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Toward a Safety Risk-Based Classification of Unmanned Aircraft

Wilfredo Torres-Pomales
Langley Research Center, Hampton, Virginia

December 2016

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Abstract

There is a trend of growing interest and demand for greater access of unmanned aircraft (UA) to the National Airspace System (NAS) as the ongoing development of UA technology has created the potential for significant economic benefits. However, the lack of a comprehensive and efficient UA regulatory framework has constrained the number and kinds of UA operations that can be performed. This report presents initial results of a study aimed at defining a safety-risk-based UA classification as a plausible basis for a regulatory framework for UA operating in the NAS. Much of the study up to this point has been at a conceptual high level. The report includes a survey of contextual topics, analysis of safety risk considerations, and initial recommendations for a risk-based approach to safe UA operations in the NAS. The next phase of the study will develop and leverage deeper clarity and insight into practical engineering and regulatory considerations for ensuring that UA operations have an acceptable level of safety.

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Acronyms and Abbreviations

ATC	Air Traffic Control
ATO	Air Traffic Organization
ATS	Air Transportation System
C2	Command and Control
C3	Communication, Command, and Control
CFR	Code of Federal Regulations
COA	Certificate of Authorization
DAA	Detect-and-Avoid
EASA	European Aviation Safety Agency
FAA	Federal Aviation Administration
FAR	Federal Aviation Regulations
FIT	Flight Into Terrain
GDP	Gross Domestic Product
GTC	Ground-space Traffic Control
ICAO	International Civil Aviation Organization
LOS	Loss of Separation
NAS	National Airspace System
NASA	National Aeronautics and Space Administration
NextGen	Next Generation Air Transportation System
NPRM	Notice of Proposed Rulemaking
ODU	Old Dominion University
OTA	Office of Technology Assessment
POI	Problem of Interest
RPA	Remotely Piloted Aircraft
RPAS	Remotely Piloted Aircraft System
RPS	Remote Pilot Station
SA	Systems Analysis
SOI	System of Interest
SRK	Skills, Rules, and Knowledge
TSE	Traditional Systems Engineering
U.S.	United States
U.S.A.	United States of America
UA	Unmanned Aircraft
UAS	Unmanned Aircraft System
UN	United Nations
UTM	Unmanned Aircraft System Traffic Management

Executive Summary

The National Airspace System (NAS) is the large and complex network of airports, airways, and air traffic control facilities that support commercial, private, and military use of the national airspace. The NAS was created and has evolved to serve primarily manned aircraft operations. However, the ongoing development of unmanned aircraft (UA) technology has created the potential for significant economic benefits, and there is growing interest and demand for greater access of UA to the NAS. The lack of a comprehensive and efficient UA regulatory framework is severely constraining the number and kinds of UA operations that can be performed. The goal of this study is to define a safety-risk-based classification that is a suitable basis for a regulatory framework for unmanned aircraft in the NAS.

This problem has a multitude of relevant dimensions. The regulations for civilian aviation are the fundamental governance rules for the operation of aircraft in the NAS. The development of aviation regulations is a complex, contextually embedded problem with a large and heterogeneous group of stakeholders. There are no clear boundaries to the scope of this problem. Subjectivity, ambiguity, uncertainty, and divergence of perspectives are all present. Many factors would influence a revised structure of the aviation regulatory framework, with safety-related risk being the primary one. The analysis must also consider relevant contextual factors such as current aviation regulations; status and trends in technology and industry; societal values and expectations; and the situation in the areas of government regulation, politics, business, and the economy.

Because of these characteristics of the problem domain, it is unrealistic to expect that the output of this study will be conclusive. Instead, the study was aimed at moving the problem forward by providing a measure of clarity and insight, and leveraging these to formulate a recommendation for a risk-based classification for unmanned aircraft. The study was divided into two major parts:

- **Understand the problem**: a survey of relevant contextual topics and an analysis of safety risk for unmanned aircraft; and

- **Provide recommendations**: synthesis of available information into a UA classification proposal informed by safety-risk considerations and other relevant factors.

The bulk of the study and this report was allocated to the survey of relevant areas of considerations. The surveyed topics include:

- Systems engineering and systems analysis,
- System safety,
- Government regulations,
- National Airspace System,
- Regulation of manned aviation,
- Unmanned aircraft technology and applications,
- Safety risk of unmanned aircraft, and
- Considerations for unmanned aircraft

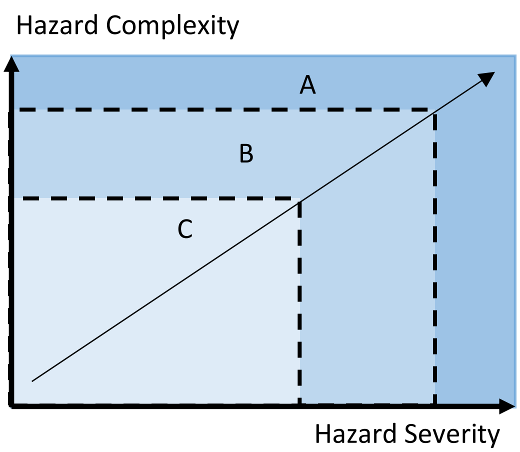
This survey was the foundation for gaining adequate understanding of the problem, and it was instrumental to the problem analysis. Together, the survey and the analysis provided the basis for the recommendations.

Recommendation 1: The regulations should allow compliance with Acceptable Level of Safety (ALOS) objectives using a combination of risk mitigation contributions from the mission, the environment, and the aircraft system.

This recommendation would enable approval of a wide range of activities and the full exploitation of the potential benefits of unmanned aviation. The implementation of mission and operational restrictions would allow a variety of performance and cost options for realizing UA applications.

Recommendation 2: Unmanned aircraft should be classified based on an ordinal scale that combines hazard severity and hazard complexity.

Based on the safety risk analysis performed in this study, hazard severity and hazard complexity are the two major factors of aircraft safety risk and the required effort to ensure an adequate level of safety. The proposed classification is based on increasingly larger sectors of the hazard severity and hazard complexity space, as shown in the following figure, where class A aircraft have the highest potential safety risk and class C aircraft have the lowest potential safety risk. This classification basis is aligned with the pattern of societal concern and demand for safety assurance.



Proposed risk-based aircraft classification

The feedback received to date from subject matter experts (SME) on the recommendation for a risk-based classification of unmanned aircraft has been positive. SMEs recommended that the study be continued with the purpose of identifying more specific and practical classification criteria and thresholds. The value of the final classification recommendations will be based on their usefulness to the unmanned aircraft community in industry, government, and academia.

1. Background

The National Airspace System (NAS), a component of the overall U.S. transportation infrastructure, is a complex network of airports, airways, and air traffic control (ATC) facilities that support commercial, private, and military use of the U.S. airspace [1]. The goals of the NAS are to ensure safety of flight, prompt movement of aircraft, and cost-efficient operations. The main traffic services provided by the NAS include flight planning and advisory information, navigation and landing aids, and air traffic control. Aviation contributes to decreasing barriers to trade, is an engine to innovation and technological progress, and provides an infrastructure that keeps the U.S. competitive in the global economy [2]. Civil aviation, in particular, contributed an average of 5.2 percent of GDP between the years 2000 and 2012. However, aircraft noise is a major issue for communities near airports, and there is a general concern about aircraft pollutant emissions that contribute to global warming and ocean acidification [3].

The continued development of unmanned aircraft systems (UAS) technology is creating potential opportunities for significant positive impact to the United States economy. In addition to military applications, UAS are currently being used in a variety of civil applications, including agricultural monitoring, weather monitoring, aerial imaging, and law enforcement, among many others [4]. Market analyses indicate that the major potential markets for UAS are in precision agriculture and public safety. Along with potential economic benefits, there are serious concerns about UAS operational safety and security, and concerns about privacy, civil rights, and civil liberties [5]. The environmental impact of UAS operations is also an issue of concern. In addition, a major concern for UAS operations is that the NAS was created and has evolved assuming that operating aircraft are manned. Technologically, operationally, or administratively (i.e., from the point of view of regulations, policy, standards, capabilities, and procedures), the NAS is not ready for large-scale, safe, and routine UAS operations while continuing to meet the goals of safe, effective, and efficient operations of manned aircraft. The problem is complicated by the ongoing comprehensive transformation of the NAS to the NextGen Air Transportation System (ATS), which is intended to increase capacity, flexibility, scalability, safety, reliability, and security, while reducing operational costs and minimizing the environmental impact in terms of noise and pollution [6]. The NextGen ATS transformation plans did not envision the ongoing developments in UAS technology and the increased demand for UAS operations.

The current Federal Aviation Regulations (FARs) do not provide the legal framework necessary for large-scale and safe integration of UA operations in the NAS. The recently released Part 107 of the FARs define the legal framework for small UAS (sUAS) weighing less than 55 pounds and a multitude of operational limitations intended to minimize the risk to other aircraft, people, and property [7]. For operations not covered by Part 107, UAS are granted access to the NAS outside of special-use airspace on a case-by-case basis under Certificates of Waiver or Authorization (COA) for public (i.e., government) operators, or a special airworthiness certificate for civil operators (i.e., everyone else, except recreational model-airplane operators) [8]. Not only is this a time and resource consuming approval process, but UAS operational access is only allowed in airspace segregated from manned aircraft traffic. These approvals also impose constrains on timeframe (daylight only), weather (visual meteorological conditional only), overflight of populated areas, and other operational factors. The aviation regulatory framework and approval process must continue to evolve to meet the demands of the UA market for less restrictive, more numerous, safe, and routine operations integrated into the overall context of the NAS. The regulatory framework for UA and its implementation should preserve the goals of the NAS, while enabling the realization of potential economic and societal benefits of the technology, and minimizing the negative impacts.

The development and enactment of such changes to the FARs is a complex and dynamic problem with a large number of stakeholders, including the manned flight operators, aircraft manufacturers, airport operators, regulatory authorities, security and defense providers, international aviation stakeholders, the general public, and others. Many factors would influence a revised structure of the aviation regulatory framework, with safety-related risk in the NAS being a major consideration [9].

The National Aeronautics and Space Administration (NASA) has underway a research project named "Unmanned Aircraft Systems Integration in the National Airspace System" [10]. One of the focus areas of this study is UAS airworthiness certification standards. A main goal of this NASA research is the development of a risk-informed UAS classification scheme that is a suitable basis for a regulatory framework. Much work has been done in this area by NASA and many others [9] [11]. This is primarily a consensus problem that is aggravated by the contextual complexity (including social, economic, political, and technological aspects with both national and international dimensions) and the potentially strong influence that regulations would have on the development of unmanned aviation, the NAS, and the economy.

2. Problem

The regulations for civilian aviation are the fundamental governance rules for the operation of aircraft in the National Airspace System. The current regulatory approach for unmanned aircraft operating in the NAS is inadequate because of the cost, time, and effort needed to obtain approval for UA operations. In addition, due to safety concerns, current regulatory policy only allows UA operation in segregated airspace away from manned aircraft. The current regulatory approach does not scale to meet current and future demand for flexible, unrestricted, and routine UA access to the NAS. A new approach to UA regulation is needed.

The goal of this study is:

Define a safety-risk-based classification of unmanned aircraft that is a suitable basis for a regulatory framework for operation in the National Airspace System.

In order for the output of the study to be useful, the analysis needs to be as comprehensive as possible in the consideration of factors relevant to the NAS, including the design, operation, and interaction of manned and unmanned aircraft, in addition to many contextual factors. The development of an effective and efficient regulatory system for UA in the NAS must consider the full variety of current and potential future UA designs and operations. As the primary purpose of the aviation regulations is to promote safe operations, UA safety risk must be a major factor in the definition of the regulations. Figure 1 illustrates the major influence paths by which UA operations can influence the safety quality measures of the NAS. Both the direct path to NAS safety (i.e., considering only UA operations), as well as the indirect path through interaction with manned aircraft operations, must be taken into consideration for a holistic safety perspective of the NAS. The analysis must also consider relevant contextual factors such as current aviation regulations; status and trends in technology and industry; societal values and expectations; and the situation in the areas of government regulation, politics, business, and the economy.

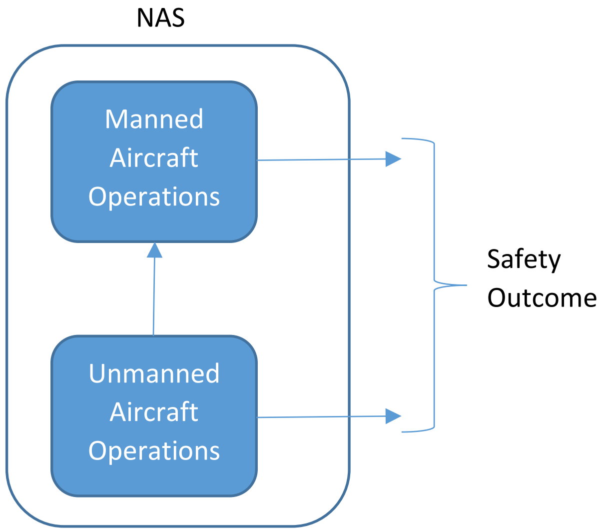


Figure 1: Major influence paths for UA operations affecting the safety quality of the NAS

3. Approach

The development of aviation regulations is a complex, contextually embedded problem with a large and heterogeneous group of stakeholders. There are no clear boundaries to the scope of this problem. Subjectivity, ambiguity, uncertainty, and divergence of perspectives are all present. Achieving meaningful progress toward a solution to this problem requires knowledge and experience in a multitude of technical and sociological topics and their interrelations.

Furthermore, because of the criticality of the regulations as a primary determinant of the evolution of the aviation industry and the consequent impact on the economy and society in general, effective problem analysis requires breadth as well as depth of understanding, as under-appreciated combinations of low-level or unknown factors could lead to unintended and undesired outcomes (i.e., emergence). Resolution of the problem can only be achieved through a managed, iterative, analytical, and deliberative approach involving stakeholders, analysts, and decision-makers in a collaborative effort of consensus building.

Because of these characteristics of the problem domain, it is unrealistic to expect that the output of this study will be conclusive. Instead, the study was aimed at moving the problem forward by providing a measure of clarity and insight, and leveraging these to formulate a recommendation for a risk-based classification for unmanned aircraft. The constraints on available resources, primarily manpower and time, mean that this study can only provide a broad and necessarily incomplete perspective on the problem. A much larger effort would be needed for a comprehensive analysis.

Based on the assessment of the scope and complexity of the problem, and what could realistically be accomplished with the available resources, the study was divided into two major parts:

- **Understand the problem**: a survey of relevant contextual considerations and an analysis of safety risk for unmanned aircraft; and
- **Provide recommendations**: synthesis of available information into a UA classification proposal informed by safety-risk considerations and other relevant factors.

The actual execution of the study followed an iterative process closer in concept to the model in Figure 2. As insight and understanding improved through data collection and analysis, the scope, depth, and schedule of the study were recalibrated to get the most value of what could realistically be accomplished. The data used in this study included publically available documents and information sources, as well as discussions with UA and aviation regulation experts at NASA Langley Research Center.

The following sections summarize the survey of contextual topics, the analysis of safety risk for unmanned aircraft, and the recommendations for a risk-based classification of unmanned aircraft.

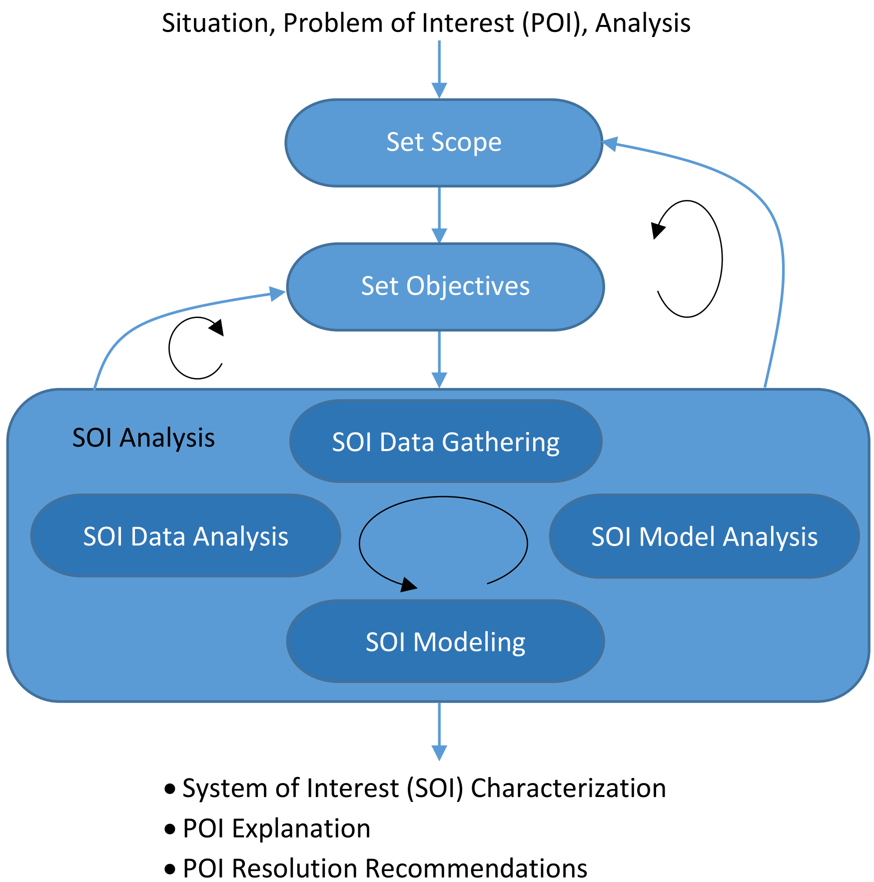


Figure 2: Iterative model of the flow of activities during the study

4. Survey of Contextual Topics

This section presents a summary of the survey results. Many technical and sociological topics are relevant to the problem of developing regulations for unmanned aircraft. For this study aimed at developing a risk-based classification, only a subset of topics were explored. Some of the topics were general and provided a basis for understanding other more specialized topics. Emphasis was given primarily to technical aspects of the problem from a systems engineering perspective. This survey served as the foundation for the analysis presented in the following section.

4.1. Systems Engineering and Systems Analysis

Many concepts from traditional systems engineering (TSE) and systems analysis (SA) were helpful in the development of this study. This section summarizes some of them.

Traditional systems engineering (TSE) and systems analysis (SA), the two major perspectives in the engineering of systems, were both instrumental in the development of this study. From the TSE perspective, a **system** is defined as "a collection of hardware, software, people, facilities, and procedures organized to accomplish some common objectives" [12], and **(traditional) systems engineering** is defined as "an interdisciplinary engineering management process that evolves and verifies an integrated, life-cycle balanced set of systems solutions that satisfy customer needs" [13]. From an SA perspective, a **system** is defined as "a set of elements so interconnected as to aid in driving toward a defined goal" [14], and **systems analysis** is defined as a combination of analytic operations research (OR) and policy analysis (PA) [14] involving both the analysis of complex systems problems and the synthesis (i.e., design) of solutions. The more concrete TSE perspective is suitable for dealing with complex technological systems and their operation, while the more abstract SA perspective is suitable for dealing with complex problems involving a mix of hard technological aspects and softer sociological aspects.

From a systems analysis perspective, the subject problem of this study can be interpreted as a symptom of a faulty (or imperfect) system. In a narrow sense, the boundary of the faulty system could be said to include only the entities directly involved in the development of aviation laws and regulations in the United States, namely the U.S. Congress, the President, and the FAA. However, a fundamental lesson from systemic thinking is to be mindful of potential systems analysis errors when framing the problem and the associated problem system, including false positive, false negative, wrong problem, wrong action, inaction, unsubstantiated inference, and systems of errors [15]. Avoidance of these errors requires an approach with a broad scope that acknowledges the soft (human) dimensions of the problem, such as social, political, organizational, managerial, and policy aspects. Such an approach may reveal a much higher level of systemic complexity than purely technological concerns, and enable the discovery of critical factors in the viability of a proposed problem solution.

A problem, defined as "an undesirable situation or unresolved matter that is significant to some individual or group and that the individual or group is desirous of resolving" [16], revolves around the needs, interests, and values of the stakeholders. A stakeholder is an individual or group who can affect or is affected by the outcome of an undertaking [17] [18]. The drive to solve a problem may come from the needs and desires of a clearly defined and possibly small group of individuals, but it is the stakeholders at large who will determine the acceptability and long-term viability of a solution. A focus on stakeholder concerns avoids a systemic error of solving the wrong problem. In the context of aviation regulations, the approach to the problem must consider the interests of those whose activities are being regulated, as well as the implications on those not directly involved with the regulations but who may indirectly experience the effects, both intended and unintended.

The purpose of an engineered system is described in terms of the desired effect on its environment, both at the interface (i.e., the system **output**) and further downstream on the state of the environment (i.e., the **outcome** of the interaction). This effect is achieved by the flow of matter, energy, and/or information between the system and the environment. Internally the system consists of a "set of components (subsystems, segments) acting together to achieve a set of common objectives via the accomplishment of a set of tasks (or functions)" [12]. A function is a "process that transforms inputs into outputs" [12]. In an abstract sense, every purposeful undertaking, whether it is as an action, process, task, operation, mission, project, or enterprise, can be conceptualized as a system that transforms input into output. Thus, the system consumes resources[1] (i.e., there is a cost) in order to produce an output that is intended to have a desired effect (i.e., there is a benefit).

However, complexity can make the output and outcome of an undertaking difficult to predict. There are multiple definitions of complexity. A simple definition is that **complexity** is the number (or size) and variety (i.e., number of types) of elements and relations in a system [19]. The Cynefin framework of system complexity defines five levels of complexity [20] [15]:

[1] In general, resources are material (i.e., matter), energy, and information. A more concrete description of resources includes man-power, material, money, methods, minutes (i.e., time) and information (M5I).

- **Simple**: the relationship between cause and effect is obvious and predictable; the system is tightly constrained with no degrees of freedom;
- **Complicated**: the relationship between cause and effect requires analysis or some form of investigation; the system is tightly coupled following governing constrains;
- **Complex**: the relationship between cause and effect can be perceived in retrospect, but not in advance and it may not repeat; the system is loosely coupled;
- **Chaotic**: there is no detectable relationship between cause and effect at the system level; the system lacks constrains and is loosely coupled; and
- **Disorder**: absolute ignorance of the type of causality; total confusion; a mess.

According to the Requisite Variety principle, as the complexity of the environment increases, so too must the complexity of the system increase in order to achieve a certain level of effectiveness (i.e., performance) [15] [21]. Furthermore, an increase in effectiveness is correlated with an increase in complexity [21]. As the complexity of the environment and the system increases, our knowledge and understanding of how the elements interact becomes increasingly incomplete and our ability to predict the evolution of the state is diminished [19]. In effect, increasing complexity is correlated with increasing uncertainty about the system and its environment. **Risk** is "the chance that an unwanted event occurs" and "taking a risk is a choice to gamble on an event whose outcome is uncertain" [22]. Thus, as the complexity of a system increases, the risk of unintended and negative consequences tends to increase too.

Every undertaking involves considerations of cost, benefit, and risk. At a high level, the engineering of systems is about ensuring that the system is "designed, built, and operated so that it accomplishes its purpose safely in the most cost-effective way possible considering performance, cost, schedule [*which is a kind of cost*], and risk" [17]. As illustrated in Figure 3, a system takes in resources and returns both desired results (i.e., performance, benefits) and undesired results (i.e., risks). The Systems Engineering Dilemma captures the correlation between these [17]:

- To reduce cost at constant risk, performance must be reduced;
- To reduce risk at constant cost, performance must be reduced;

- To reduce cost at constant performance, higher risks must be accepted;
- To reduce risk at constant performance, higher costs must be accepted.

This tension captures the essence of systems engineering. A successfully engineered system achieves an acceptable balance of cost, performance, and risk (Figure 4).

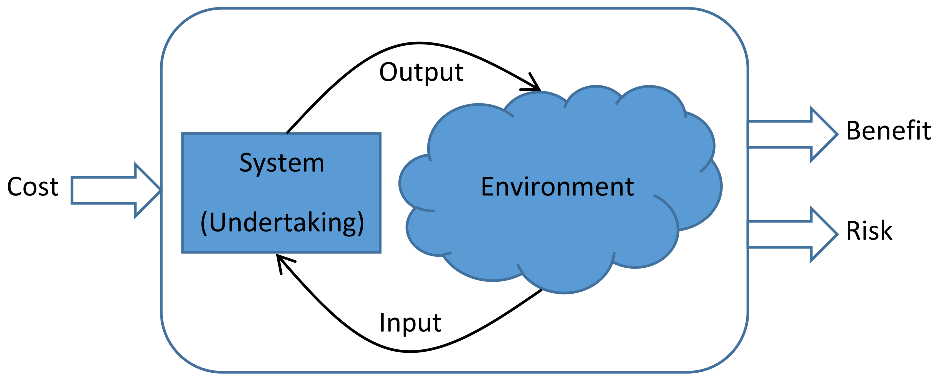


Figure 3: Considerations of cost, benefit, and risk in an undertaking

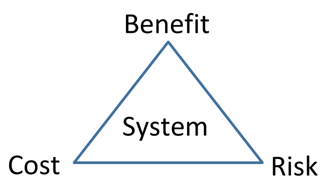


Figure 4: General top-level trade-off space of a system

4.2. System Safety

System safety is a specialty within systems engineering concerned with the development of safe systems and products through the application of engineering and management principles, criteria, and techniques [23] [24] [25]. There are multiple conceptualizations of safety. A simple, non-technical definition of **safety** is "freedom from accident or losses" [26]. However, realistically, complete freedom from harmful unplanned events is not possible [25] [23]. In an aviation context, all system operations represent some degree of risk [23]. A more sensible way to think of **safety** is in terms of risk as "the state in which the risk of harm to persons or property damage is acceptable" [27]. From the point of view of safety, risk (i.e., potential for unwanted outcome) refers to **mishap risk**, which is a composite of the severity of a mishap and the probability that the mishap will occur [24]. A **mishap** is "an unplanned [*i.e., unintended*] event resulting in death, injury, occupational illness, damage to or loss of equipment or property, or damage to the environment" [24]. A mishap-centered technical definition of **safety** is the state in which the mishap risk is acceptable. The term **safety risk** is used to distinguish safety-related risk from other forms of risk associated with an undertaking or operation of a system.

Another perspective on safety is in terms of hazards. A **hazard** is a source of danger as a real or potential condition, event, or circumstance that could lead to or contribute to an unplanned or undesired event, such as a mishap or a state of higher mishap risk [23] [24] [25]. **Hazard risk** (or **hazard level**) is a composite of the hazard severity (i.e., the worst possible mishap that could result from the hazard given the environment in its most unfavorable state) and the likelihood of the hazard occurring [26]. From this perspective, safety risk is a function of the hazard risk, the exposure to the hazard (i.e., the duration and/or number of times that an entity is vulnerable to the hazard in the sense that the state of the entity depends on the state of the hazard), and the likelihood that exposure to the hazard will lead to a mishap.

Risk-based safety [25] is an approach to safety based on the identification of hazards, analysis of risk, and mitigation of risk to an acceptable level. This approach stands in contrast to the prescriptive safety approach where specific features are required in a system to achieve a known basic level of safety [25]. To measure safety risk, severity and likelihood scales are constructed in a way that is meaningful to outcome criticality and stakeholder risk averseness. A common ordinal and qualitative severity scale used in aviation by the FAA has the levels No Safety Effect, Minor, Major, Hazardous, and Catastrophic, corresponding to degrees of safety-relevant effects on things such as the aircraft itself (e.g., effects on functional capabilities and safety margins), the occupants (e.g., from minor discomfort to fatalities), and the flight crew (e.g., workload level, physiological discomfort, and fatalities) [23]. Depending on the situation under consideration, a severity scale may also account for effects on air traffic control, air space traffic (e.g., separation between aircraft), and people on the ground. Quantitative severity scales for safety risk are also used based, for example, on number of fatalities [28] and cost of property damage. Ordinal and qualitative likelihood scales may have levels such as frequent, probable, occasional, remote, and improbable [23]. Quantitative likelihood scales measure probability of an event in terms of frequency per unit of exposure (e.g., per flight hour, per mile traveled, or per flight).

Acceptable Level of Safety (ALOS) describes the level of safety risk that is acceptable to stakeholders, including customers, operators, oversight authorities, society, and others. ALOS is determined by values and preferences applied consciously or subconsciously to considerations of benefits and costs of an undertaking [29] [30] [31]. The general pattern of ALOS is an inverse relation between the severity and the likelihood of an event (Figure 5), where there is broad agreement on the extreme regions of acceptable and unacceptable risk, and a transition region of risk acceptability that must be resolved by analytic-deliberative group decision-making processes. The acceptability of risk depends on objective and subjective factors, and thus, it can vary among individuals, groups, and societies. Some of the subjective factors that influence judgments of risk acceptability include [30] [32]:

- voluntariness of assuming the risk;
- controllability of the risk;
- severity of the risk;
- uncertainty averseness;
- delay of effects;
- availability of alternatives;
- familiarity with the risk;
- exposure as a necessity vs. as a luxury;
- occupational vs. non-occupational exposure; and
- reversibility of effects.

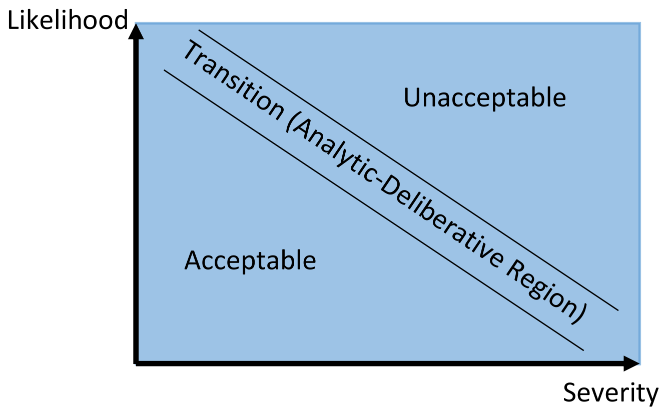


Figure 5: General model for Acceptable Level of Safety (ALOS)

The European Aviation safety Agency (EASA) has proposed a risk hierarchy as a basis for assessing the acceptable level of safety risk, such that the higher a person is in the hierarchy, the lower the acceptable risk level is (i.e., ALOS is higher); and the lower a person is in the hierarchy, the more accepting they are of the risks of the activity [33]:

1. Uninvolved third parties;
2. Fare-paying passengers in commercial air transport;
3. Involved third parties (e.g., air show spectators, airport ground workers);
4. Aerial work participants and air crew involved in aviation as workers;
5. Passengers and participants on non-commercial flights; and
6. Private pilots on non-commercial flights.

This hierarchy captures the general gradient of societal concern for safety and the expected level of governmental responsibility in ensuring an acceptable level of safety [34].

A risk analysis requires a description and modeling of the system of interest (SOI). The level of detail in the system model must be suitable for the analysis and the intended audience. In general, the level of detail in the description (i.e., the depth) varies inversely with the scope (i.e., the breadth) of the SOI [23]. A 5M system model contains the types of elements considered in most systems:

- **Mission**: the purpose or central function of the system;

- **Man**: human elements of the system involved in activities such as operations, maintenance, installation, etc.;
- **Machine**: hardware and software of the system;
- **Media**: the environment, including operational (e.g., traffic density, workload) and ambient (e.g., temperature, precipitation, humidity) conditions; and
- **Management**: the procedures, policies, and regulations relevant to the system.

The identification of safety hazards is necessarily a subjective and qualitative activity driven primarily by judgment, experience, and stakeholder and regulatory requirements. Because of this, it is generally impossible to ascertain the completeness of the identified hazard scenarios, and underappreciated and unknown scenarios and hazards may remain missing from the analysis [35]. Furthermore, as the complexity of the system increases, it becomes increasingly difficult to describe the system accurately and both epistemic (i.e., knowledge) and aleatory (i.e., variability) uncertainties become a concern [36]. However, the primary threat to system safety in complex systems is epistemic uncertainty (i.e., lack of knowledge about the system and its environment). An interesting and insightful observation is that "if enough were known about factors such as design errors to define a probability for them, the safety would be more effectively enhanced by removing the design error than by measuring it in order to convince someone that it will never cause an accident" [37].

The system safety discipline uses primarily qualitative risk characterization. The reason for this is that for a large system with many hazards, it can be cost prohibitive to quantitatively analyze and predict the risk for every hazard [37] [25] [38]. In addition, as the required analytical precision depends on the magnitude of the target level of safety, low-risk hazards can be adequately analyzed with a lower degree of precision than high-risk hazards [38]. In general, higher-severity hazards with lower-likelihood targets require qualitative and quantitative analyses to achieve adequate confidence in the results.

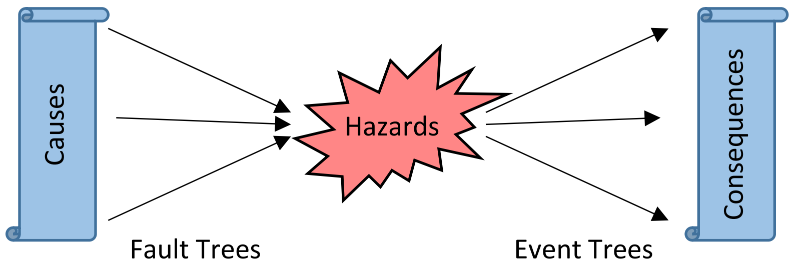


Figure 6: Bow-Tie model for hazard analysis

A Bow-Tie model is a tool for structured analysis of the causes and effects of hazards. As illustrated in Figure 6, a Bow-Tie diagram identifies the causes of hazards and their consequences using, for example, fault trees and event trees. In general, the links between causes, hazards, and consequences are a function of the state of the system and the environment.

The goal of the system safety process is to ensure that the safety risk profile meets the ALOS requirements. This can be accomplished with a balanced combination of risk mitigation strategies:

- **Risk Avoidance**: This involves the selection of a different approach, including possibly not developing or operating the system and not performing the activity at all;
- **Risk Transfer**: Transfer ownership and responsibility to another party who may be in a better position to deal with the risks. Examples of this include transferring the development and operation of the system to a more mature organization and acquiring an insurance policy to guard against financial losses due to potential mishaps;
- **Risk Assumption**: This is simply accepting the risk level. This may be an acceptable strategy depending on cost-benefit considerations; and
- **Risk Control**: This involves the implementation of strategies to mitigate (i.e., reduce) the risk by controlling the likelihood of hazards, their consequence, or both.

A risk control strategy may use a combination of approaches to prevent the occurrence of hazards and protect against their effects. These include, in order of preference based on cost and effectiveness [27]:

1. **Design for minimum risk**: eliminate risks;
2. **Incorporate safety devices**: reduce risks by means of safety features and checks;
3. **Provide active warning**: avert the effects of a hazard by detecting the condition and producing adequate warning; and
4. **Develop procedures and training**: prevention and protection by following prescribed procedures.

These risk controls are conceptualized as managerial, system development, and operational barriers for hazard prevention and protection (Figure 7). One concern with this approach is that as the complexity and criticality (i.e., hazard severity) of the system increases, many more paths of potential causes and consequences of hazards become relevant to ensuring that the required level of safety is achieved, simply because a much lower likelihood of safety-related events is required. In effect, the fault trees of hazard causes and the event trees of hazard consequences become both wider and deeper, with a consequent increase in the required number and sophistication of safety barriers. This leads to a possibly exponential increase in the complexity of the system and its administration, development, and operation. It has been observed that "if it weren't for the potential failures resulting from physical faults, threats, misuse, or errors, most of the complexity of today's modern systems would be unnecessary" [39]. Thus, actions intended to increase system safety may instead lead to reduced safety by increasing the complexity of and uncertainty about the system. At high levels of complexity and criticality, the safety risk profile of the system becomes sensitized to decisions and actions made far removed from the system, including staff, management, company, regulator, and government levels [40] [41].

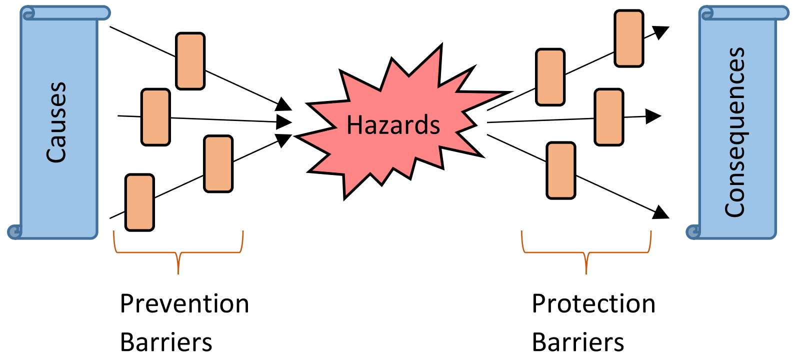


Figure 7: Bow-Tie model with prevention and protection barriers

The positive correlation between productive complexity (i.e., for the purpose of effectiveness and benefits) and protective complexity (i.e., for the purpose of safety) leads to a development and regulatory conundrum. Figure 8 illustrates the notional relation between safety effort and costs [23]. As the size and rigor in the system-safety program increase, the cost of accidents due to an inadequate safety program decreases exponentially, but unfortunately, the cost of the program itself increases exponentially because of the scope and complexity of the effort. This high cost of ensuring a safe system reduces the incentive of manufacturers to develop innovative systems that would reduce the risk of accidents, simply because the cost to the manufacturer would outweigh the benefits. As shown in Figure 9, the safety effort exponentially reduces the safety risk due to inadequacies of the safety program, but the risk of accidents increases exponentially due to lack of safety innovations as the environment evolves, which in the case of the NAS is due to changes like new operational procedures, airspace structure changes, new systems, and airport changes [42]. The challenge for NAS regulators is to achieve and preserve a favorable balance of cost and safety risk by managing factors such as [42]:

- prescriptive vs. performance-based regulations;
- standardization vs. rapid evolution of regulatory material;
- optimize for one industry segment vs. accommodate a range of equipment and operations;
- optimize airspace procedures vs. accommodate a range of capabilities and non-normal operation;

- local optimum and specificity vs. global harmonization and applicability;
- expert based operation vs. reliance on procedures and checklists; and
- personal vs. organizational accountability.

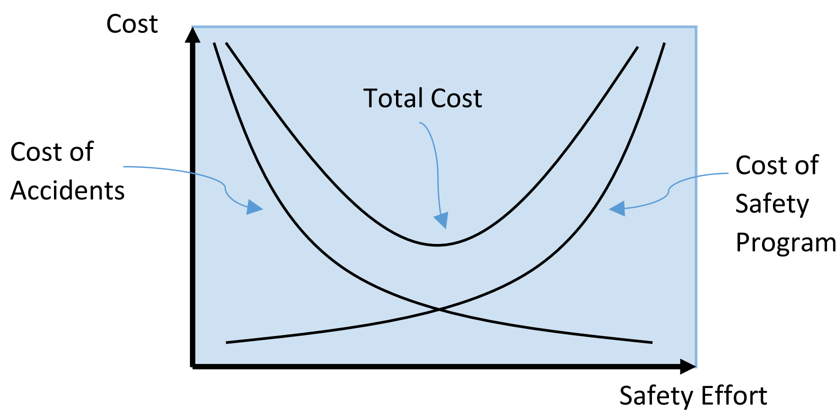


Figure 8: Cost vs. Safety Effort [23]

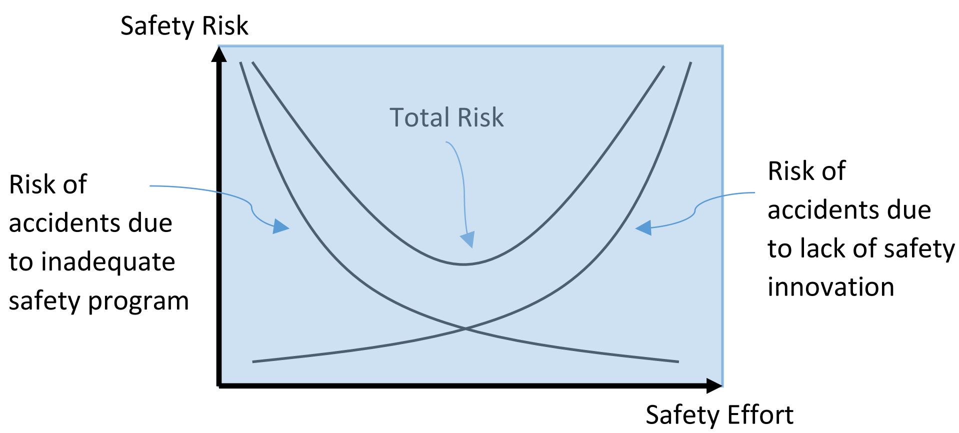


Figure 9: Risk vs. Safety Effort [42]

4.3. Government Regulation

Government regulation has been defined as "any government measure or intervention that seeks to change the behavior of individuals or groups" by giving them rights or restricting their behavior [43]. Also, regulation is sustained and focused control by a public agency over activities that are valued by a community [44]. For decades, there have been complaints from businesses and the public about government over-regulation, legalism (in the sense of prodigiously enacting laws and strictly enforcing them), inflexibility, indifference to the cost of compliance with regulations, and ineffectiveness of laws and regulations [45]. As a result, there has been a long-term push in government to adopt private sector practices of organizational management and operation for greater effectiveness, efficiency, transparency, and accountability. Other desirable attributes of regulations include independence (i.e., unbiased and objective), clarity (i.e., coherent, logical, and practical), proportionality (i.e., appropriate to the problem of concern and cost-effective), consistency (i.e., regulation should complement each other and be enforced consistently), and targeting (i.e., focus on defined problems and minimization of unintended effects) [43] [46].

In general, government regulations can be seen as being about the control of risks (i.e., potential for unintended and undesired outcomes) [44]. Government regulators have a range of strategies they can use to achieve their objectives including [44]:

- command and control: i.e., legal authority is used to impose standards by prohibiting certain forms of conduct, demanding positive actions, or setting minimum conditions for participation;
- incentives: i.e., use of contracts, grants, loans, subsidies, or other incentives for influence conduct;
- harness market controls: e.g., channeling of competitive forces for desired ends;
- disclosure: e.g., deployment of information to enable better decision-making by the public;
- direct action: e.g., physical government action to control a hazard; and

- rights and liabilities laws: i.e., allocated in order to create incentives and constraints on undesirable behavior.

Risk-based regulation is "the prioritization of regulatory actions in accordance to the assessment of the risks that parties will present to the regulatory body's achieving its objectives" [44]. This approach to regulations focuses on the control of relevant risks to the achievement of specified system-level or activity-level goals and objectives, rather than ensuring compliance with a set of rules. An important observation regarding risk-based regulation is that risk in this context refers to the general sense of the term as potential for unintended and undesired outcomes of an activity or undertaking, and not only the sense of safety-related risk that is the major focus of this report. In the case of aviation, the goals would be related to operational safety, performance (e.g., orderly and expeditious flow of aircraft), and cost efficiency. Another important observation relevant to the domain of aviation is the distinction between prescriptive and performance-based regulation. Prescriptive regulation specifies detailed requirements to use things such as methods, techniques, designs, or materials in an activity, but the rationale for these requirements is usually implicit. On the other hand, a performance-based (or outcome-based) approach to regulations specifies what the desired outcome is, and the regulated are mostly free to choose how to achieve the required outcome. The role of the regulator in this regime is to set the goals and objectives and to provide oversight to ensure that these are achieved. Many in industry prefer this approach because of the transparency and flexibility it enables. A more accurate term for this approach combining aspects of risk and performance would be *risk-managed, performance-based regulation*.

In the nuclear industry, for example, where risk and performance-based approaches to regulation have been used for a long time, safety performance objectives are captured in the form of an objectives hierarchy consisting of goals, top-level fundamental objectives, and means objectives (which support the accomplishment of the fundamental objectives) (see Figure 10) [47] [12]. An analytic-deliberative decision-making process such as illustrated in Figure 11 is then followed during system development and operation to identify and evaluate risks and decide appropriate actions to mitigate the risks relative to the objectives [48]. A conceptually similar approach can be used for aviation regulation [27]. Risk-regulations are commonly seen as a more rational, cost-effective, controllable, transparent, and easily justified approach [44].

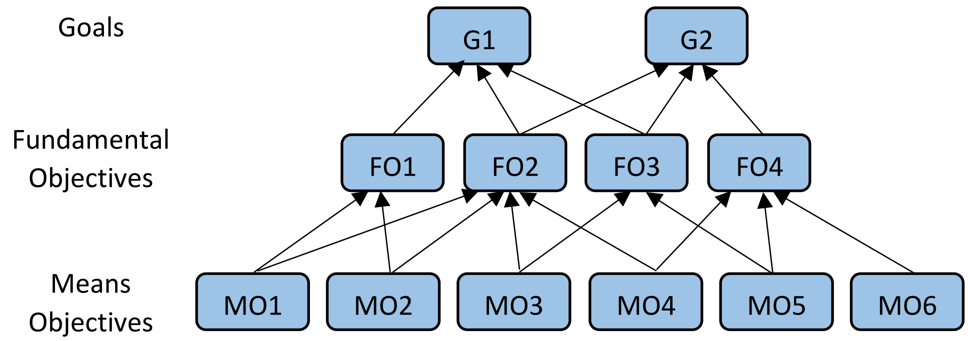


Figure 10: Notional objectives hierarchy

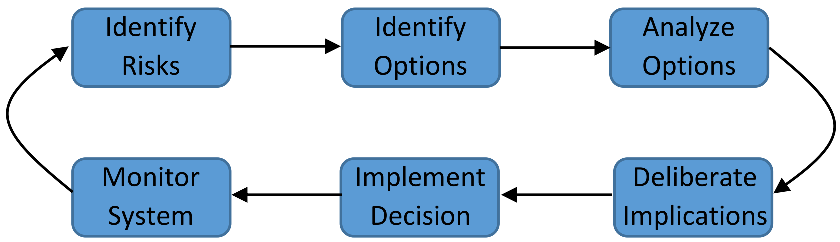


Figure 11: Risk-based analytic-deliberative process for decision-making [48]

However, risk-based and performance-based regulation approaches present a number of challenges that limit their applicability and effectiveness. One of these is the need for the performance goals and objectives to be measurable or calculable with a suitable level of precision [49]. Likewise, it must be possible to identify and adequately evaluate performance risks. Another challenge is being able to meaningfully compare and contrast the effectiveness of alternative actions [44]. These challenges are due, in part, to complexity, uncertainty, competing objectives, and different stakeholder perspectives [47]. Because of the limitations of purely risk-based evaluations, decision-making processes instead follow a risk-informed approach that incorporate other considerations such as multiple technical analyses; evaluation of assumptions, uncertainties, and sensitivities; stakeholder input; resource and schedule constraints; and other factors [48].

4.4. National Airspace System

The NAS was created to protect persons and property on the ground, and to establish a safe and efficient environment for civil, commercial, and military aviation [50]. The NAS consists of air navigation facilities, ATC facilities, airports, technologies, and operational rules and regulations (Figure 12). Today, the U.S. National Airspace System is a complex technical and social system embedded in the super-system of the national and international transportation systems. Viewed as an operational system, the NAS consumes resources (M5I) to enable aircraft of diverse sizes, configurations, and performance to share safely, effectively, efficiently, and dynamically a common airspace for a myriad of purposes such as movement of goods, policing, firefighting and rescue, personal and business travel, and recreation. Entry and exit from the airspace by commercial, private, and military aircraft takes place at a large number of geographically distributed airfields and airports with a wide range of sizes, traffic volumes, weather, and surrounding topography. The airfields and airports in the U.S. have widely varying available resources and levels of sophistication in local ATC capabilities and ground facilities for aircraft, goods, and people. Flights can range from short duration flights originating and ending at the same airport, to cross-country or international flights with distant starting and ending locations and routes that cross multiple ATC sectors that must coordinate their activities to ensure safe and expedient operations [51]. The major structural elements of the NAS, i.e., airports, air traffic control, the airspace, and aircraft, all vary in capabilities and dynamically evolve over time as changes are introduced, for example, at airports, airspace structure, navigation systems, ATC systems, and operational procedures (Figure 13). In 2010, the NAS had 20,000 airports; 242,000 aircraft; 628,000 pilots; 16,000 air traffic controllers; and 59,000 pieces of communication, weather, and navigation equipment; and there were about 58 million safe aircraft operations [52]. From a complexity perspective, the NAS has a very large irreducible variety in the sense that there are a large number of local cases with particular circumstances and conditions on the ground and in the airspace that require customized solutions.

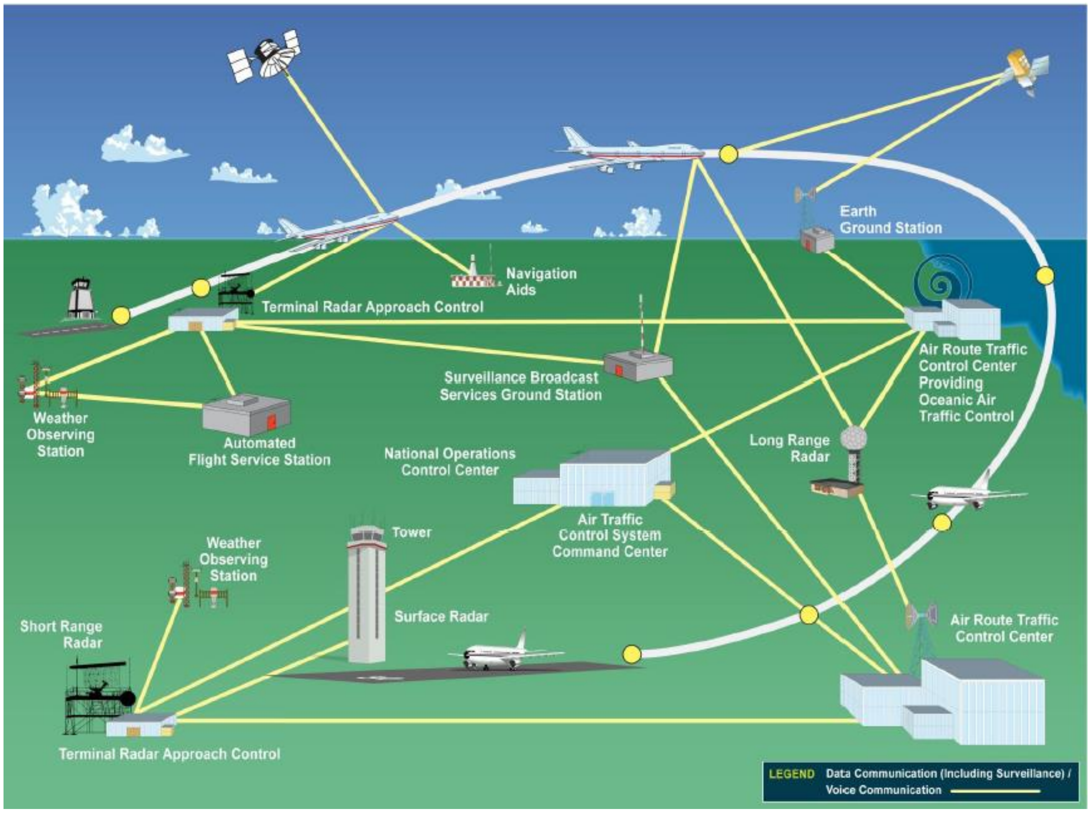


Figure 12: Operational concept view of the current NAS [90]

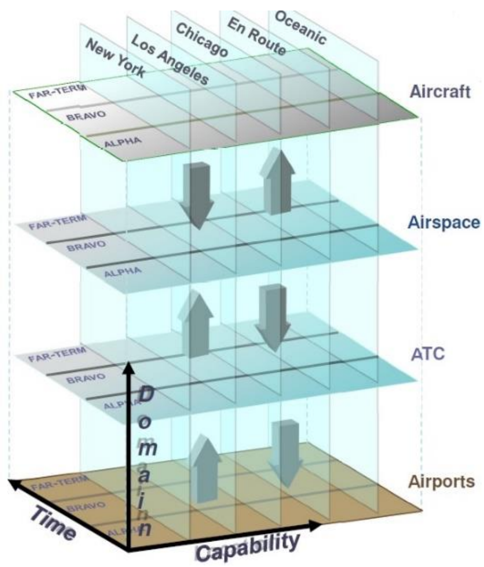


Figure 13: Notional depiction of major NAS components [57]

The structure of the national airspace is a complex environment that requires highly technical ATC procedures [50]. In the context of the NAS regulations, there are two major categories of civil aircraft: commercial (including scheduled and non-scheduled transport of passengers and cargo) and general aviation (i.e., everything else). Aircraft operate under two categories of flight rules: visual (VFR) and instrument (IFR). VFR operation is permitted only when and where the weather is good or fair as determined by visibility and cloud ceiling; IFR operation is required under all other conditions. Under VFR, the pilot has primary responsible for seeing and maintaining safe separation from other aircraft. Under IFR, ATC exercises positive control over all aircraft in the controlled airspace and has primary responsibility for aircraft separation. The majority of commercial air traffic operates under IFR regardless of the weather, although ATC can delegate visual separation responsibility to IFR aircraft if the weather is favorable. IFR operation is allowed only if the pilot is certified for this type of operation and the aircraft satisfies requirements for minimum level of communication and navigation equipage. Under IFR operations, aircraft must file a flight plan, follow ATC instructions, and request ATC clearance to deviate.

The airspace is structured into different classes of airspace as illustrated in Figure 14. These classes are in accordance with the International Civil Aviation (ICAO) airspace classification [53]. The classes of airspace are:

- **Class A**: From 18,000 to 60,000 ft. mean seal level (MSL); IFR only operation; ATC clearance to enter; ATC-provided separation;
- **Class B**: From the surface to 10,000 ft. above the surface surrounding the busiest airports in terms of operations or passenger enplanements; IFR and VFR operations; ATC clearance to enter; ATC-provided separation;
- **Class C**: From the surface to 4,000 ft. above the surface surrounding airports that have an operational control tower, are serviced by a radar approach control, and have a certain rate of IFR operations or passenger enplanements; IFR and VFR operations; two-way radio communication with ATC required to enter and operate; ATC provides separation for all IFR aircraft and for VFR aircraft from IFR aircraft; Traffic information and avoidance advice provided upon request;

- **Class D**: From the surface to 2,500 ft. above the surface surrounding airports with an operational control tower; IFR and VFR operations; two-way radio communication with ATC required to enter and operate; ATC provides IFR – IFR separation only; Traffic information and avoidance advice provided upon request;

- **Class E**: Controlled airspace other than A, B, C, or D; No requirement for VFR to contact ATC upon entry; ATC provides IFR – IFR separation only; VFR traffic information provided as far as practical; and

- **Class G**: Uncontrolled airspace; No ATC services for IFR or VFR.

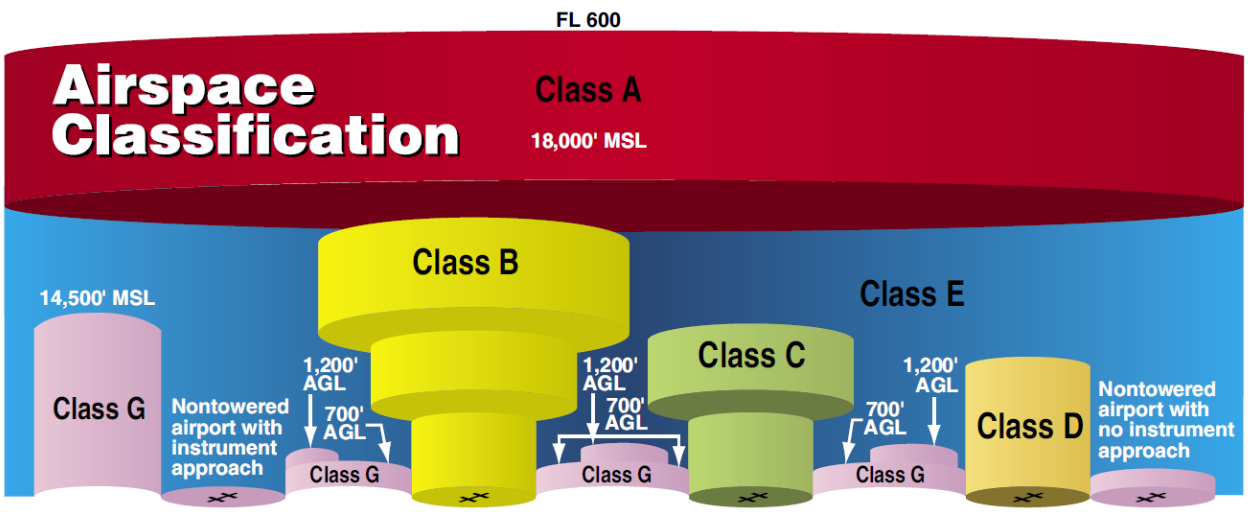


Figure 14: Airspace classifications [91]

In addition to these airspace classes, there is airspace designated as Special Use where certain activities must be confined or limitations are imposed on aircraft not performing part of those activities. This space is further sub-divided into:

- **Prohibited**: aircraft flight is prohibited for security or other reasons;

- **Restricted**: operations are potentially hazardous and subject to restriction;

- **Military Operations Area (MOA)**: areas designated for military training activities;

- **Warning**: similar to Restricted, but outside of U.S. jurisdiction;

- **Alert**: may contain unusual type of aerial activity such as pilot training; and
- **Controlled Firing Areas (CFA)**: presence of potentially hazardous activities, but these must be suspended if an aircraft approaches the area.

Because of the complexity of the airspace and the need to handle contingencies, the design of the NAS generally favors uniformity, order, and predictability to ensure safety and efficiency. This is a general characteristic in the management and operation of highly complex systems [21].

The technical operational layer of the NAS is governed by a managerial, organizational, and legal structure that monitors and coordinates NAS operations; interacts with internal and external stakeholders to ascertain the overall performance and impact of the NAS, and to identify trends that might necessitate changes to the NAS; and establishes governance principles, regulations, and policies for every aspect of the NAS. This higher-level governing system is run and managed by the Federal Aviation Administration (FAA), a large administrative organization of the U.S. federal government with internal and external cultural and political factors and conditions that constrain the ability of the organization to perform and adapt in a time- and cost-effective manner and provide services that meet customer expectations. Successful operation of the NAS depends on the structure and dynamics of the interactions of both technical and administrative elements of the system, as well as the interactions of the system with the external environment and context. From an organizational standpoint, this system has formally defined boundaries that separate internal from external elements. However, from the point of view of influence on the operation and evolution of the system, the boundary is much more uncertain and dynamic because, as a Government-administered system, the stakeholders outside the formal boundary of the system hold a large degree of power (i.e., influence) over what happens within the system. Each of these stakeholder groups has a different perspective on the NAS, as well as different interests in the outputs and outcomes of the NAS. A thorough stakeholder analysis (for example, as proposed by [18]) is outside the scope of this report. However, it seems clear that there is a large number of relevant stakeholders and that they have varying degrees of power (i.e., ability to influence other stakeholders), legitimacy (i.e., perception that the actions of the stakeholder are desirable, proper, or appropriate), and urgency (i.e., claims require immediate attention).

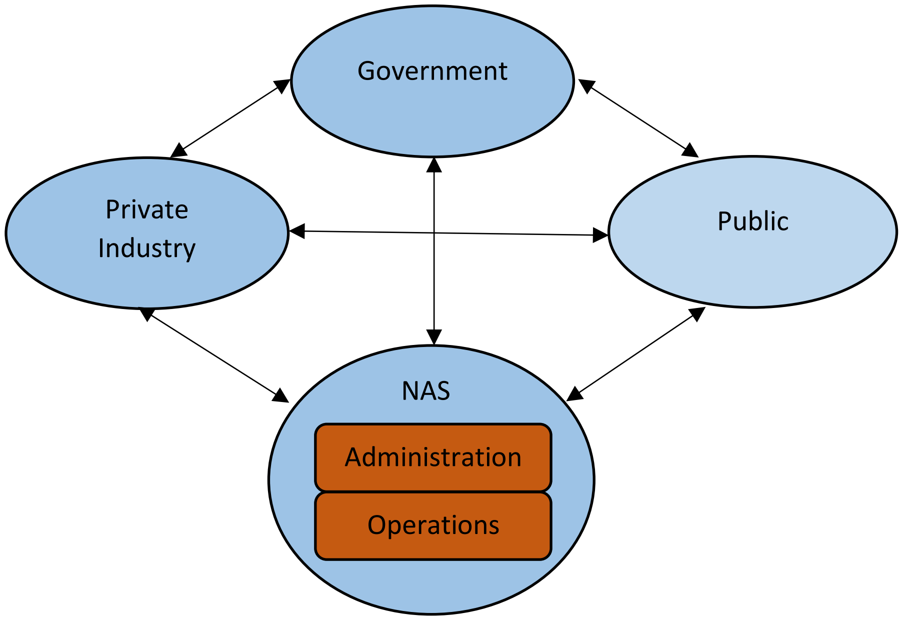


Figure 15: High-level contextual model of the NAS

The NAS is influenced by a complex contextual structure of resources, technology, information, skills, policies, regulations, economics, politics, culture, and social dynamics at local, state, national, and international levels. Figure 15 is a simple model of the NAS with administrative and operational layers, and external environmental and contextual elements that include government, private industry, and the public. The importance of the system context is that it bounds what the system is and does, and the impact it has on its environment. As such, the context contains much of the soft aspects of the human dimension, including organizational, managerial, political, policy, and social. The stakeholders are present in the NAS system itself, the environment, and the context. The attitude of individual stakeholders and stakeholder groups toward the NAS and proposed local and system-wide changes to the NAS can range from entirely supportive (i.e., enabling; in favor and cooperative) to entirely opposing (i.e., constraining; a threat and non-cooperative)

In general, a socio-technical system such the NAS can be conceptualized in terms of hard and soft layers (see Figure 16). The hard layer is objective, explicit, and unitary relative to purpose and goals. The soft layer is subjective, tacit, and pluralistic. The hard layer contains things such as physical entities, technology, plans, actions, decisions, organizational structures, work processes, and policies. The soft layer contains values, attitudes, intention, mood, ethics, morale, and culture. The hard and soft layers interact to make and implement decisions. As illustrated in Figure 16, more-strategic decisions made upwards are implemented downwards by more-operational decisions. Soft aspects tend to be more dominant upwards in the system. In general, each strategic decision is implemented by a multitude of lower level decisions. The outcomes of decisions higher in the system can have a higher impact but can also be more uncertain and the time between implementation and outcome can be larger. In addition, the higher layers of the system tend to change more slowly than the lower layers. To remain viable, the system must have feedback between higher and lower layers to account for implementation constraints and unintended down-stream effects [54].

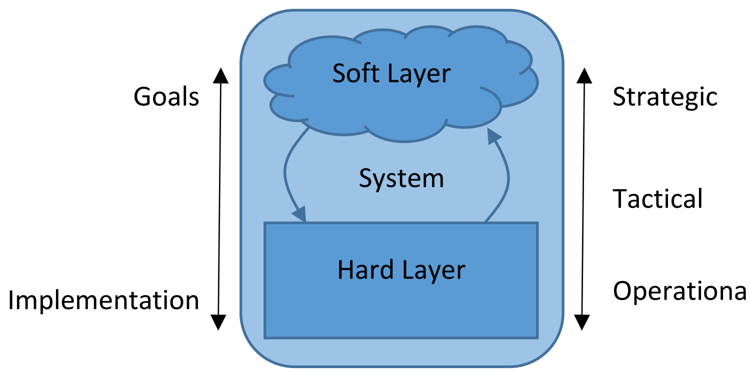


Figure 16: Hard and soft layers of the NAS

Figure 17 shows a process model for system transformation. This model is an adaptation of the one proposed by Mozdzanowska et al. [55]. The transformation process receives as input the operational demand, the system capability options, and the values of the stakeholders. Decisions for system change are the result of negotiation and implementation processes aimed at incorporating the system capability preferences of the stakeholders in realistic implementations that satisfy regulatory constraints about the operation of the system. This model is generic and applicable to systems and subsystems. Not shown in Figure 17 are feedback paths through the external environment that interact with the dynamic cycles within the system and can influence positively or negatively the operational demand on the system (i.e., there can be positive or negative feedback through the environment).

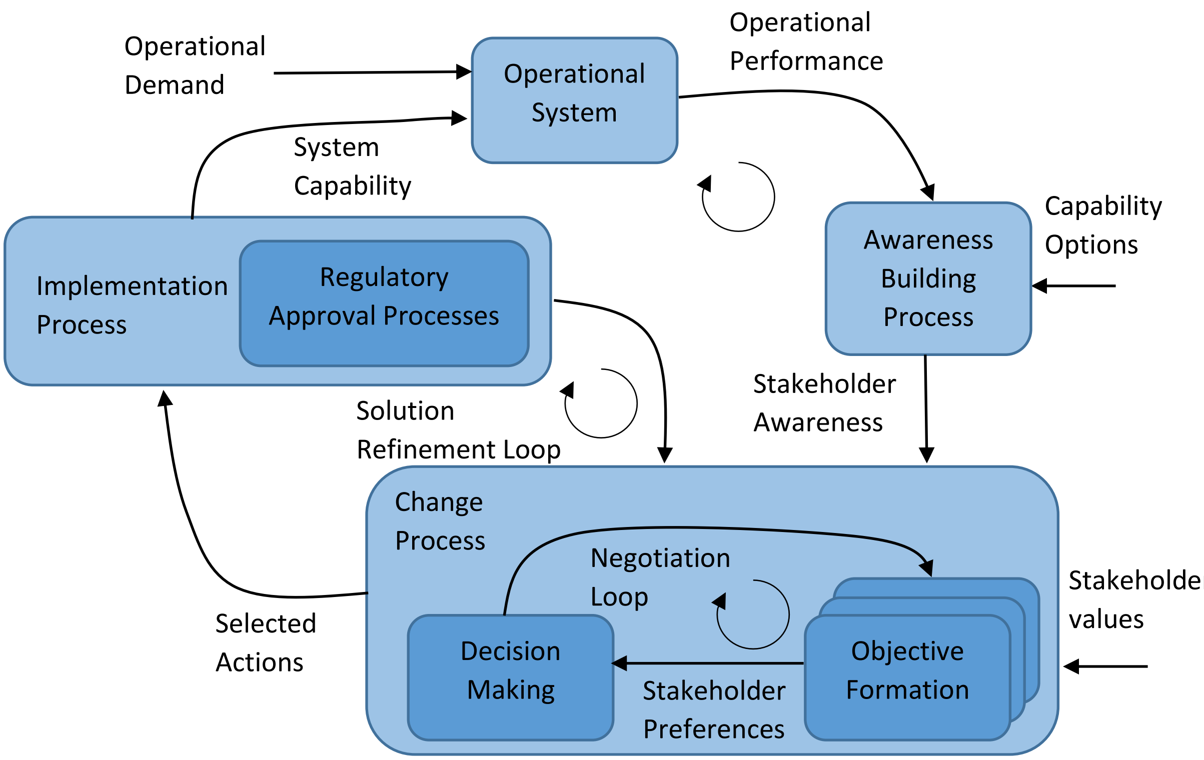


Figure 17: General process model of system transformation (Adapted from [55])

The current NAS is one of the safest means of transportation, but the system is already strained and it cannot scale to meet future demand. A shortfall in NAS capacity will result in lost productivity, increased operational cost, higher fares, and lost value to the airlines due to the elimination of flights to keep delays to an acceptable level [56]. The FAA is currently working on the Next Generation Air Transportation System (NextGen ATS) in an effort to transform and modernize the NAS to meet the future capacity demands, while maintaining safety and protecting the environment (Figure 18). NextGen will be a comprehensive transformation of the NAS. The transformation to NextGen is intended to increase capacity, flexibility, scalability, safety, reliability, and security, while reducing operational costs and minimizing the environmental impact in terms of noise and pollution. Through a combination of upgrades to airports, ATC, and aircraft enabled by new technologies and new operational procedures, data, information, and policies, NextGen will introduce [57] [58]:

Figure 18: NextGen ATS Operational View [93]

- collaborative air traffic management (ATM) with distributed decision-making involving air traffic controllers and aircraft flight crews and operators;
- performance-based operations by which operational procedures are selected based on the level of performance of the aircraft;
- reduced weather impact through enhanced weather information and forecast sharing and integration into ATM decision-making;

- high-density airport operations on the ground and in the air with reduced spacing and separation requirements; and

- flexible terminals and airports by exploiting the ability of aircraft to fly precise routes to uncover untapped ATS capacity and increase airport throughput.

This section provided a high-level overview of the NAS in its current state of transformation to improve its safety and performance for manned aircraft operations. It is in this environment that the push for integration of unmanned aircraft is taking place. The next section presents a high-level overview of regulations for manned aircraft operations.

4.5. Regulation of Manned Aviation

The governmental responsibilities in the regulation of aviation safety are:

- Ensure airworthiness of aircraft;
- Ensure the highest level of safety for public transportation;
- Ensure a basic level of safety for passengers in aircraft used for other purposes; and
- Ensure that aircraft can satisfy their safety-related responsibilities for mutual separation [34].

This is accomplished by:

- Certifying aircraft and supporting ground systems;
- Establishing operating rules; and
- Providing or incentivizing certain capabilities [34].

Aviation laws, policy, regulations, and guidance material can be viewed as a form of risk management [34]. From this perspective, the primary regulation strategy is the establishment of safety-related requirements to ensure ALOS conditions in operations. As harm to people and property during aviation operations can be described in terms of scenarios of unsafe (i.e., unintended and undesired) flow or movement of mass and energy, the regulations mitigate safety risks by targeting the causes and effects of such scenarios, either at the level of systems (i.e., whole purposeful structures) or at the level of individual elements and interactions. Certification in this context means approval and authorization for use, and applies to aircraft, personnel, operations, procedures, facilities, and equipment. The regulations address the three major kinds of aviation hazards: technical factors, human factors, and organizational factors [59].

The U.S. Federal Aviation Regulations (FARs) are contained in Title 14 of the Code of Federal Regulations (14 CFR) [60]. The FARs consist of 68 parts organized into volumes and subchapters as shown in Table 1 [61]. The regulations recognize two kinds of aircraft airworthiness certifications: standard and special. Table 2 lists the aircraft categories for airworthiness certificates, which attest that an aircraft is in condition for safe operation based on compliance with applicable regulations of aircraft design and manufacture. Notice that UA are classified as Experimental aircraft. Aircraft airworthiness regulations are extensive and detailed, covering most aspects of aircraft design and performance characteristics, as can be seen in Table 3 for Part 23 of the FARs regarding airworthiness standards for Normal, Utility, Acrobatic, and Commuter category airplanes.

Table 1: Structure of the Federal Aviation Regulations

Volume	**Subchapter**	**Content**
1	A	Definitions and Abbreviations
	B	Procedural Rules
	C	Aircraft
2	D	Airmen
	E	Airspace
	F	Air Traffic and General Operating Rules
	G	Air Carriers
3	H	Schools and Other Certified Agencies
	I	Airports
	J	Navigational Facilities
	K	Administrative Regulations
	L – M	Reserved
	N	Risk Insurance

Table 2: Aircraft airworthiness certificates

Airworthiness Certificate Classification	Category	Characteristics
Standard	Normal (Airplane)	• Maximum takeoff weight of 12,500 lbs. • Maximum passenger seating capacity of 9
	Utility	• Maximum takeoff weight of 12,500 lbs. • Maximum passenger seating capacity of 9
	Acrobatic	• Maximum takeoff weight of 12,500 lbs. • Maximum passenger seating capacity of 9
	Commuter	• Multiple engines • Maximum takeoff weight of 19,000 lbs. • Maximum passenger seating capacity of 19
	Transport (Airplane)	• Multiple engines • Maximum takeoff weight greater than 19,000 lbs. • Maximum passenger seating capacity greater than 19
	Manned Free Balloons	• Lighter-than-air aircraft that is not engine driven, and that sustains flight through the use of either gas buoyancy or an airborne heater
	Normal (Rotorcraft)	• Maximum takeoff weight of 7,000 lbs. • Maximum seating capacity of 9
	Transport (Rotorcraft)	Category A: • Maximum takeoff weight of 20,000 lbs. • Seating capacity of 10 or more Category B: • Maximum takeoff weight greater than 20,000 lbs. • Maximum seating capacity of 9
	Special class	• Aircraft for which airworthiness standards have not been issued (e.g., gliders, airships, and other nonconventional aircraft)
Special	Primary	• Maximum takeoff weight of 2700 lbs. (3375 lbs. if seaplane) • Maximum seating capacity of 4 • Unpressurized cabin
	Restricted (Airplanes)	• Maximum takeoff weight of 12,500 lbs. • Operated under the limitations for the intended use: Agricultural, Forest and wildlife conservation, Aerial surveying, Patrolling (pipelines, power lines), Weather control, Aerial advertising, Other operations specified by the FAA
	Multiple	• Multiple airworthiness certificates

Airworthiness Certificate Classification	Category	Characteristics
	Light-Sport	• Light-sport aircraft, other than a gyroplane, kit-built, or transitioning ultralight like vehicle; includes Airplanes, Gliders, Gyroplanes, Powered parachutes, Weight-shift-control aircraft (trikes), Lighter-than-air aircraft (balloons and airships) • Maximum weight of 1,320 lbs. for landplanes and 1,430 lbs. for seaplanes • Maximum airspeed of 120 knots • Maximum seating capacity of 2 • Maximum number of engines: 1
	Limited	• Issued to operate surplus military aircraft converted for civilian use • Limitations imposed as necessary for safe operation
	Experimental	Purpose: • Research and development • Showing compliance with regulations • Crew training • Exhibition • Air racing • Market surveys • ***Unmanned aircraft*** • Optionally operated aircraft • Amateur-built aircraft • Kit-built aircraft
	Special Flight Permit	• Special-purpose flight of an aircraft that is capable of safe flight (e.g., Flying the aircraft to a base where repairs, alterations, or maintenance are to be performed, or to a point of storage; Delivering or exporting the aircraft; Production flight testing new production aircraft)
	Provisional	• For special operations and operating limitations
	Restricted (Rotorcraft)	• Must have been used by the U.S. military

Table 3: FAR Part 23 structure

Part 23: Airworthiness Standards: Normal, Utility, Acrobatic, and Commuter Category Airplanes	
Subpart	**Sections**
A – General	
B – Flight	General, Performance, Flight Characteristics, Controllability and Maneuverability, Trim, Stability, Stalls, Spinning, Ground and Water Handling Characteristics, Miscellaneous Flight Requirements
C – Structure	General, Flight Loads, Control Surface and System Loads, Horizontal Stabilizing and Balancing Surfaces, Vertical Surfaces, Ailerons and Special Devices, Ground Loads, Water Loads, Emergency Landing Conditions, Fatigue Evaluation
D – Design and Construction	General, Wings, Control Surfaces, Control Systems, Landing Gear, Floats and Hulls, Personnel and Cargo Accommodations, Pressurization, Fire Protection, Electrical Bonding and Lightning Protection, Miscellaneous
E – Powerplant	General, Fuel System, Fuel System Components, Oil System, Cooling, Liquid Cooling, Induction System, Exhaust System, Powerplant Controls and Accessories, Powerplant Fire Protection
F – Equipment	General, Instruments: Installation, Electrical Systems and Equipment, Lights, Safety Equipment, Miscellaneous Equipment
G – Operating Limitations and Information	General, Markings and Placards, Airplane Flight Manual and Approved Manual Material

In addition to airworthiness regulations based on type of design, aircraft are classified based on intended use and further airworthiness requirements are applied accordingly. This classification in based on three factors:

- Is the service provided for private carriage or common carriage?
- Is the aircraft for hire or not for hire?
- Is the aircraft small or large? [61]

Per the FARs, an aircraft is large if it has a maximum takeoff weight greater than 12,500 lbs. A common carriage aircraft offers for-hire transport service to the general public. A private carriage for hire offers transport service on contract to one or several selected customers. All aircraft including general aviation aircraft (i.e., not-for-hire private aircraft) operate under general operating rules in Part 91: General Operating and Flight Rules. In addition:

- Common carriage aircraft (i.e., airliners) provide scheduled transport services and operate under Part 121: Operating Requirements: Domestic, Flag, and Supplemental Operations;
- Private, for-hire aircraft operate under Part 125: Certification and Operations: Airplanes Having Seating Capacity of 20 or more Passengers or a Maximum Payload Capacity of 6,000 Pounds or more; and Rules Governing Persons On Board Such Aircraft; and
- Scheduled-service, common-carriage, commuter aircraft and nonscheduled-service, common-carriage aircraft (referred as air taxis or air charters) operate under Part 135: Operating Requirements: Commuter and On Demand Operations and Rules Governing Persons on Board such Aircraft.

National aviation regulations are harmonized, to the largest extend practicable, with the standards and recommended practices of the International Civil Aviation Organization (ICAO), a specialized agency of the United Nations charged with the administration and governance of the Convention on International Civil Aviation (Chicago Convention), which establishes agreed principles and arrangements for safe and orderly international aviation [62]. Table 4 lists the annexes to the articles of the Chicago Convention.

Table 4: Annexes to the Convention on International Civil Aviation

Annex 1	Personnel Licensing	Annex 10	Aeronautical Telecommunications
Annex 2	Rules of the Air	Annex 11	Air Traffic Services
Annex 3	Meteorological Service for International Air Navigation	Annex 12	Search and Rescue
Annex 4	Aeronautical Charts	Annex 13	Aircraft Accident and Incident Investigation
Annex 5	Units of Measurement to be Used in Air and Ground Operations	Annex 14	Aerodromes (Airports)
Annex 6	Operation of Aircraft	Annex 15	Aeronautical Information Services
Annex 7	Aircraft Nationality and Registration Marks	Annex 16	Environmental Protection
Annex 8	Airworthiness of Aircraft	Annex 17	Security
Annex 9	Facilitation	Annex 18	Safe Transport of Dangerous Goods by Air

In 2009, the FAA published the results of an FAA-industry study into the adequacy of Part 23 regulations [63]. The motivation for this study and the later recommendations by the Aviation Rulemaking Committee [64] was the general concern in the aviation community that certification costs were too high and that the regulations were inadequate for new technology and overly prescriptive to the point of discouraging modern safety innovations. There was general agreement that over time the regulations had become more comprehensive and complex driven by the need to ensure an adequate level of safety for larger aircraft certificated under Part 23, but this had created a situation in which the complexity and cost of certifying smaller aircraft had become a barrier to the introduction of affordable entry-level aircraft and reduced industry competition and innovation. As illustrated in Figure 19, Part 23 regulations h evolved to a state where aircraft of simple design but adequate level of safety, such as those certificated decades ago under earlier versions of the regulations, could not be certificated under the current regulations. In essence, for a long time the focus and scope of Part 23 regulations had shifted to address the safety concerns of larger and complex airplanes to the detriment of smaller and simple ones, and this was (and still is) having a major impact in the development of the general aviation market.

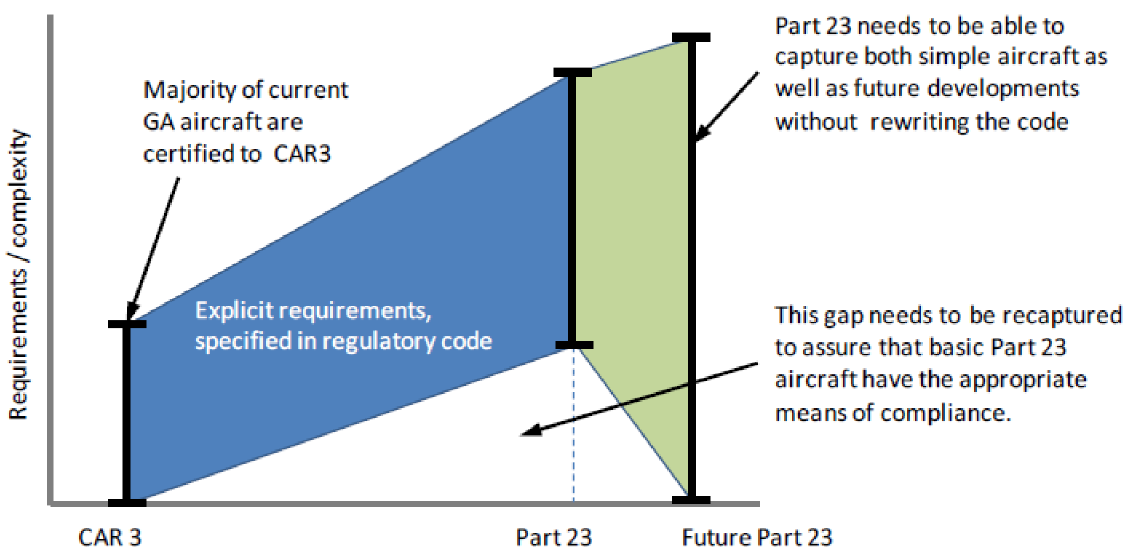


Figure 19: Evolution of Part 23 Regulations [64]

These studies proposed a number of recommendations to remedy the situation. One critical observation from these studies was that decades ago aviation technology was such that smaller Part 23 aircraft were simple and slow and larger aircraft were more complex and faster, but as technology and designs have evolved, this is no longer the case. The existing aircraft classification approach based on weight and engine type has become an ineffective measure for aircraft capability and performance. Hence, it was recommended that Part 23 be reorganized based on more direct measures of airplane complexity and performance. In March of this year, the FAA published a Notice of Proposed Rulemaking (NPRM) that puts forth a systematic revision to Part 23 regulations that moves away from prescriptive regulations and towards a performance-based certification approach. Furthermore, this NPRM proposes a redefinition of aircraft categories based on passenger seating capacity and aircraft performance for aircraft with maximum takeoff weight no larger than 19,000 lbs [65]. According to the NPRM, this offers a better approach to accommodate the large diversity of airplane performance, complexity, technology, intended use, and seating capacity covered under the current Part 23 regulations. This perspective on aircraft classification will be explored later in this report as a basis for an approach to UA classification.

4.6. Unmanned Aircraft Technology and Applications

The advent of unmanned aircraft in large numbers has created confusion about what an aircraft is and what aviation is about. Unmanned aircraft, especially small ones, are different from the common notion of *aircraft*, which usually means a flying machine in the form of an airplane, helicopter, or a variation of these and controlled by an onboard pilot. One definition of aviation is the operation of heavier-than-air aircraft [66], which aligns with the common notion. But the dictionary also gives a more general definition of aviation as the practice of flying aircraft [66]. The FARs define an *aircraft* as a device that is used or intended to be used for flight in the air [60]. ICAO defines an *aircraft* as any machine that can derive support in the atmosphere from the reactions of the air other than the reactions of the air against the earth's surface [67]. ICAO also gives the aircraft classification shown in Figure 20. An inspection of this figure reveals that unmanned aircraft are not included as a separate class. Per ICAO, an *unmanned aircraft* is an aircraft that is intended to operate with no pilot on board [67]. The FARs offer a similar definition of *unmanned aircraft* as an aircraft operated without the possibility of direct human intervention from within or on the aircraft [60]. Based on these definitions, a UA is an aircraft like any other, and what differentiates a UA from other aircraft as commonly understood is not any new aerodynamic principles, but simply the absence of an onboard human pilot to control the aircraft. In theory, any current manned aircraft could be flown as an unmanned aircraft if properly equipped for remote operation [68]. According to ICAO, in the future there may be unmanned versions of every category of aircraft [67].

Aircraft	Lighter-than-air aircraft	Non-power-driven	Free balloon	Spherical free balloon	
				Non-spherical free balloon	
			Captive balloon	Spherical captive balloon	
				Non-spherical captive balloon	
		Power-driven	Airship	Rigid airship	
				Semi-rigid airship	
				Non-rigid airship	
	Heavier-than-air aircraft	Non-power-driven	Glider	Land glider	
				Sea glider	
			Kite		
		Power-driven	Aeroplane	Landplane	
				Seaplane	
				Amphibian	
			Rotorcraft	Gyroplane	Land Gyroplane
					Sea Gyroplane
					Amphibian Gyroplane
				Helicopter	Land Helicopter
					Sea Helicopter
					Amphibian Helicopter
			Ornithopter	Land Ornithopter	
				Sea Ornithopter	
				Amphibian Ornithopter	

Figure 20: ICAO aircraft classification

By not having to provide an environment suitable for an onboard human pilot, aircraft designers are free to explore new configurations, performance regimes, and missions not possible previously. Now aircraft can be designed based on required functionality and payload for potential missions, rather than the design of the cockpit [68]. Figure 21 illustrates a UA classification used by the U.S. Department of Defense and examples of existing and future UA. The classification criteria here includes aircraft weight, maximum operational altitude, and maximum speed. Figure 22 illustrates the range of military UA based on endurance (i.e., flight duration) and payload capacity. These figures show that the scope and variety of design characteristics of UA (i.e., size, weight, speed, altitude, range, flight duration, and others) may be as large as or larger than for manned aircraft.

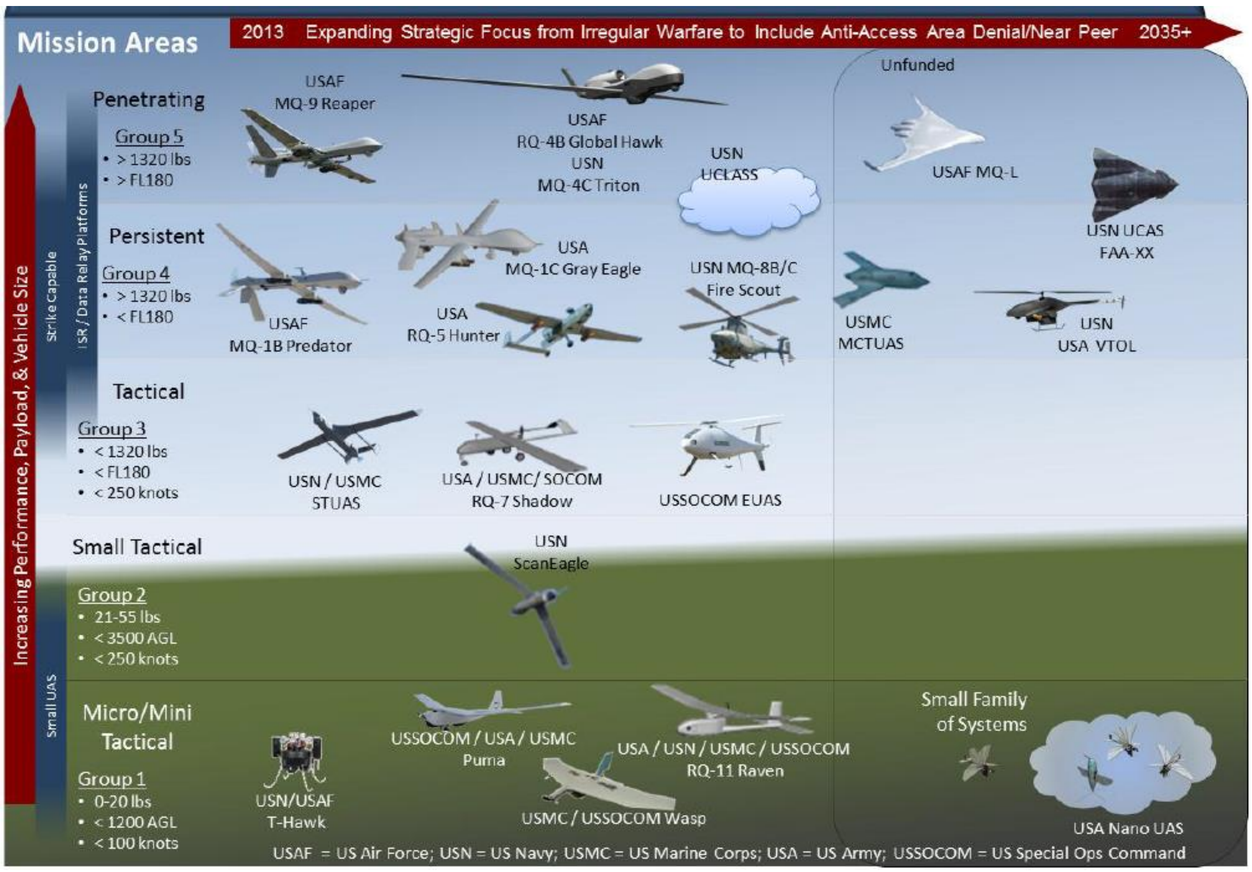


Figure 21: Military unmanned aircraft classification and examples [69]

The wide range of technical performance characteristics available to UA enables a myriad of applications beyond what is possible or desirable to do with manned aircraft. From the perspective of military applications, UA provide persistence, versatility, survivability, and reduced risk to human life, and may be the preferred aircraft choice for missions that are "dull, dirty, or dangerous" [69]. In a civilian context, there are three basic kinds of UA applications: surveillance (i.e., data collection), support (e.g., communication and data relay, payload drop, airborne refuel), and transport (of cargo or passengers) [70]. Table 5 lists some of the applications for unmanned aircraft. UA must have adequate vehicle and payload capabilities to perform missions like these.

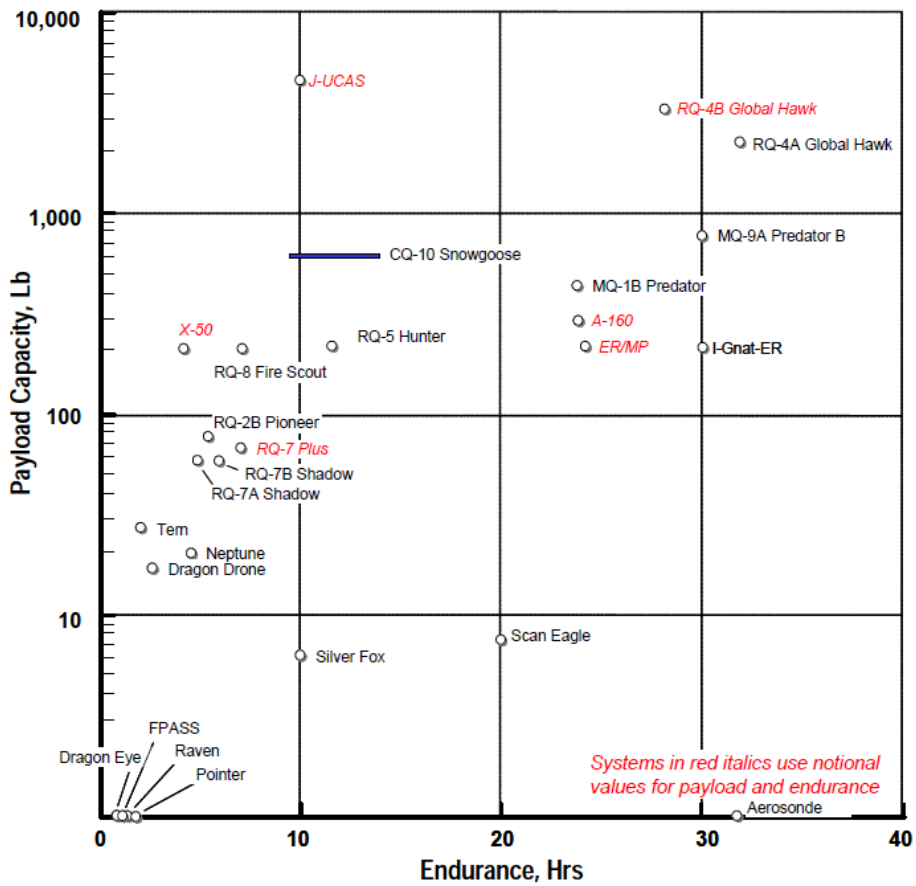


Figure 22: Range of DOD unmanned aircraft based on endurance and payload capacity [94]

Table 5: Partial list of potential applications for unmanned aircraft

Wildlife mapping	Law enforcement
Agricultural monitoring	Border patrol
Weather monitoring	Search and rescue
Traffic flows monitoring	Fisheries protection
Environmental monitoring	Fire fighting
Aerial imaging	Emergency management
Power line surveys	Telecommunications
Oil and gas exploration	News coverage
Freight transport	Research (atmospheric, geological, ecological, etc.)
Film making	Real estate imaging and monitoring
Construction	Training
Recreation	

ICAO documents define the concept of a remotely piloted aircraft (RPA) as a subcategory of UA in which the flying pilot is not onboard the aircraft (Figure 23). This distinction is needed because model aircraft fall outside the provisions of the Chicago Convention and autonomous aircraft, although subject to the provisions of the Convention, are not expected to be able to integrate into the international civil aviation system (of which the U.S. NAS is a part) in the near future. ICAO defines autonomous aircraft as UA that do not allow pilot intervention in the management of the flight. Special rules apply to model aircraft in the NAS, where a model aircraft must satisfy requirements such as:

- capable of sustained flight in the atmosphere;
- operated in accordance with a community-based set of safety guidelines;
- weighs no more than 55 lbs., unless otherwise certified through safety program administered by a community-based organization;
- operated in a manner that does not interfere with and gives way to any manned aircraft; and
- flown for hobby or recreational purposes [8] [68] [71].

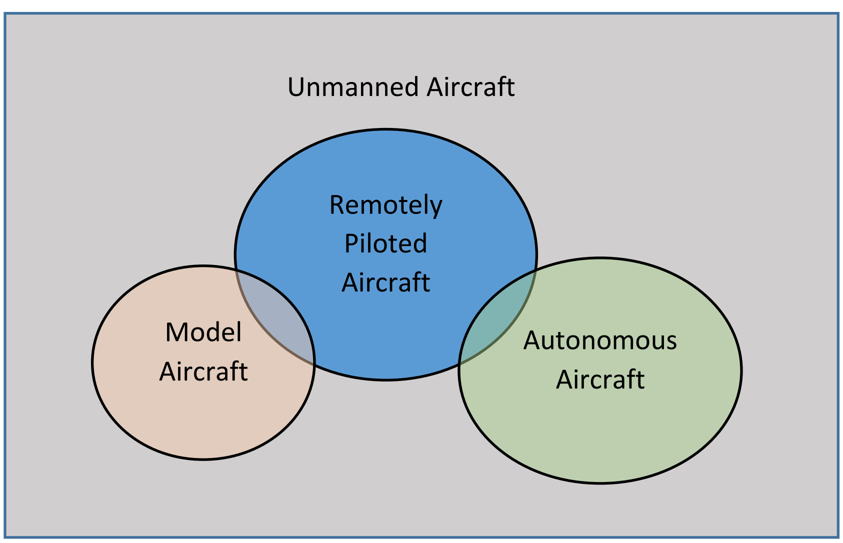


Figure 23: Unmanned aircraft as remotely piloted aircraft [72]

The rest of this report deals specifically with RPA UA that may have automated or semi-autonomous functionality, but there is always a remote pilot that can intervene in the management of the flight.

An RPA UA is piloted from a remote piloting station (RPS) via a command and control (C2) link. An RPA, RPS and C2 link together comprise an RPA system (RPAS) [72]. The C2 link function can be realized with two basic architectures, depending on the structure of the physical data flow path: radio line-of-sight (RLOS) and beyond RLOS (BRLOS). In an RLOS configuration, there is direct electronic point-to-point contact between the transmitter and receiver as they are in mutual radio link coverage [67]. This configuration applies to visual line-of-sight (VLOS) operations, in which the pilot maintains direct visual contact with the RPA, and also RLOS operation beyond VLOS (BVLOS), where data flows directly between the RPS transmitter and the RPA receiver (Figure 24), or through a mediating transceiver network with comparable time delays. In a BRLOS configuration, the data flows through a transceiver network, with terrestrial, airborne, and/or orbital satellite elements (see Figure 25), and the delay is significantly larger than for RLOS to the extent that it can affect the time precision and the kinds of actions implemented through the C2 link.

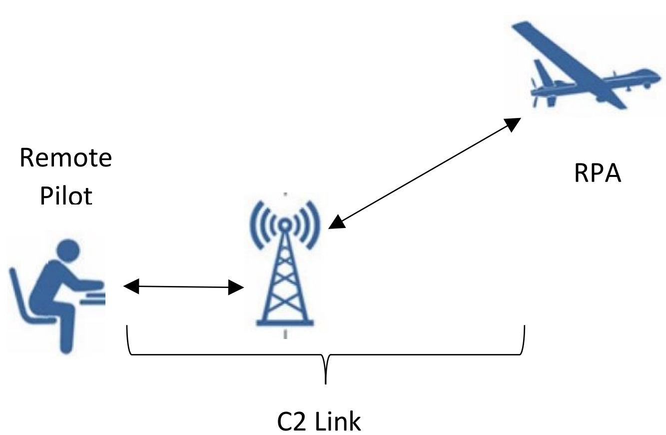


Figure 24: Basic RLOS C2 link [72]

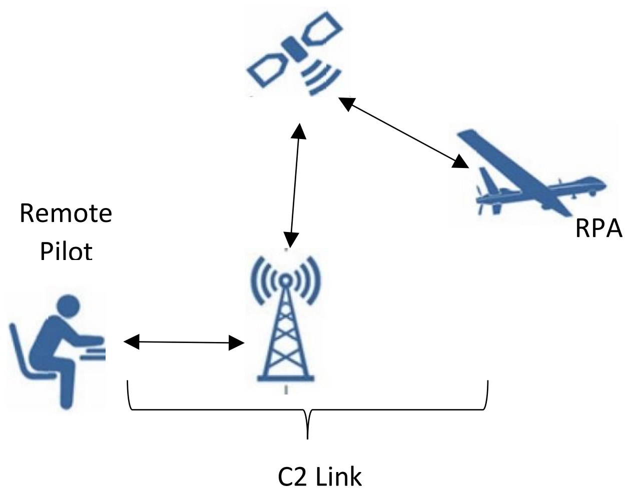


Figure 25: BRLOS C2 link with satellite relay [72]

In (air traffic) controlled airspace, the pilot must be able to communicate and respond to ATC commands with effectiveness and efficiency comparable to that of manned aircraft. A number of communication architectures are possible, including:

- RLOS in which the RPA serves as a relay between the RPS and ATC (Figure 26);
- BRLOS with intermediate relay transceivers as well as relay through the RPA itself;
- Direct radio communication between RPS and ATC (i.e., not relayed through the RPA) (Figure 27);
- Direct ground communication between RPS and ATC (e.g., a telephone line);
- RPS-ATC ground communication though a mediating network (Figure 28); and
- Satellite-based RPS-ATC communication [72].

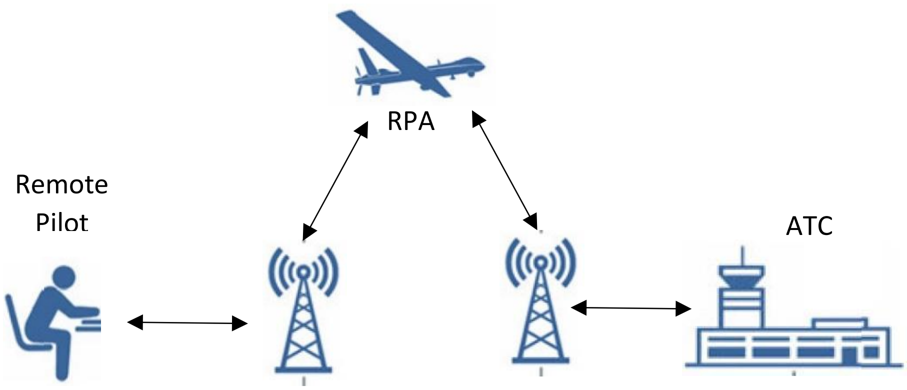


Figure 26: RPS-ATC communication with RPA relay [72]

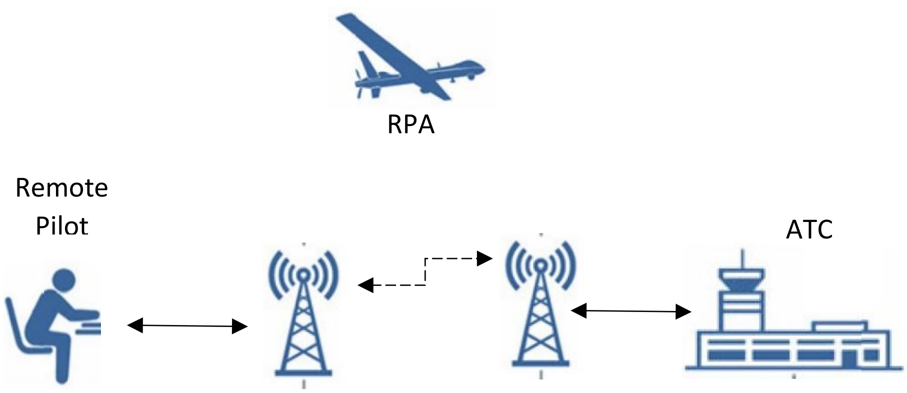


Figure 27: RPS-ATC direct radio communication [72]

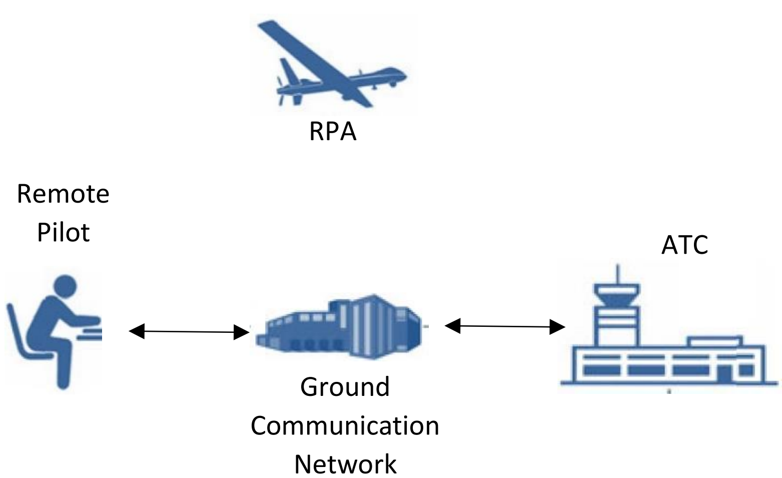


Figure 28: RPS-ATC communication through ground-based network [72]

Currently there are proposals for an ATC system specifically designed for managing UA traffic operating near ground level in airspace normally not used by manned aircraft. NASA's UAS Traffic Management (UTM) concept is an example of such a system (Figure 29) [73]. For the purpose of this report, this low-altitude region will be referred to as *ground-space* and includes the airspace (and the air traffic within it) and the surface topography with natural (e.g., mountains, trees) and manmade features (e.g., buildings, tower, bridges, etc.). ATC in this region will be referred to as ground-space traffic control (GTC). Thus, an RPA pilot may interact with ATC and/or GTC during a mission (i.e., an operation) (see Figure 30).

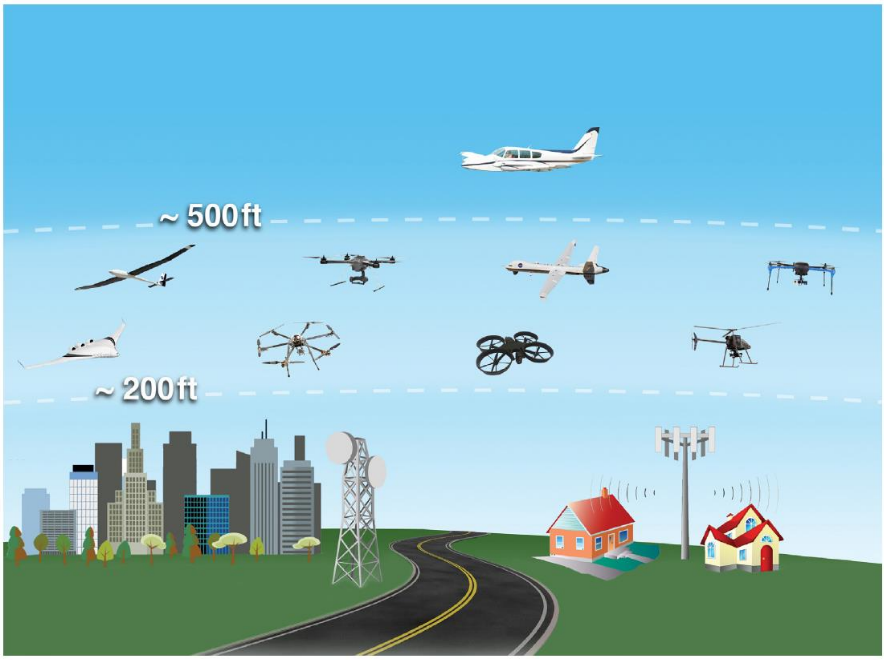


Figure 29: Concept graphic for NASA UA Traffic Management (UTM) [96]

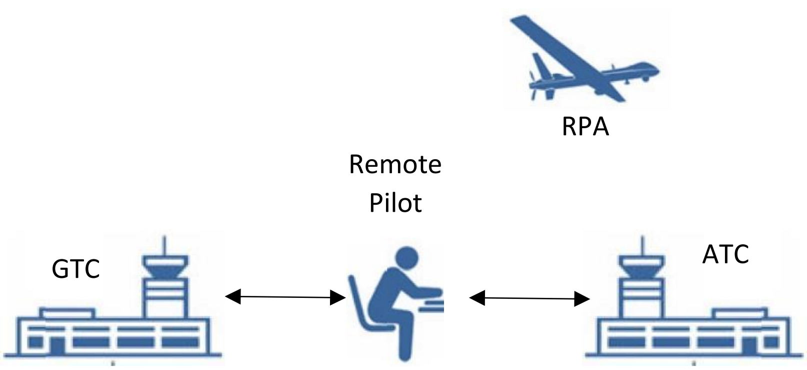


Figure 30: ATC-RPS-GTC communication

4.7. Unmanned Aircraft Safety Risk

The operational environment of remotely piloted unmanned aircraft includes the airspace and the ground-space, as illustrated in Figure 31. To accomplish its mission, the UA pilot must navigate this environment with the help of RPS and UA sensors, as well as ATC and GTC if operating in traffic-controlled areas. From a safety perspective, the major concerns are mishaps involving manned and unmanned aircraft in the air, and people and property on the ground (Figure 32). Relative to the environment, the operation of the UA itself can be a hazard as the potential proximate cause of a mishap. In this sense, there are two scenarios of interest, with two subcases each: Flight Into Terrain (FIT) and Loss of Separation (LOS), both under controlled and uncontrolled flight [74]. Hazardous controlled flight can be due to inadequate or incorrect information available to the pilot and loss of situational awareness (e.g., confusion) about the state of the UA and the environment. Hazardous uncontrolled flight includes cases such as loss of C2 link, internal failure of the UA, and in-flight upset where the UA is in an uncontrollable attitude (e.g., upside down).

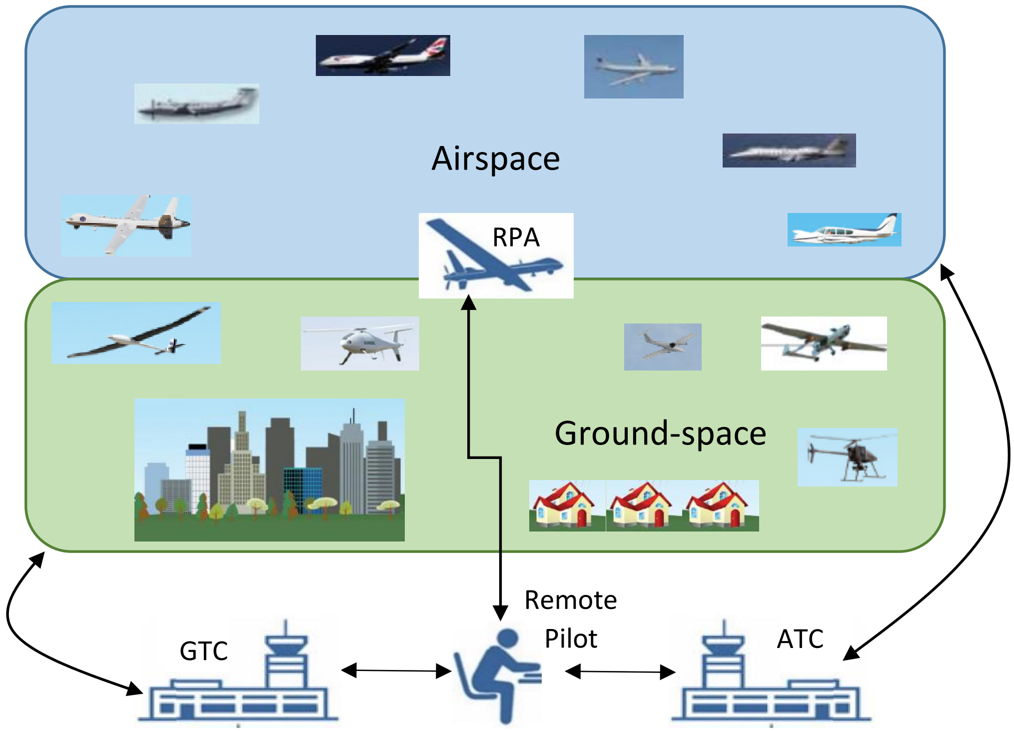


Figure 31: Unmanned aircraft in operational environment

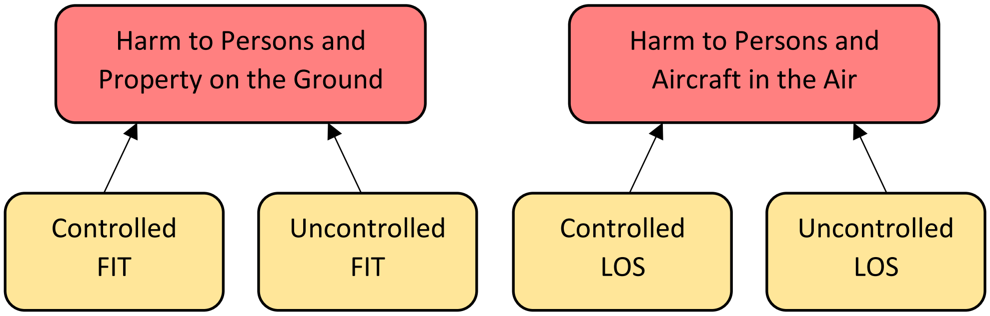


Figure 32: Major mishap scenarios for unmanned aircraft

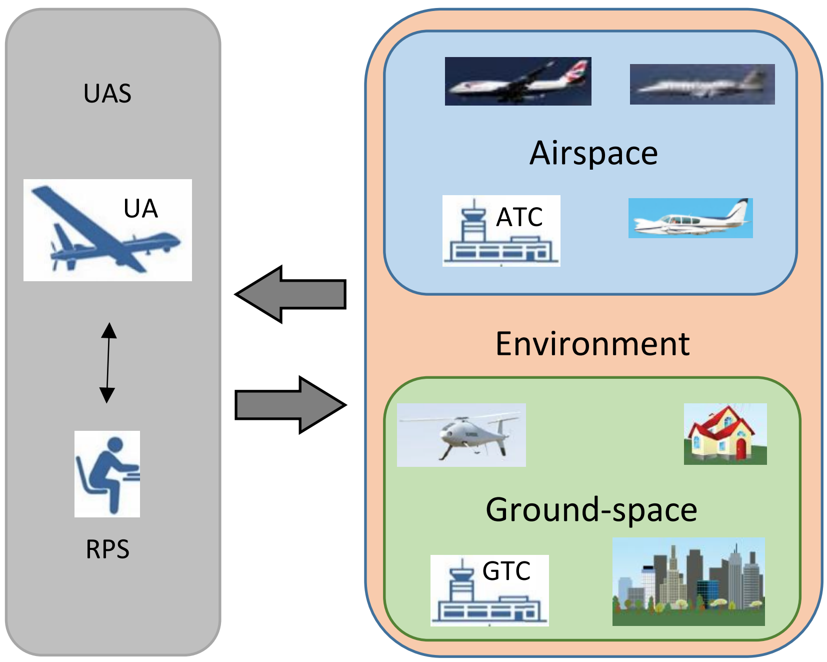


Figure 33: Structural view of UAS interacting with its environment

For a deeper understanding of the safety-related aspects of RPA UA operation, we need a structural view of the UAS and its environment. This is illustrated in Figure 33. The UAS consists of hardware and software systems (including mechanical systems, electrical systems, electronic systems, hydraulic systems, avionics, and so on), as well as the flight and mission crew in charge of operating the UA and its payload. The environment includes the operational and natural environments with which the UAS must interact, both in the airspace and the ground-space. In this partitioned abstract view, the flows of interest between the UAS and the environment include only information (i.e., data). To accomplish the mission, the pilot must navigate the environment using: the mission plan and procedures; information from the airspace, ATC, ground-space, GTC, the RPA UA, and the RPS; and the capabilities of the UAS in terms of aerodynamic and functional performance, including information-processing capabilities.

According to one model, the UAS, including the pilot, RPA, and RPS, performs four top-level functions: Aviate, Navigate, Communicate, and Mitigate [75]. The Aviate function consists of the actions to control (i.e., change and stabilize) the attitude and flight path of the UA. The Navigate function includes all the activities for managing the desired trajectory and execute the mission plan. The Communicate function deals with the exchange of information (both voice and data) with ATC, GTC, and other aircraft. The Mitigate function manages (i.e., prevents and minimizes the impact of) unintended interactions and contingencies related to the operational and natural environments and the UAS itself. The execution of these functions must be coordinated to ensure overall success and safety of the mission. The UAS may incorporate automation systems intended to reduce the workload of the pilot in the performance of these functions.

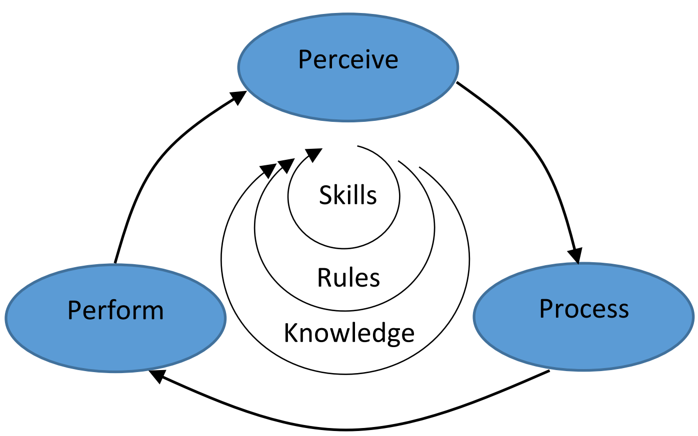


Figure 34: 3P model of task management augmented with SRK model of behavior

The 3P model, illustrated in Figure 34, describes the iterative process in managing piloting tasks [76]. In the Perceive step, the pilot gains situational awareness by gathering information relevant to the task and making sense of it. In the Process step, the pilot decides how to proceed based on the intent, the plan, and the current situation. In the Perform step, the pilot performs the decided action to make progress toward achieving the current goal. With each step, the scope of the world under consideration gets progressively smaller as information is ranked by criticality (i.e., impact and urgency) to the task and the step being performed (see Figure 35).

In the iterative 3P process of task management, the pilot uses a mix of skill-based, rule-based, and knowledge-based behavior (SRK) to accomplish the mission objectives [77]. Skill-based behavior is mostly automatic and subconscious sensory-motor acts that process information from the pilot's environment as signals representing continuous variables. Rule-based behavior is the semi-conscious application of existing rules or procedures (either empirically derived or otherwise acquired) to known situational patterns recognized by signs in the state of the environment. Knowledge-based behavior is mostly conscious and deliberate problem solving and decision making by contextualizing information about the state of the environment at an abstract level as symbols and deriving suitable actions to handle situations unlike those previously experienced. Each step-up in behavior is triggered by the demands of the task to deal with progressively complex and unfamiliar situations. Higher-level behaviors also take progressively longer time to execute. Generally, automation systems are designed to perform actions that require skill-based behavior and some rule-based behavior. The pilot then is responsible for managing the automation, including possibly taking over in case of a failure.

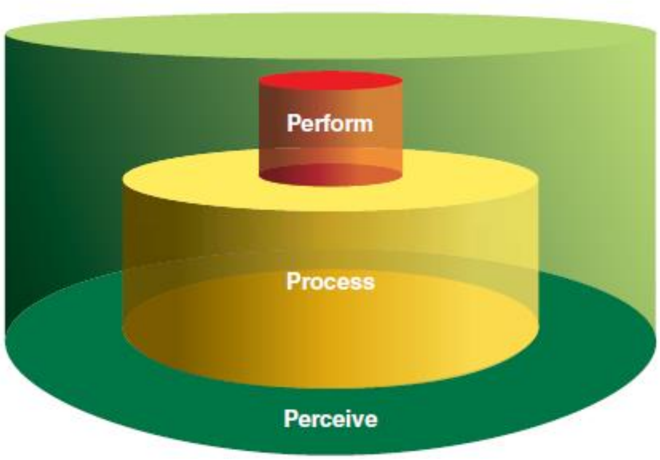


Figure 35: Progressive scope of information relevance in the 3P model of task management [76]

UAS mishaps, both FIT and LOS, may be caused by human error or technical system failures. Human error accounts for 80% of all aviation mishaps and technical system failures account for 20%. [78]. Human errors can be errors in perception, processing, or performance, either slips or lapses in skill-based behavior, or mistakes in rule-based and knowledge-based behavior [79]. Human error can also be due to routine or exceptional violations of established operational norms and procedures. In general, the higher the amount and complexity of the workload, the more likely that human error will happen. Technical system failures can have a number of causes. These systems are usually developed using recognized international standards, such as ARP-4754A for systems [80] and DO-178 for software [81], and are allocated reliability and safety requirements suitable to their functional criticality. The major technical concerns for UA are detect-and-avoid (DAA) capability and lost-C2-link procedures [82]. Non-existing or inadequate DAA capability, either ground-based or airborne, can impact situational awareness and the ability of the UAS to avoid collisions, especially during VFR operation. Failure of the C2 link must usually be mitigated by on-board automatic contingency procedures and ATC or GTC procedures to protect the air traffic.

4.8. Considerations for Unmanned Aircraft Regulations

The NAS is a system created and managed for the benefit of society. At the system level, the intent is to maximize the benefits of this enterprise and to minimize the costs and undesired consequences of its operation. This means that primary assessment criteria for the NAS are safety (relative to harm to people, property, and the environment), effectiveness (e.g., capacity and expediency of operations), and efficiency (e.g., cost-benefit ratio). The system is expected to adapt to the trends in service demand and to changes in stakeholder values, preferences, and expectations. The evolution of the system is enabled by knowledge and technological advances, and it is constrained by complexity, polytely (i.e., multitude of competing goals), resources, and circumstances and conditions external to the system.

The NAS is undergoing the transformation to NextGen, which is intended to achieve a step increase in performance to meet projected future demand in manned aviation [6]. However, the NextGen planning and architecture did not anticipate the demand for UAS in the NAS, and the system is not suitable for the introduction of these types of aircraft [83]. Nevertheless, the FAA's intent is to accommodate initially UAS operations with special procedures and mitigations to ensure minimum adverse impact on NAS safety and efficiency, and to gradually proceed toward integration as policy, regulations, standards, and operational procedures are developed [84].

Part 107 of the FARs applicable small UAS (sUAS) is the most recent step in this direction. Part 107 sets a multitude of operational restrictions, among them:

- UA must weigh less than 55 pounds;
- VLOS operation;
- daylight operation;
- remote pilot is allow to control only one aircraft at a time;
- minimum weather visibility of 3 miles from the control station;
- no flight over persons not directly participating in the operation;
- maximum groundspeed of 100 mph; and
- maximum altitude of 400 feet, or remain within 400 feet of a structure if flying higher than 400 feet above ground level;

Part 107 requires the remote pilot to have a remote airman pilot certificate with a small UAS rating. Preflight inspections of the UAS are required, but airworthiness certification is not required.

The issues pertaining to the integration of UA into the NAS include:

- **UAS certification**: lack of experience in certifying UAS; Figure 36 given a sense of the scale and variety of regulatory products that must be generated to certify and approve the operation of UAS;
- **Operating rules and procedures for UAS**: many existing operating rules and procedures require human vision from onboard the aircraft;

- **UA performance**: UA generally do not satisfy communication, navigation, and surveillance (CNS) performance required in some areas of the airspace;
- **UAS operational profiles**: UA aerodynamic performance characteristics can be quite different from manned aircraft and this complicates the task of ATC;
- **Inadequacy of ATM automation**: ATC decision support tools are not suitable for managing the complexity of integrated manned and unmanned aircraft operations;
- **UAS airport operations**: many airports and support infrastructure are not intended nor suitable for handling UAS;
- **UAS communication link with ATC**: inadequate communication infrastructure and service quality; and
- **UAS C2 link**: signal delays and link reliability may impact UA control performance, responses to lost-link conditions are not consistent or predictable, and the frequency of lost-link conditions may have a detrimental impact in NAS traffic performance [82] [84] [85].

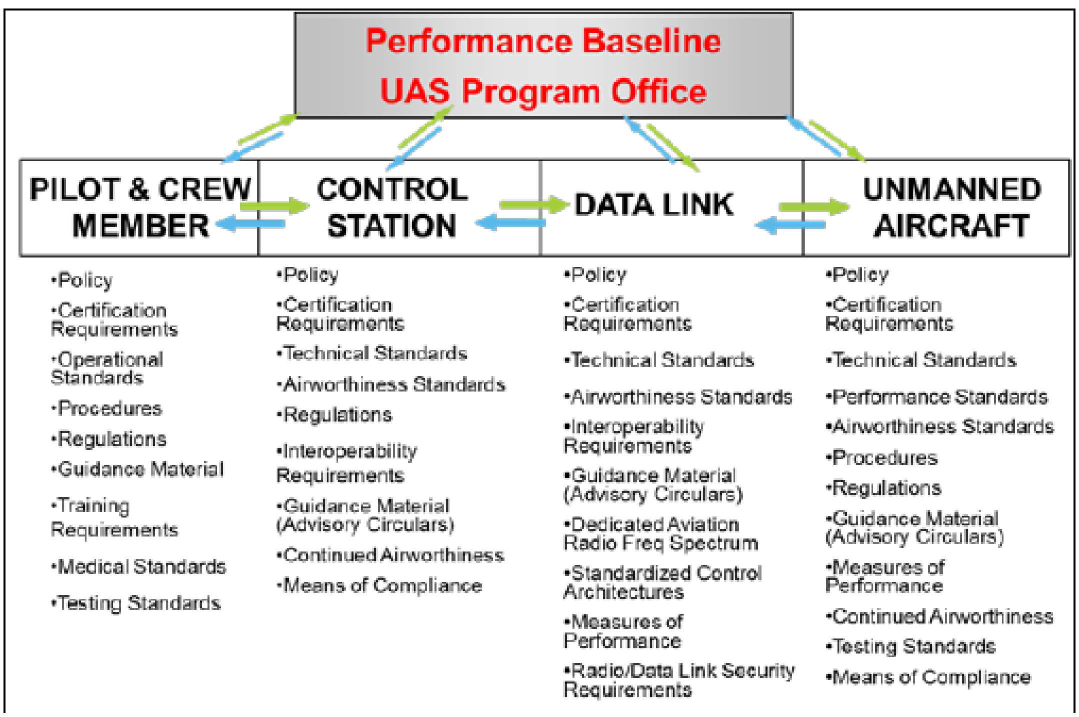


Figure 36: Sampling of regulatory products for certification and operational approval of UAS [88]

From the perspective of society, UA are simply aircraft and the expectations for safety are based on the perception of the potential for harm to third parties and the people involved. As a result, manned and unmanned aircraft exist in a common continuum of public concern and demand for safety assurance, as illustrated in Figure 37 [34] [42] [86].

Figure 37: Safety Continuum demanded by society [86]

In addition to technical and safety aspects of UAS operations in the NAS, other considerations for UA regulations include security, privacy, civil rights, civil liberties, trespass and nuisance concerns, preemption of state and local regulations, insurance liability, economic impact, noise, and pollution [5] [68] [87]. As with manned aircraft regulations, there is interest from regulators and industry that the regulations for unmanned aircraft be:

- **operation-centric** (i.e., based on UA safety in the intended operational environment);
- **safety-risk-based** (i.e., based on safety risk considerations regardless of whether the operation is for commercial purposes or otherwise);

- **proportionate** (i.e., safety requirements tailored to the safety risk posed by the operation);
- **progressive** (i.e., tiered); and
- **performance-based** (as opposed to prescriptive regulation) [63] [64] [88] [89].

5. Analysis

The aviation regulations are the principal instrument to attain the main goal of the NAS of ensuring safety of flight. The structure and content of the regulations is currently, and will continue to be in the future, determined primarily by safety considerations. The aviation regulations must evolve and adapt to the changing realities and expectations of the public, industry, and government, but they must not change so quickly or be so complex that it creates an environment of uncertainty and discourages participation and innovation. In addition, at any point in time, the regulations must be flexible in allowing multiple means of participation and compliance as determined by the needs and resources of the regulated, but they must not be so permissive as to endanger the very goals they are intended to advance. The regulatory framework must also promote other major goals of the NAS, such as expediency and cost-efficiency, as well as accommodate other social, economic, and political interests and concerns.

The safety concern in aviation is the potential for unintended and undesired harm to people, property, and aircraft, both in the air and on the ground. The degree of concern increases with the perceived magnitude of loss that could befall from aircraft in operation. This is captured (i.e., modeled) by the inverse relation between severity and likelihood of mishaps for an acceptable level of safety (ALOS). The severity scale must account for the objective and subjective dimensions of criticality and value. The likelihood scale, too, must account for objective and subjective dimensions of probability and uncertainty. From a technical standpoint, the ALOS relationship implies that both aleatory (i.e., randomness) and epistemic (i.e., systemic, knowledge) components of uncertainty must be accounted for. That is, the ALOS relationship applies to both aleatory safety risk and epistemic safety risk (Figure 38). Ensuring aviation safety means that both aleatory risk and epistemic risk in operations are acceptable.

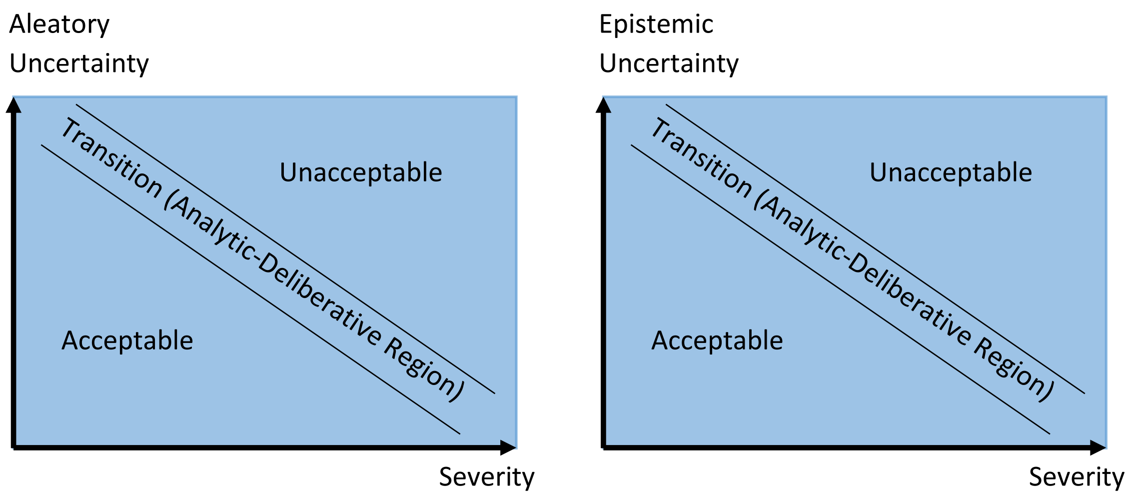


Figure 38: ALOS components: aleatory risk and epistemic risk

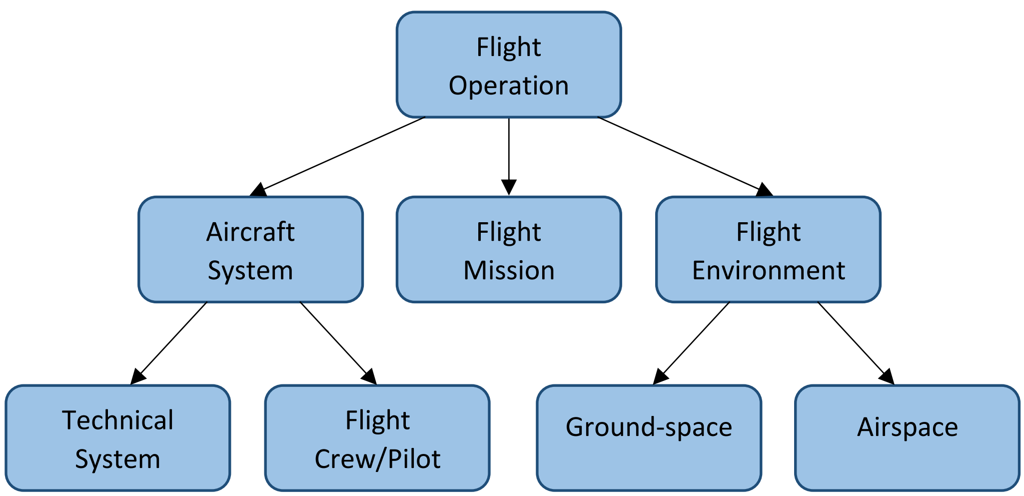


Figure 39: Major elements of a flight operation

A flight operation consists of four major elements: the mission, the pilot, the aircraft, and the environment (Figure 39). The mission includes the purpose, plan, and procedures. From preceding discussion, manned and unmanned aircraft exist in a common continuum of safety concern, and unmanned aircraft (RPA in particular) are simply aircraft with a non-conventional command, control, and communication (C3) arrangement. Thus, it makes sense to generalize the concept of aircraft to that of **aircraft system** (**AS**) that encompasses both self-contained aircraft with onboard-pilot and flight systems, and unmanned aircraft with remote pilot and physically distributed flight systems. The environment includes the operational airspace and ground-space with air traffic, ATC, and GTC, as well as the natural environment.

To accomplish the intended missions, the aircraft system must have aerodynamic and functional capability profiles compatible with the requirements of the missions and the environments in which the operations will take place. Both inadequate and excessive capabilities could result in unfavorable operational effectiveness and/or efficiency, as well as potential interaction incompatibility with the environment that could have safety and air-traffic performance implications.

In general, an increase in the desired effectiveness (i.e., benefit) and efficiency (i.e., benefit-cost ratio) of aircraft operations is correlated with an increase in the complexity of the missions and the variety of operational environments, as well as an increase of the operational productive capabilities of the AS. Higher AS capabilities develop along the dimensions of capacity and sophistication of aerodynamic and functional performance. That is, increased operational effectiveness and efficiency implies a progressively larger space of power and refinement of AS flight dynamics and functions. These measures map to the safety-relevant measures of performance (e.g., speed, altitude, take-off weight, climb rate, turn rate) and complexity (of physical and functional design) identified in the study on Part 23 small airplane certification sponsored by the FAA [63]. As aircraft systems are designed for their intended operations and customers, their optimum balance of operational effectiveness and efficiency varies. As observed in the Part 23 study, given today's spectrum of available aviation technologies, flight performance and design complexity are not correlated in the aircraft fleet. Thus, in effect, increased operational effectiveness is correlated with increased flight performance and increased complexity of design, both functional and physical, but performance and complexity are loosely correlated (Figure 40).

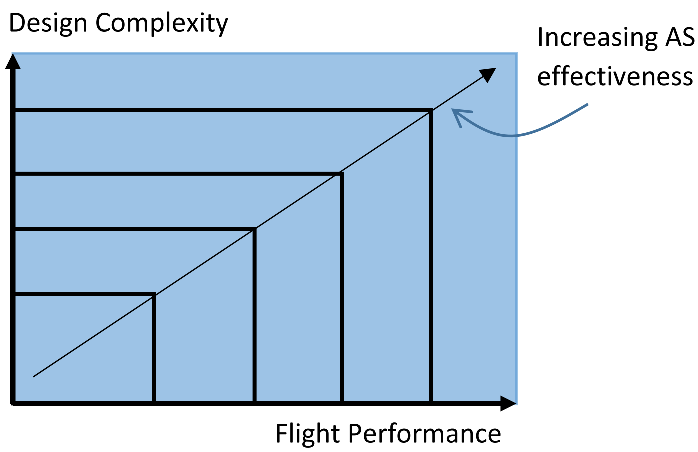


Figure 40: Aircraft system performance and complexity space with increasing effectiveness

These measures of AS performance and complexity are significant from a safety standpoint because they are critical factors in the potential severity and likelihood of mishaps. As stated previously, relative to the operational environment, the operation of the aircraft itself can be a hazard as the potential proximate cause of a mishap involving people, property, and other aircraft. The AS hazards of interest are hazardous controlled flight and uncontrolled flight, which can lead to FIT and LOS. To assess the safety risk of an operation, we need to consider the causes and effects of AS hazards (Figure 41). As described in Section 4.2, the safety risk factors are: hazard risk, which is a combination of hazard likelihood and severity (i.e., the worst possible mishap with the environment in its most unfavorable state); exposure; and likelihood of mishap given that the hazard has occurred [26]. The exposure and mishap likelihood are determined by the space and time distributions of the mission actions and the environment entities, both on the ground and in the air (i.e., what is exposed to the hazard and for how long). The severity of the hazard is determined by the level of performance of the aircraft, in terms of measures such as mass and energy, and the space and time distribution characteristics of persons, property, and aircraft in the operational environment. The hazard likelihood is determined by the gap between required and available capabilities, the complexity of the physical and functional design of the AS, and the aleatory and epistemic uncertainties about the structure and behavior of the technical system, its components, and the flight crew.

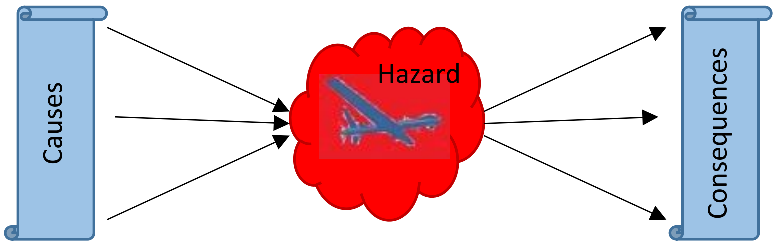


Figure 41: Aircraft system as a hazard in the operational environment

There are many possible ways of achieving an acceptable level of operational safety. The general conceptual approach is to start with a risk evaluation for a baseline configuration of mission, aircraft system, and environment, and then introduce risk mitigation contributions from these until the ALOS level is reached. This is illustrated in Figure 42. Figure 43 illustrates a situation in which an environment constraint is introduced in order to eliminate mishap severities above a level S_{env} that have an unacceptable likelihood. In this example case, only one element of the operation contributed to the risk mitigation and all others remain at their baseline configuration. Note that likelihood reductions to reach ALOS can be achieved by design and operational reductions in aleatory and epistemic uncertainties, as well as the introduction of hazard prevention and protection barriers, as discussed in Section 4.2.

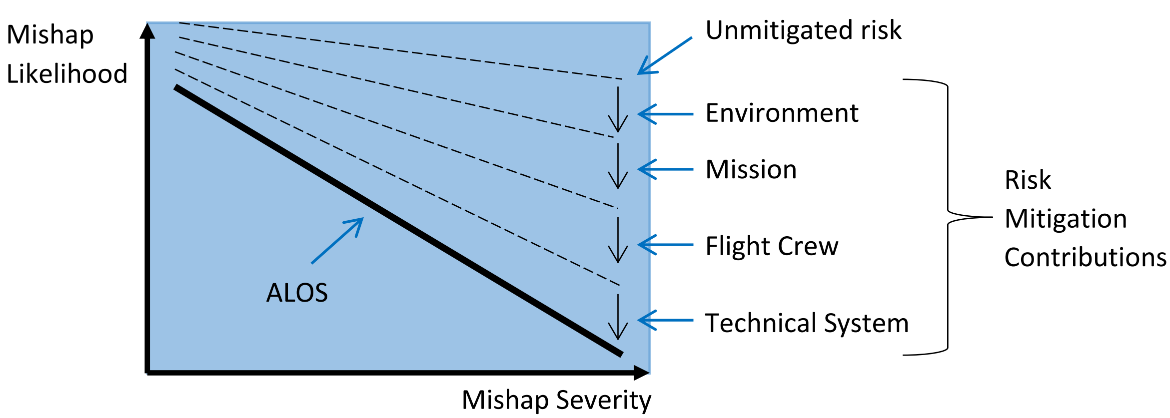


Figure 42: Achieving ALOS with multiple risk mitigation contributions

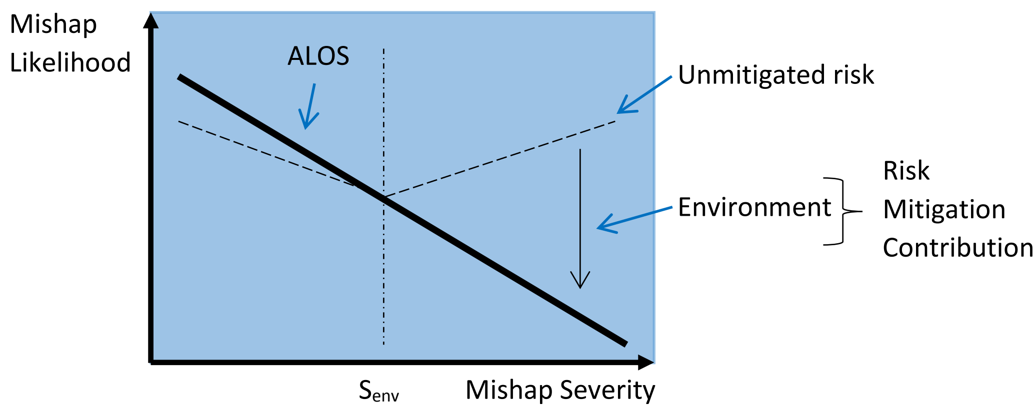


Figure 43: Achieving ALOS with environment limitations

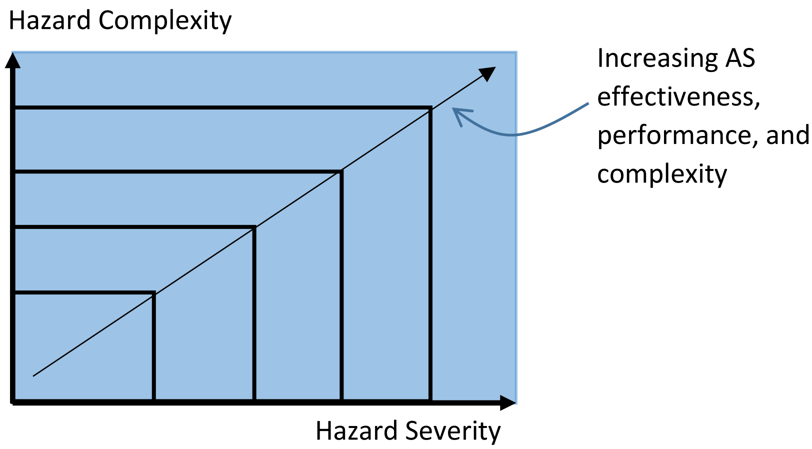


Figure 44: Scope of hazard severity and complexity as AS performance and complexity increase

The AS performance and complexity are directly related to the hazard severity and complexity. As the system performance and complexity increase so do the hazard severity and complexity (Figure 44). Given the inverse risk relation for ALOS, an increase in the scope of the system performance and complexity results in a simultaneous increase in hazard severity and a corresponding decrease in acceptable uncertainty. This means that the safety effort, in terms of size and rigor, must increase, potentially exponentially, as protective features are introduced to account for the increase in the number, modes, and interrelation of relevant hazard causes (i.e., the hazard complexity). Figure 45 illustrates this increase in unacceptable risks and safety effort as AS performance and complexity increase. As shown in Figure 46, as the safety effort increases with performance and complexity, the achieved AS risk mitigation decreases rapidly at first but becomes increasingly ineffective and the cost of the effort increases exponentially.

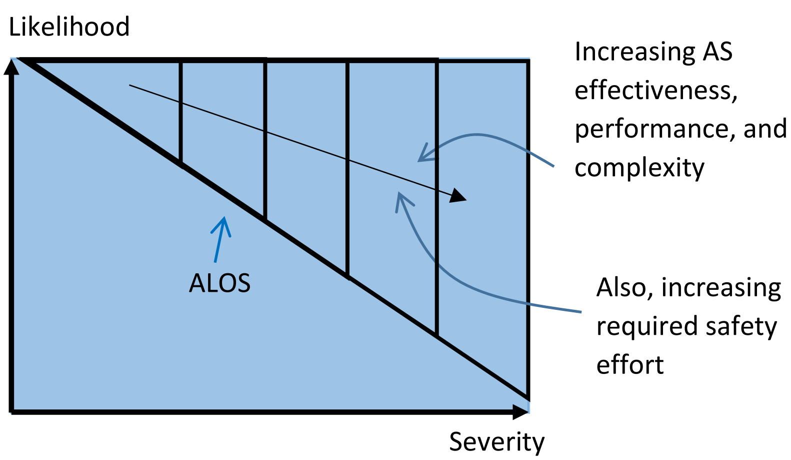


Figure 45: Increasing area of unacceptable risk as AS performance and complexity increase

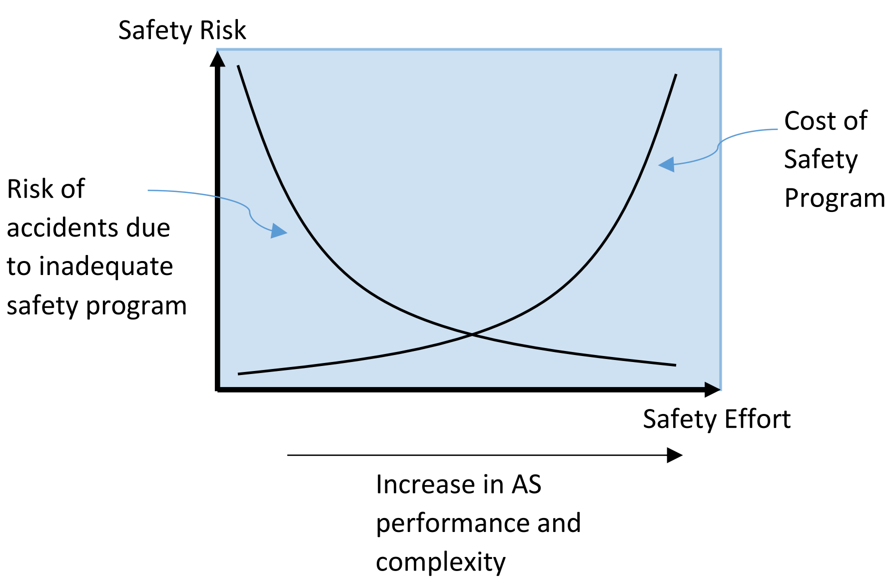


Figure 46: Relation of safety risk and cost with safety effort

In summary, it appears that there are multiple ways to achieve operational ALOS with combinations of risk mitigations in the mission, the environment, and the aircraft system. For a given AS, ALOS might be achieved with mitigations in the mission and the environment, but this may require precluding whole categories of mission and environment complexity and/or vulnerabilities (i.e., exposed valuable assets). For unconstrained missions and environments, operational ALOS requires that risk mitigation be achieved entirely with the AS. Aircraft performance and design complexity, both physical and functional, are the primary determinants of AS safety risk. As the unmitigated risk of the AS increases, the required safety effort and the cost of the effort increase rapidly, potentially exponentially.

6. Recommendations

Two recommendations come out of the preceding analysis.

Recommendation 1: The regulations should allow compliance with ALOS objectives using a combination of risk mitigation contributions from the mission, the environment, and the aircraft system.

This recommendation would enable approval of a wide range of activities and the full exploitation of the potential benefits of unmanned aviation. This approach would be aligned with the desire from regulators and industry that the regulations be operation-centric, safety-risk-based, proportionate, and performance-based. The implementation of mission and operational restrictions would allow a variety of performance and cost options for realizing UA applications.

A potential drawback of this recommendation is the complexity of the regulatory approval process and the increased complexity of the airspace. The potential complexity of the regulatory process could be mitigated by developing standard classifications of missions, environments, and aircraft systems that combined cover the majority of cases with a standardized and well-understood approval process. Exceptional situations would be handled with a customized approval process. The mission and environment classifications would correspond to airspace and ground-space sectors with limitations in the kinds of missions that can be performed and the kinds of aircraft that may operate in the sectors based on level of safety requirements.

Recommendation 2: Unmanned aircraft should be classified based on an ordinal scale that combines hazard severity and hazard complexity.

The boundaries of the classes should correspond to required levels of safety defined based on a partitioning of the safety effort vs. cost and risk relations. Figure 47 shows one classification concept that partitions the risk vs. safety-effort relation into three regions: low (C), medium (B), and high (A) effort, where the threshold points are referenced to the approximate areas where the risk curve exhibits high, medium, and low risk-reduction-to-effort return, respectively. The meaning of risk used here is the probability (i.e., likelihood) that an unfavorable outcome is realized [22]. These risk likelihood regions are mapped to the ALOS risk curve, and then to the hazard severity and complexity space, where regions A, B, and C are defined. Additional criteria would be needed to define the hazard complexity thresholds between the three regions. One possibility is to map these to the performance and design complexity space, where practical AS features could be used as criteria to define the thresholds.

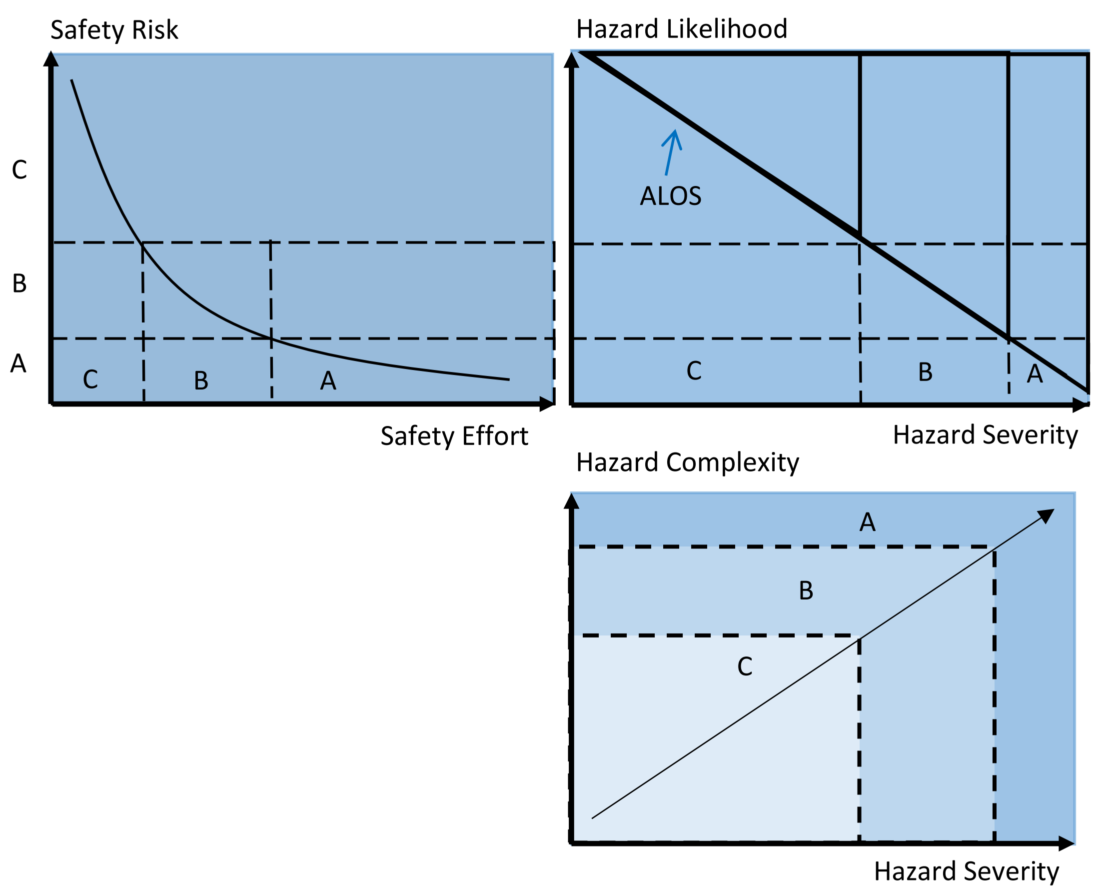


Figure 47: Notional AS classification based on risk levels

7. Final Remarks

The feedback received to date from subject matter experts (SME) on the recommendation for a risk-based classification of unmanned aircraft has been very positive. Although much of the study was developed at a conceptual level, this approach allowed a broad examination of relevant topics to the generation and justification of the classification scheme. However, much work remains to evolve, refine, and make the classification practical. It was recommended by SMEs that the study be continued to investigate further the UA classification problem and identify more specific and practical classification criteria and thresholds for a suitable basis for airworthiness certification.

To that end, the next step in the continuation of this study will be to develop a much deeper practical understanding of aircraft technology and certification. The current study did not investigate in sufficient depth the practical aspects of actually using regulations to certify aircraft and approve operations. There are human and organizational factors that determine the effectiveness and efficiency of certification processes which warrant a much closer examination. The matter of international harmonization is necessarily as strong factor in the acceptability and practicality of a classification and deserves a closer analysis. A much deeper understanding of short and long-term implications of a classification to the development of the industry is needed. Also, consultation with a larger number of subject matter experts would be advantageous in order to gain a broader and deeper understanding of the problem and desirable attributes of a solution.

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14. ABSTRACT

There is a trend of growing interest and demand for greater access of unmanned aircraft (UA) to the National Airspace System (NAS) as the ongoing development of UA technology has created the potential for significant economic benefits. However, the lack of an effective and efficient UA regulatory framework is severely constraining the number and kinds of UA operations that can be performed. This report presents initial results of a study aimed at defining a safety-risk-based UA classification as a plausible basis for a regulatory framework for UA operating in the NAS. Much of the study up to this point has been at a conceptual high level. The report includes a survey of contextual topics, analysis of safety risk considerations, and initial recommendations for a risk-based approach to safe UA operations in the NAS. The next phase of the study will develop and leverage deeper clarity and insight into practical engineering and regulatory considerations for ensuring that UA operations have an acceptable level of safety.

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Aircraft; Airspace; Regulations; Risk; Safety; Unmanned

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