mitigations can be applied to an Unmanned Aerial System both to reduce the likelihood of occurrence of primary hazards, and to reduce risk after being in an initial hazardous state. To categorize different types of mitigation measures, an event tree formalism is used in this analysis and is shown in Figure 5. The event tree shows the sequence of events that lead from an initial hazardous state to their possible outcomes. The event sequence begins with the initial exposure rate to a hazardous state, denoted by (A) in the figure, the input to the event tree. Mitigation measures that reduce the probability of entering a hazardous state will be referred to as exposure mitigations. Incorporation of exposure mitigations result in a given rate of occurrence of the hazardous state per hour, which is the exposure risk of the operation.

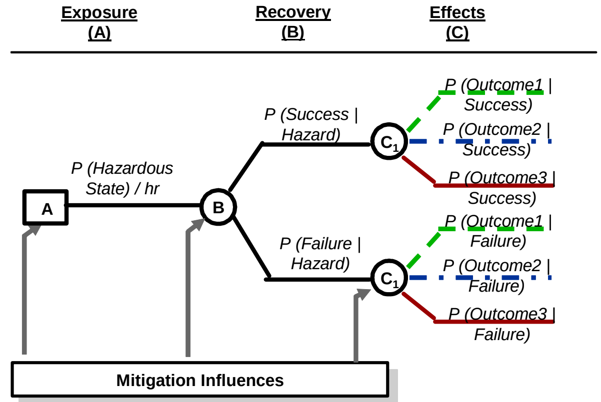

Figure 5: Event Tree Model of Risk Propagation after Initial Hazard

Additional events can occur after the exposure to the hazardous state. These potential events are represented as decision nodes in the event tree, denoted by circles in Figure 5. The decision node represents possible downstream states of interest. For this analysis, two potential nodes are considered. Recovery from the initial hazardous state (B) either succeeds or fails, and then there are effects (C) after the recovery, resulting in possible outcomes categorized by the worst-case consequence that can occur. The recovery node (B) can be further divided into detection or recognition of the hazardous state, and recovery actions conditional on detection. For this analysis, the functions were combined to simplify evaluation of mitigation measures that typically couple detection and recovery functions.

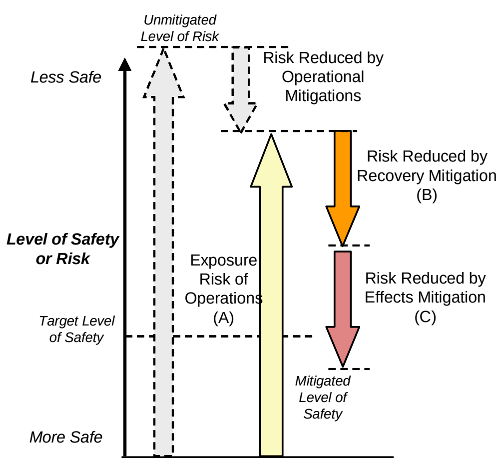

Figure 6: Illustration of Effectiveness of Mitigation Measures

Each decision node has a set of conditional probabilities that describe the probability of occurrence of each branch conditional upon the previous states. The overall likelihood of each outcome is determined by multiplying conditional probabilities through the tree, and risk is aggregated along potential consequences in different branches of the tree. Mitigations reduce risk of exposure, by modifying the likelihood of occurrence of the exposure state, and reduce risk after exposure to a potential hazard by modifying the distribution of conditional probabilities at each decision node. By varying mitigation measures and their conditional probabilities in the event tree, the influence on overall risk can be inferred.

The effectiveness of mitigation measures can be visualized as shown in Figure 6, where the vertical axis represents the level of risk at different stages of the event tree analysis. In this representation, it is recognized that there is an unmitigated level of risk that exists based on an assumed mission profile and type of operation described by the concept of operation. If operational exposure limitations are imposed such as overflight restrictions of populated areas or altitude restrictions, the level of risk is reduced. When discussing the example operational concepts, the risk of operation will be discussed in terms of the exposure risk, which in some cases includes the incorporation of some exposure mitigation measures. Therefore, the reduction from an unmitigated level of risk is denoted by dashed arrows, as it refers to effects that occur before the event tree analysis begins, at state (A).

The descending solid arrows on the right side illustrate reduction of risk from the exposure risk level by the two other classes of mitigation: recovery mitigation measures (B) and effects mitigation measures (C). The fully mitigated level of safety is the vector sum of arrows (A) (B) and (C), labeled as the mitigated level of safety. For most cases, the mitigated level of safety will need to exceed target level of safety requirements to account for uncertainties in the effectiveness of different mitigation measures.

V. High Altitude, Long Endurance Concept Example

A. Concept Definition

The high altitude, long endurance (HALE) concept of operation is representative of a large UAS performing long duration missions in the NAS[5]. The concept is shown in Figure 7. The concept assumes an initial phase in deployment of HALE operations, where the UAS operates above FL 180 in Class A airspace, while later phases of integration into the NAS will include operation in classes C, D, and E as well as Class A airspace. For the initial analysis, this paper will only consider the initial steps of the program, and examine risks relevant to operation in Class A airspace. Other functional details include:

- Combined over the horizon (satellite) and within line of sight (direct link) control
- Large power and payload capabilities of vehicle
- Human supervisory control in a ground station
- Loiter and transit missions above FL 180

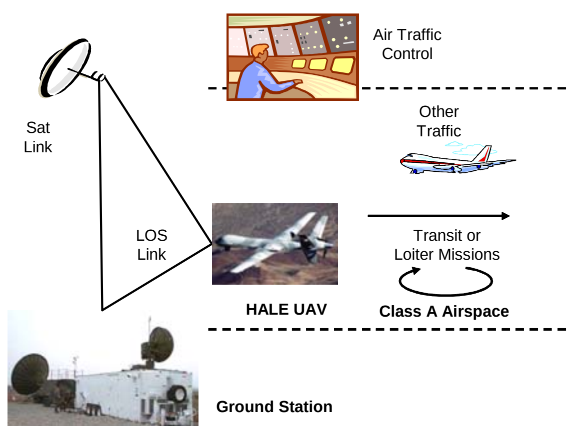

Figure 7: HALE UAS Concept of operation

B. Midair Collision Mitigation Measures

To illustrate mitigation measures applied at different points in the system, the midair collision hazard will be examined for the HALE concept of operation. The influences on the different branch probabilities, and associated potential mitigation measures are shown in Figure 8. The initial exposure risk is influenced predominantly by type of operation. Higher traffic density and less procedural separation will influence the probability that conditions will create a potential midair collision scenario. Risk reducing mitigations in this category could take the form of airspace-related operational restrictions.

After a potential midair collision state is present, detection capability depends on encounter characteristics, sensor performance, composition and equipage of other traffic, and capability of the HALE ground station. Recovery will be influenced by the operational architecture: whether recovery actions are performed autonomously on the vehicle, or by an operator removed by a control link with additional latency. For the HALE concept of operation, flight occurs in Class A airspace where all aircraft are positively separated by Air Traffic Control. A large UAV also has the potential to incorporate advanced collision avoidance systems, including TCAS, which is being evaluated for the Global Hawk[8]. Additionally, detect sense avoid systems capable of detecting both transponder equipped and non-equipped aircraft have been the focus of significant current UAV research to replace an onboard pilot's ability to avoid other traffic.

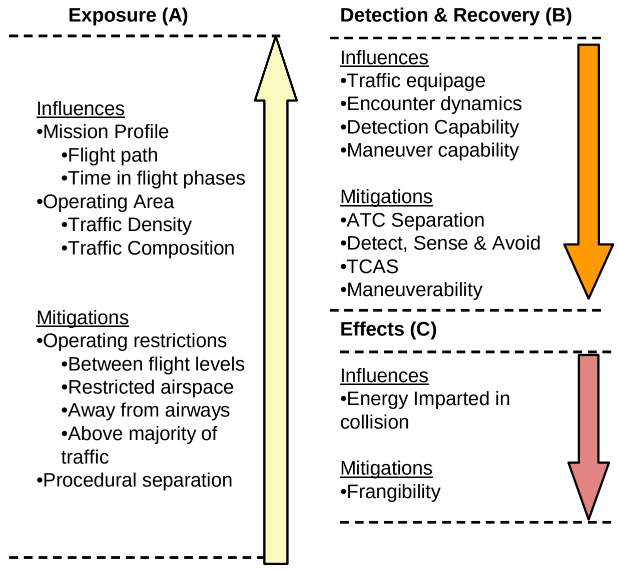

Figure 8: Midair Collision Mitigation Measures and Influences

Effects mitigation reduces the severity of the outcome given that a collision with another aircraft is certain to occur. Such mitigation measures reduce the force or energy imparted to the vulnerable aircraft, and are not typically employed in manned aircraft. For a HALE UAV, the impact force imparted could be limited to mitigate damage imparted on another aircraft through frangible, distributed mass design of the air vehicle.

C. Detect Sense and Avoid & Equivalent Level of Safety

A significant amount of current research is directed towards developing detect, sense, and avoid technologies for UAVs. The stated goal is to develop an "equivalent level of safety" to current manned aircraft operations. This approach is illustrated in Figure 9, where Potential HALE UAS mitigation measures are compared to those used in the current manned system. Manned aircraft use three layers of collision avoidance capability: through air traffic control, the Traffic Collision Avoidance System (TCAS), and the pilot's capability to see and avoid other traffic, although this capability is diminished in Instrument Meteorological Conditions (IMC).

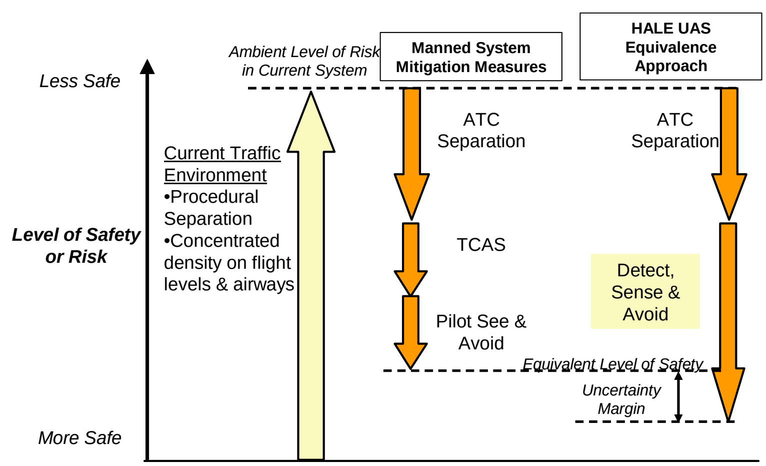

Figure 9: Detect, Sense and Avoid for HALE UAS

Integrating the HALE UAS in a similar manner to manned aircraft assumes the same ambient collision risk and air traffic control separation capability will exist, but an addition detect sense and avoid system must be incorporated to replace the performance of TCAS and the onboard pilot. It is likely that the new system will need to be designed beyond an equivalent level of safety to account for uncertainties in performance. The equivalent level of safety design approach reduces requirements for new UAS policies. The approach compartmentalizes the requirements and system capabilities that must be transferred to the UAS design by equating performance by the same mitigation mechanisms in detection and recovery.

D. Additional Mitigations and Target Level of Safety

There are several combinations of exposure, detection and recovery, and effects mitigations that could be used to achieve a target level of safety. In this section, example operational restrictions and effects mitigation combinations will be used to illustrate a few notional combinations.

Operational traffic patterns in the NAS concentrates traffic density along airways and on major flight levels. In a prior UAV risk analysis[2], a simple gas collision model was used to determine the risk of midair collisions averaged across all airways in the U.S. The analysis assumed random location of a UAV with respect to other air traffic, and averaged air traffic density based on an FAA ETMS surveillance source over 24 hours in 2003. The estimated collision risk is shown in Figure 10. The collision risk shown is an estimate based on the assumptions of the model, but it can be noted that the rate of exposure to midair collision condition over several orders of magnitude. The analysis did not consider the flight path of the UAV, which also influences exposure risk if it is different from the operational characteristics of other traffic.

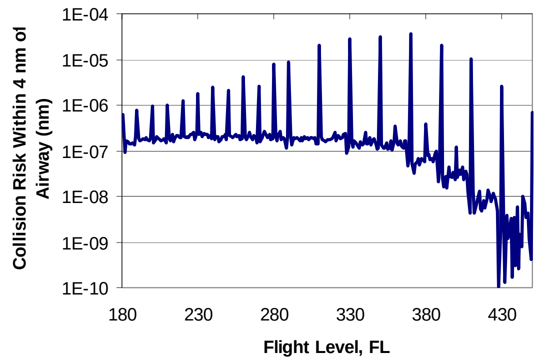

Figure 10: Expected Collision Rate from a Gas Collision Model Averaged Over All U.S. Jet Routes for a 24 Hour Period

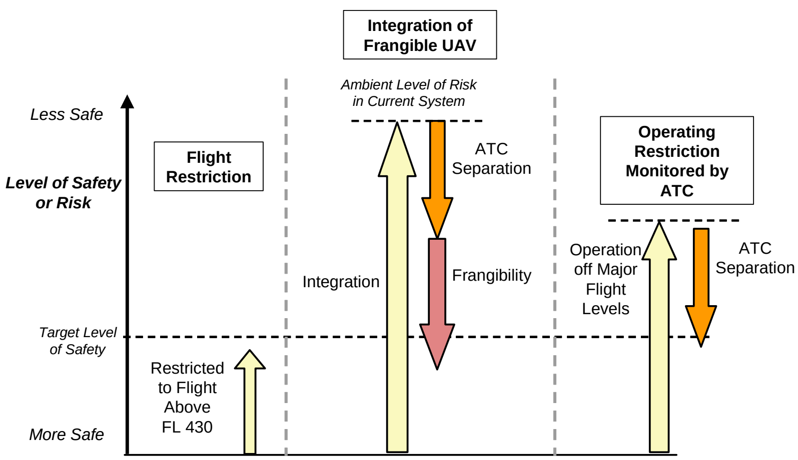

Figure 11: Mitigation Approaches to Achieving a Target Level of Safety

Noting the dependence on areas of operation, mitigation measures than influence initial exposure rate could be implemented as operating rules that restrict operations of the UAS to specific areas of airspace. Several potential mitigation combinations to achieve an acceptable level of safety are shown in Figure 11. Under certain restrictions, such as operation above the majority of commercial air traffic above flight level 430, the ambient risk could be controlled to be lower than the most stringent FAA TLS of 10^{-9} collisions / hr. Other possibilities include the integration of UAVs without detect sense and avoid, but with frangible design characteristics that lower the risk of a catastrophic outcome should a collision occur, as shown in the middle of the figure. The scenario shown in the right side of the figure is an intermediate level of operating restrictions, with the UAV restricted to operation between major flight levels, where traffic density is lower.

It should be noted that the purpose of this discussion has been to illustrate the different systems-level approaches on achieving a target level of safety under several assumptions. The main assumption is that the primary influence on risk is the operational phase of the mission. During climb or descent, or in abnormal/emergency situations, the interaction with other air traffic is different, and risk may increase. While FAA guidance on safety analysis considers an average flight, there is a limit in practice to the amount of risk accepted during different phases of operation. One example of this is the current practice of reporting and reducing accident rates per takeoff and departure in commercial operations, as those phases of flight are low as a percentage of flight time, but have a disproportionately large rate of accidents[9].

VI. Small, Local Operational Concept Example

A. Concept Definition

The small, local operational concept is representative of several current demonstration missions where UAVs were used for surveillance of a local area for crowd surveillance and local law enforcement. The concept is illustrated in Figure 12 and shows the use of a relatively inexpensive UAV with limited logistical support, controlled through line of sight control at low altitude, where the goal is to provide a limited surveillance capability of a local area. Functional details include:

- Small (30 lb or less) UAV with limited payload and power capabilities
- Line of sight control through limited ground station
- Short duration operation over a limited area

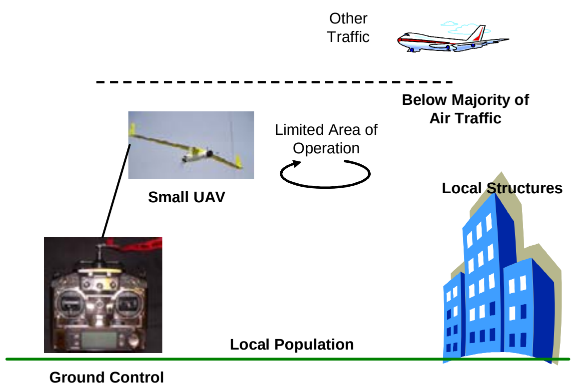

Figure 12: Small UAS Concept of operation

B. Ground Impact Mitigation

Small UAVs present unique opportunities to mitigate the risk of potential ground fatalities that have not been used in current manned operations. Potential mitigation measures are summarized in Figure 13 for the three categories of mitigation evaluation previously introduced. With respect to ground impact, the likelihood of exposure to harm is influenced primarily by the population characteristics in the area of operation. To control exposure risk, potential mitigation approaches are to operate over local regions of low population density, or over areas where the population is specifically sheltered from harm through a risk-based guidance system. Other possibilities include limiting UAV mass, or segregating the UAV to areas of low population density.

Small UAS in this concept are likely to be operated in populated areas. In this case, there are additional measures that can be used to reduce risk. Detection and recovery capability includes both the prevention of system failures and recovery from potential failures. Therefore, mitigation approaches include increased reliability levels to prevent system failures that would cause a ground impact. Recovery from system failures in small UAS may be limited due to interfaces with less diagnostic capability, but contingency plans for reacting to vehicle failures can also reduce the potential risk to the general public. For example, after a potential failure is recognized, the UAS operator or guidance system could guide the UAV to a low risk landing site.

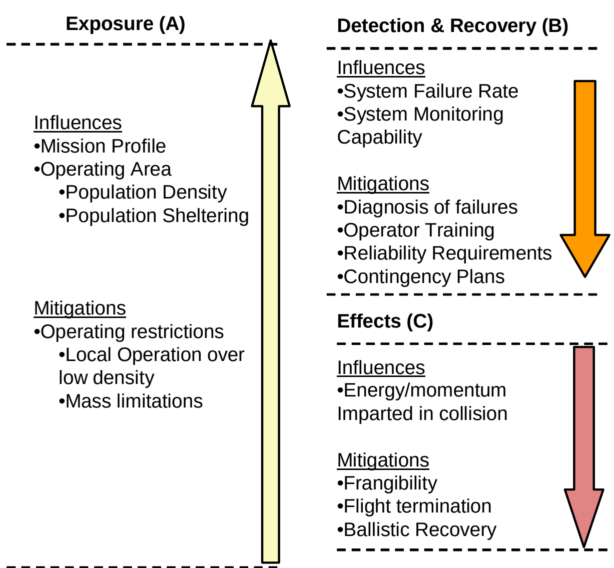

Figure 13: Ground Impact Mitigation Measures and Influences

Small UAVs present a unique opportunity to incorporate damage mitigation measures that would not be possible in manned aircraft. Without a person onboard, UAVs can be sized specifically to fit desired sensors, which are continuously shrinking and increasing in performance. The small size of many current UAV designs makes ground fatality risk very small, both due to the size of potential impact area, and the kinetic energy imparted by impact, and prior analysis showed that this significantly contributed to a reduction in ground impact risk[2]. Effects mitigation approaches are possible that would not be possible with occupants onboard the aircraft. Active systems can be used that reduce the size of vehicle debris by terminating the flight or utilizing ballistic recovery systems if UAV control is lost.

C. Mitigation Measures and Level of Safety

Three examples are shown in Figure 14 to illustrate potential systems-level mitigation approaches to achieving a target level of safety. In the first example, flight restrictions could limit UAS to areas of low population density, to limit the exposure risk to the general public and achieve a target level of safety without additional mitigation. This is often the approach taken for initial experimental operation of aircraft in isolated areas. On the other hand, the UAS could be operated over high density regions, with vehicle reliability requirements that ensure that failures are less likely to expose the public to harm. The final example illustrates the use of a flight termination system, that has the capability to detect if a UAV has entered a high population area, or has lost control such that it will impact the ground.

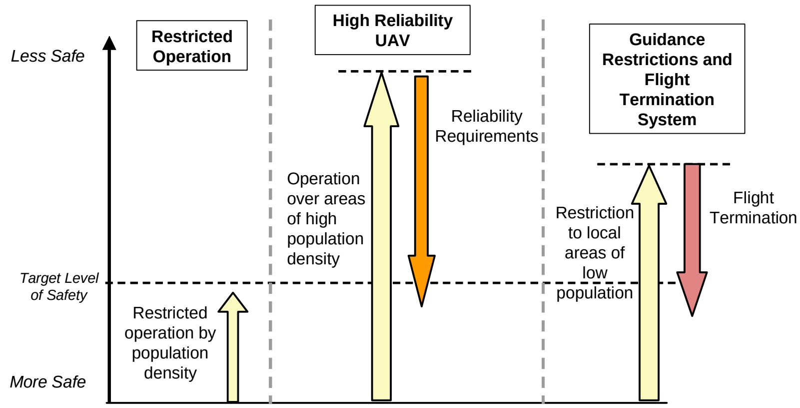

Figure 14: Mitigation Approaches to Achieving a Target Level of Safety

VII. Conclusions

Unmanned Aerial Systems will be required to meet target levels of safety for operation in the National Airspace System. Based on previous analysis, there is a need to incorporate mitigation measures to reduce risk levels to potential regulatory targets. A methodology was developed to systematically examine the effectiveness of mitigation measures at reducing the risk of critical hazards in the operation of Unmanned Aerial Systems. The methodology divides mitigations measures into three categories, based on how they reduce risk. Exposure mitigations reduce the entry into a potentially hazardous state. Examples include altitude, airspace, or population-based operating restrictions. Recovery mitigations facilitate recovery from a potential hazard, such as detection and avoidance of a midair collision through Air Traffic Control. Effects mitigations reduce risk by reducing the likelihood or severity of potential outcomes. Examples include energy reduction measures such as frangible design, or flight termination systems. Based upon the examination of two different concepts of operation, there is clearly a variety of alternate mechanisms that can be used to achieve a target level of safety. Continued investigation is needed to determine what mitigations are most effective at reducing risk, and what regulations and policies can be implemented to ensure that unmanned aircraft are safely integrated into the National Airspace System.

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