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Survey of Methods for Assessing Safety Compliance of sUAS BVLOS Operations

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Executive Summary

To ensure the safety of small Unmanned Aircraft System (sUAS) Beyond Line of Sight (BVLOS) operations in the National Airspace System (NAS), the FAA offers a guideline on how sUAS operators can demonstrate compliance with FAA rules, including regulations, advisory circulars, policy statements, and acceptable means of compliance (AMOC), using a formal and top-down approach. According to FAA Advisory Circular 23.2010-1, the AMOC refers to "one method, but not the only method, to show compliance with a regulatory requirement." It is common for regulations to include a performance and safety standard rather than a detailed design or operation requirement, which allows for flexibility in fulfilling the regulatory requirements while still achieving a predetermined level of safety.

This technical report explores existing frameworks for sUAS BVLOS safety analysis. It begins by discussing how sUAS BVLOS operations can be strategically deconflicted and then discusses their hazards. The next step is to establish safety assessment methods commonly used by the aviation industry and the FAA, illustrate how these methods can be applied to several safety-critical air traffic systems, and list collision models that the FAA and industry use. This investigation documents the processes for assessing safety risks in sUAS BVLOS operations and will allow sUAS BVLOS operations to be assessed for safety compliance more efficiently.

Table of Contents

List of Figures

List of Tables

1 Introduction

A wide variety of commercial applications and opportunities exist for small Unmanned Aircraft System (sUAS) operations Beyond Visual Line of Sight (BVLOS) at low altitudes, e.g., infrastructure monitoring, delivery of goods, precision agriculture, public safety, search and rescue, disaster relief, weather monitoring, etc. This operation offers incentives and business cases for allowing these operations within the regulatory, operational, and technical environment of the National Airspace System (NAS). The Federal Aviation Administration (FAA) is responsible for developing safe procedures to enable sUAS operations. To facilitate this, a regulatory framework must be established, airspace operations requirements and procedures must be developed to ensure accountability by operators, and access to the airspace should be made efficient and equitable for all sUAS operators. To support sUAS BVLOS applications for authorization in the NAS, a performance-based safety compliance method is required to provide the process and metrics that are accepted by the regulator for the risk related to sUAS BVLOS operations. Operational certification which is considered after airworthiness covers a wide range of FAA regulations (Federal Aviation Administration, 2016) [1]. The FAA provides a guideline of the formal and top-down approach for sUAS operators to demonstrate compliance with the FAA's rules, including regulations, advisory circulars, policy statements, and acceptable means of compliance (AMOC). According to FAA Advisory Circular 23.2010-1, the AMOC refers to "one method, but not the only method, to show compliance with a regulatory requirement." In addition, the method of compliance describes how compliance will be demonstrated, including flight testing, analysis, and describing how all relevant compliance data will be collected as well as how all findings can be collected to demonstrate compliance with a regulatory requirement (AC 23.2010-1 - Accepted Means of Compliance Process for 14 CFR Part 23, 2017) [2]. As such, the AMOC provides organizations that apply for authorization for their sUAS BVLOS operations with a way to demonstrate compliance with FAA's regulations. In general, the regulations include performance and safety standards rather than a detailed design or operational requirement. These allow for flexibility in satisfying the regulatory requirements while still ensuring the required level of safety.

The goal of this report is to survey existing frameworks for safety analysis of sUAS BVLOS operations. We began by discussing strategic deconfliction of sUAS BVLOS operations, followed by investigating their hazards. Next, safety assessment methods we reviewed that are commonly used by the aeronautical industry and the FAA, and then illustrated how these methods can be applied to several safety critical air traffic systems. By documenting the safety risk assessment processes, the investigation will survey the literature on sUAS BVLOS safety compliance assessment processes and examine how the level of safety associated with sUAS BVLOS operations is determined. As a result, the systematic approach outlined in the investigation can be used to assess the level of safety of any proposed sUAS BVLOS operation.

2. Strategic Deconfliction of sUAS BVLOS Operations

The FAA maintains regulatory and operational authority over sUAS BVLOS operations, although FAA-sponsored traffic services manage the operations. The operations are coordinated and managed by a federated set of automated systems. Automated services are used to comply with regulatory requirements, plan flight operations, identify nearby sUAS for data exchange, perform strategic deconfliction by sharing operational intent and negotiations, and monitor flight intent conformance.

By using strategic deconfliction and conformance monitoring functions, sUAS BVLOS operations can achieve an acceptable level of safety. As the common component shared by both functions, four-dimensional operational intent needs to be established so that both functions can operate effectively. As part of the UTM concept [4] [5], the four-dimensional (4D) volume of airspace should be developed, submitted, and shared prior to the initiation of the operation. The operational intent that is represented by the 4D volume represents the airspace and time bounds that contain sUAS flight, including the earliest entry time and the latest exit time, as well as horizontal and vertical boundaries [6]. An operational intent can be either area- or trajectory-based. The trajectory-based 4D volumes, i.e., the set of contiguous or overlapping 4D volumes that make up the intended flight profile. Unlike the trajectory-based operational intent that comprises a series of volumes following the flight route, an area-based operational intent consists of a single volume for the flight duration. Operational intent boundaries are determined by uncertainties associated with path definition, navigation systems, departure time, weather conditions, and sUAS performance characteristics. Moreover, the sUAS must remain within the operational intent boundaries for a specified percentage of flight time (e.g., 95% of flight time) while in flight to achieve TLS.

Conformance monitoring provides situational awareness by indicating whether a sUAS is in compliance with an operational intent, or in other words, whether its 4D position is within the temporally correlated operational intent. When an aircraft's 4D position does not coincide with a temporally and spatially correlated operational intent over a specified flight time, the aircraft is considered Nonconforming. When the aircraft stays nonconforming for more than the system specified temporal threshold, then it is considered Contingent. Although both Nonconforming and Contingent states are referred to off-nominal states, aircraft in the nonconforming state can return to the operation intent by reestablishing the operational intent, whereas aircraft in the contingent state cannot be controlled to return within the operational intent [6][7].

3. Hazards in sUAS BVLOS Operations

In a safety risk analysis, the primary goal is to identify and understand hazards, risk levels, causes, effects, and outcomes [3], along with metrics for assessing the level of safety associated with sUAS BVLOS operations. The FAA Air Traffic Operation (ATO) Safety Management System (SMS) policy defines a hazard as "a condition that can lead to or contribute to an aircraft accident" [8] and Table 1 [9][10][11][12][13][14][15] summarizes the hazards associated with sUAS BVLOS operations based on data collected from government accident reports.

Table 1 Hazards Set for sUAS BVLOS Operations

Hazard	Contributing Factors	Effect	Outcomes
sUAS Loss of Control	• Control System Malfunctions • Weather, Wind, Turbulence • Power Loss • Electromagnetic Interference (EMI) • Bird Strike	• Undesired Trajectory that is Unpredictable • Unstable Control Response	• Mid-Air Collision • Crash into Obstacle • Debris Injuries People on Ground
sUAS Non-Conformance	• Erroneous Waypoints • Navigation System Failures/Errors • Autopilot/Pilot Error	• Loss of Control sUAS from Ground • Failure of Monitoring sUAS Position and Velocity	• Mid-Air Collision • Crash into Obstacle • Debris Injuries People on Ground
Lost/Defect Communication Link	• Electromagnetic interference at sUAS • Signal Obscureness • Frequency Overlap	• Loss of Control sUAS from Ground • Failure of Monitoring sUAS Position and Velocity • Inability to Initiate Flight Termination or Return to Base	• Mid-Air Collision • Crash into Obstacle • Debris Injuries People on Ground
Loss of Navigation Capability	• Onboard Navigation System Failure • Loss of/Erroneous GPS Signal	• Inability to Follow Operational Intent	• Mid-Air Collision • Crash into Obstacle • Debris Injuries People on Ground
Failure / Inability to Avoid Mid-Air Collision	• Missed Detection of Intruders • Vision System Failure	• Intrusion of other sUAS Operational Intent	• Mid-Air Collision • Crash into Obstacle • Debris Injuries People on Ground
Rogue / Noncompliant sUAS	• Inability to Detect Rogue / Noncompliant sUAS • Lack of Mechanism for Containment of Rogue/Noncompliant sUAS	• sUAS Not Operating within the Assigned Operational Intent / Airspace • Operation Intent Unknown to Other sUAS	• Mid-Air Collision • Crash into Obstacle • Debris Injuries People on Ground

sUAS may take emergency measures to avoid unwanted outcomes in the presence of identified hazards. The contingency procedures may include [6][16][17]:

- Flight Termination: A rapid safe landing or return to the launch site or rally site is performed by a sUAS
- Emergency Divert: sUAS diverts to another operation from the original/assigned flight plan, including landing in a safe location

The prompt yet unnoticed execution of these predetermined emergency procedures may increase the chance of midair collisions.

4 The Framework of Means of Safety Compliance

In relation to aviation safety, the FAA has published the following documents:

- FAA Order 8040.6A, Unmanned Aircraft System (UAS) Safety Risk Management (SRM) Policy
- FAA Order 8040.4, Safety Risk Management Policy
- FAA Order VS 8000.367, Aviation Safety (AVSSMS) Safety Management System Requirements
- FAA Order 8000.368, Flight Standards Service Oversight
- FAA Order 8000.369, Safety Management System
- FAA Order 1100.154, Delegations of Authority
- FAA Order JO 1000.37, Air Traffic Organization Safety Management System
- Air Traffic Organization Safety Management System (ATO SMS) Manual

The scope of AMOC processes is outlined below and the detailed processes are described in Ref. (Unmanned Aircraft Systems (UAS) Safety Risk Management (SRM) Policy, 2023) [3]:

1. Identify Safety Analyst or Team: Depending on the request under consideration, the safety risk analysis may be conducted by an individual or a team. It is important that the individual analyst or team members conducting the analysis have the appropriate subject matter expertise and SMS training. It is imperative that all necessary AVS and FAA stakeholder organizations are involved. The safety analyst or team reviews the application package and other available information to determine the level of safety. Each analyst or team member must complete the AVS SMS SRM Overview course prior to participating on an AVS UAS SRM Panel for the first time, and again when the course is updated. The current course, FAA Safety Risk Management Overview (FAA27000023), may be found in the FAA's Learning Management System.
2. System Analysis: The applicant provides the technical and operational information needed for the safety analyst or team to verify or perform SRM.
3. Identify Hazards, Risks, Causes, Effects and Outcomes: During this step, the SRM analyst or team must identify hazards, risk levels, causes, effects, and outcomes. A hazard is a condition that could foreseeably cause or contribute to an aircraft accident. When analysis reveals that a condition could cause damage to an aircraft or injury to a person, regardless of the severity, it should be assumed that the condition could cause an accident and therefore meets the definition of a hazard[1].
4. Qualitatively Analyze Safety Risk: During this step, the safety analyst or team must determine the initial risk levels expected with the proposed UAS operation, new regulation, or modification to a regulation. The initial risk is based upon the proposed operation including applicant controls and existing controls, the new regulation, or change to the regulation. Existing controls are always looked at prior to determining credible outcomes. Existing controls are verified controls and may be provided by the FAA or by the applicant. For initial risk, the safety analyst or team relies upon information provided by FAA stakeholders or the UAS applicants, e.g., the system assessment, and their own FAA SMEs to determine the severity and likelihood of the hazard's outcomes. The safety analyst or team's rationale for how they arrived at their determination is just as important as the severity[2] and likelihood[3].
5. Quantify Safety Risk: A risk matrix[4] provides a visual depiction of the safety risk levels and enables prioritization in the control of the hazards. The safety analyst or team uses the determined severity and likelihood to plot the initial risk level on the risk matrix. The safety analyst or team

[1] A hazard is a constant, and risk is a result of the hazard. Risk may be mitigated or eliminated.
[2] The consequence or impact of a hazard's effect or outcome in terms of the degree of loss or harm.
[3] The estimated probability of frequency in quantitative or qualitative terms of a hazard's effect pr outcome.
[4] The risk matrix consists of likelihood and severity, where likelihood refers to the probability of mid-air collision and the severity refers to the casualty from the mid-air collision.

documents the initial risk level(s), the rationale of how the severity and likelihood were determined and compares the level(s) against the risk acceptance criteria.

6. Additional Safety Risk Controls and Residual Safety Risk: During this step, the safety analyst or team assesses the need for additional controls (e.g., conditions and limitations in exemptions and special provisions in waivers) to reduce the risk of the operation to an acceptable level. Conditions and limitations and special provisions are intended to document specific safety risk controls presented by the FAA. Further analysis is performed to ensure that the sUAS operation's mitigations do not introduce new hazards, impact existing hazards, or compromise existing safety risk controls. The safety analyst or team must record a description of the additional safety risk controls that were considered prior to analyzing and assessing the residual safety risk. The safety analyst or team documents the new severities, likelihoods, rationale, and residual risk level on the risk matrix with the additional safety risk controls considered.
7. Safety Risk Acceptance: Once the assessment is complete and the findings and alternatives/proposals for safety risk mitigations/controls are documented, the results are delivered to the appropriate management official within the Office of Primary Responsibility (OPR). The OPR is responsible for obtaining necessary approval(s) and safety risk acceptance(s). The appropriate management officials either accept the safety risk associated with the identified hazard(s) within their purview or send the assessment back to the panel for additional analysis or identification of additional proposed alternatives for safety risk mitigations/controls. Risk acceptance is a management decision. However, the risk acceptor cannot modify the risk levels determined by the SRM team. Hazards may also be identified through the Safety Assurance functions used to monitor the aerospace system. In these situations, it is necessary to determine whether continued operation is acceptable (and for how long) while new safety risk controls are introduced. If an existing hazard is identified and the operation is allowed to continue, any risk associated with the hazard is inherently accepted by management officials and/or the FAA.
8. Safety Performance Monitoring and Hazard Tracking: When the safety risk assessment is complete, residual risks must be tracked and monitored in accordance with FAA Order 8040.4 for medium and high residual risk levels. Per the monitoring plan, safety performance monitoring is conducted to verify the risk assessment and the safety controls. The safety analyst or team provides a description of the data to be collected, at specific intervals for a specific duration, defines safety performance targets for each hazard, and provides the point of contact (POC) responsible. The safety performance targets are used to verify the predicted residual risk levels

According to FAA AC-23.2010 [18], an Accepted Means of Compliance (AMOC) is a detailed design standard meeting the regulatory requirements and established level of safety. In short, an AMOC is a methodology for system criteria satisfying all required safety regulatory implications. By applying this definition, we can see the level of safety as a quantitative yet analytical decision criterion and demonstrate it in terms of the method of compliance. In order to determine the findings, all necessary compliance-related data should be collected, an explanation of the way the minimum performance requirements are met, and testing, validation, and analysis will be used. Moreover, a quantitative examination of safety related events should be systematically established by means of the mathematical methods available to determine the expectation of the outcome of the events.

The assessment of safety compliance comprises the definition of the proposed operation, the collection of data, the quantification of risks, and the analysis of safety, as illustrated in Figure 1**.** It begins with the identification of the functions and characteristics of operational environments required for the sUAS BVLOS operation, followed by the requirements for safety and performance. Quantitative effects of hazards can be calculated using the data collected from operations, field tests, or Monte Carlo simulations, using the logic of qualitative analysis of operational hazards. According to FAA Order 8040.6, the level of safety consists of likelihood and severity. The likelihood is the estimated probability of mid-air collision, while the severity is the potential consequence in terms of casualty of the given mid-air collision. With the combined quantities of likelihood and severity, the level of safety of the proposed operation can be determined.

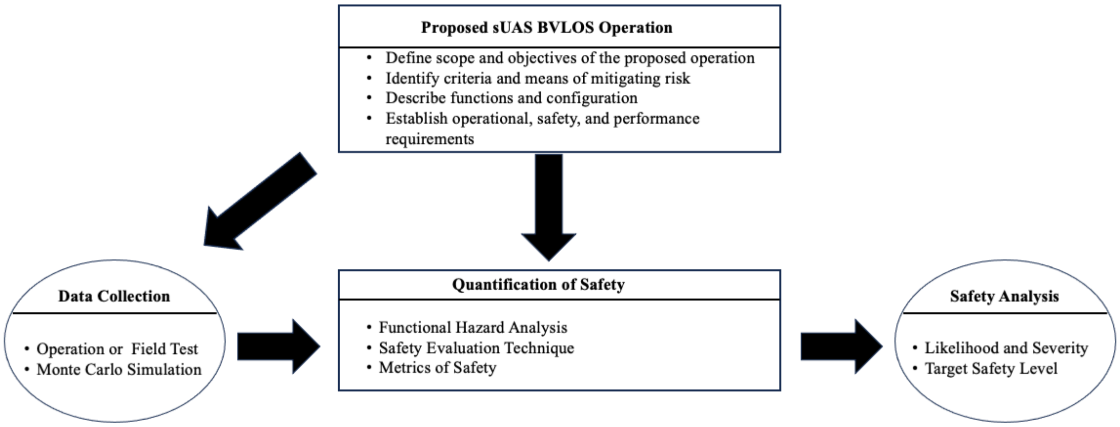

Figure 1 Safety Compliance Assessment Mechanism

An analysis of safety will also determine the severity and likelihood of the hazards [20], which are summarized in the risk matrix, corresponding to the proposed sUAS BVLOS operation. Using the risk matrix, sUAS BVLOS operations can be better assessed in terms of safety impacts. Using well-established safety engineering techniques, operations requirements, the operational environment, and operational risk must be identified as part of adapting accepted methods. Furthermore, using the accepted means of compliance with the level of safety will assist applicants in complying with existing regulations as well as greatly facilitate FAA approval.

The qualitative definition of severity is summarized in Table 2 [3][10], where the severity is characterized by human injury and/or fatality.

Table 2 Qualitative Definition of Severity

Minimal	Minor	Major	Hazardous	Catastrophic
Negligible safety effect	Physical discomfort to persons	Non-Serious Injuries	Multiple serious injuries and/or single fatality	Multiple fatalities

The quantities of likelihood per flight hours and the qualitative description of intensity of the likelihood are defined in Table 3 **[3]**.

Table 3 Definition of Likelihood

Frequent	Expected to occur more than 100 times per year or more than approximately 10 times per month
Probable	Expected to occur between 10 and 100 times per year or approximately 1-10 times per moth
Remote	Expected to occur one time every 1 month to 1 year
Extremely Remote	Expected to occur one time every 1 to 10 years
Extremely Improbable	Expected to occur less than one time every 10 years

By defining and calculating the severity and likelihood of potential hazard impacts of proposed sUAS

BVLOS operations, a risk matrix[5] can be generated, presenting the probability of occurrence of a hazard and its consequences in a visualized manner. Based on the likelihood of each identified hazard and the severity of the consequence, the risk matrix shown in Figure 2 indicates the level of safety. As a result of safety analysis, high-risk grids, i.e., red grids, are unacceptable for a proposed operation; otherwise, the operation is considered to meet the TLS.

Severity / Likelihood	Minimal	Minor	Major	Hazardous	Catastrophic
Frequent					
Probable					
Remote					
Extremely Remote					

Figure 2 Risk Matrix based on a Safety Analysis of a Proposed Operation

[5] The risk matrix provides the visualization of the level of safety that combines the likelihood of a hazard (mid0air collision) and the consequence of the hazard.

5 Safety Analysis Techniques

Although every sUAS BVLOS operation has its own version of safety nets that reduce the risk of mid-air collision, the safety analysis must demonstrate whether the operation meets existing safety criteria, which are represented by the TLS per flight hour. In the safety quantification, operational data is input, and an appropriate analysis method is selected to verify that a proposed operation meets a predefined TLS. There are several factors to consider when selecting a safety analysis method, including:

- Is it well received by the majority of the aviation community?
- Is it sufficiently broad to cover all the technical aspects associated with the operational safety?
- Can the method be implemented with ease and the limitation of the method will not compromise the integrity of the results?

In this section, candidate safety analysis methods are identified that satisfy the criteria previously mentioned.

5.1 Common Cause Analysis

Common Cause Analysis (CCA) identifies a common cause shared by two or more events that contribute to hazard. The analysis process of CCA identifies the sources of common events that have impact on the safety of the operation. The failure may affect several independent vents simultaneously. The CCA therefore is able to identify independent events and their dependencies, contacting factors associated with the hazard, and deviations from the initial assumptions and the implications of these deviations [22].

The process of the CCA can be summarized as follows [23]:

- Identify the critical functions to be analyzed.
- Check for commonalities of the characteristics of the functions that could produce a generic defect.
- Within each identified commonality, identify the trigger events where the functions miss the required behaviors.
- Identify the common causes that lead the functions to fail.

The general disadvantages of the CCA can be summarized as follows [24]:

- It may be challenging to identify the common cause in a high degree of integrations among functions in the UTM operations.
- The method is not well structured.
- The CCA does not have clear terminal conditions.

5.2 Failure Mode and Effects Analysis

According to the definition stated in ARP4761, Failure Mode and Effects Analysis (FMEA) is a "*systematic, bottom-up method of identifying the failure modes of a system, item, or function and determining the effects on the next higher level*." [25]. In short, the FMEA identifies potential failure modes for a function and evaluates their consequences. Identifying the contributing factors to a hazard is accomplished using the FEMA method [32]:

- Identify the functions managing the proposed operation and their failure modes.
- Evaluate the effects of the failure for each failure mode and the severity of the impact on the operation.
- Given the severity of the failure, identify the causes of the failure and the likelihood that the identified causes will occur.

The FMEA process is illustrated in Figure 3.

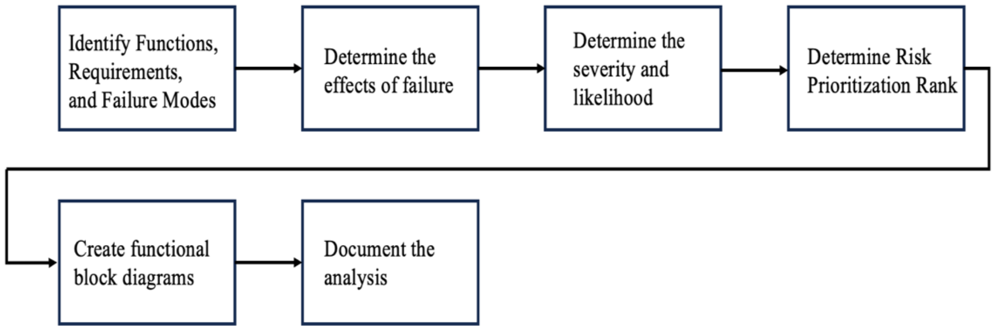

Figure 3 FMEA Flow Diagram

The general weakness of the FMEA method is summarized as follows [33]:

- This method can become quite time-consuming in identifying the failure modes affecting the safety of a complex operation.
- This method does not group the items causing the failure, so the effects may be repeated.
- The method is not suitable for identifying the failure modes associated with the temporal aspects of the operation.
- The method provides a tunnel-sighted approach in modes that it does not address combinations of effects reached by different paths [26].

In conclusion, FMEA is useful in assessing the safety of an operation, but it is not well suited to identifying human-induced safety issues [33].

5.3 Event Tree Analysis

The Event Tree Analysis (ETA) models the hazard and the sequence of associated events in the cause-consequence fashion, where the events are modeled as consequences and the hazard is modeled as the root of the events. The ETA for an operational system managing the proposed operation is constructed in the following steps [27]:

- List of the hazard based on the operational safety goal.
- Identify the functions of the system managing the proposed operation.
- Identify the expected response of each of the functions.
- Construct the sequence of the events linking to the function responsible for managing the event and indicate the expected outcome of the functions leading to the consequence.
- Compute the probabilities of each step in the event tree and assign the total probability of occurrence to the sequence of the hazard.

Figure 4 illustrates the reasoning of the ETA method with a functional tree, where the analysis is initiated with a hazard and moves forward with branches of events representing the defect of the functions [28][29]. When there is no influence factor leading to further consequences, the branch will stop splitting.

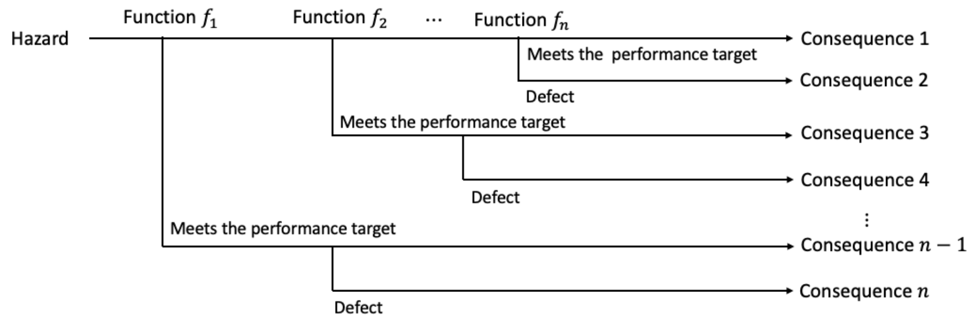

Figure 4 Event Tree Analysis

A conditional probability associated with each branch will be used to quantify the success or failure of the operation. The probabilities of each consequence are the products of the probabilities at each event leading to the consequence, and the sum of the probabilities for all consequences must be unity [30].

The main disadvantages of the ETA are summarized as follows [33]:

- The exploration of all relevant events and their consequences can be extremely time-consuming and resource-exhaustive.
- Defining the order of functions sequenced in the events can be difficult and complex.
- A separate tree is required for a hazard independent of other hazards, and this makes it difficult to connect the event tree to events in the separate tree.
- The ETA model is limited to intended and anticipated actions and can only address dependencies in a limited fashion.

5.4 Fault Tree Analysis

The Fault Tree Analysis (FTA) constructs a tree path in a top-down fashion starting with the immediate cause of a hazard. The causes ramified from the hazard are described with logical operators graphically. A set of symbols representing logic gates (such as AND, OR, XOR, NOT, etc.) that perform a Boolean function on one or more binary inputs that produce one output.

The approach to analyzing a Fault Tree Analysis follows the steps listed below [33]:

- Analyze the operational requirements to determine the hazard, initial conditions, and existing events.
- Construct the Fault Tree for the identified hazard.
- Construct the causal events linking the hazard and the upper-level events until the lowest terminal condition is reached.

Figure 5 illustrates the approach to constructing a Fault Tree with a set of causal events that coexist with the top event, where a top event linked with an ‘OR’ or ‘AND’ logical gate followed by many ‘OR’ and ‘AND’ logical gates. Each logical gate connects elements corresponding to events ramified from the hazard or an upper-level event that represents the common cause. Quantification of the fault tree seeks the probabilities of occurrence of the basic events at the lowest level of the tree, where the product of the probabilities yields the probability of the occurrence of the hazard. If probability density functions are sought, Monte Carlo simulation can be employed to determine the functions.

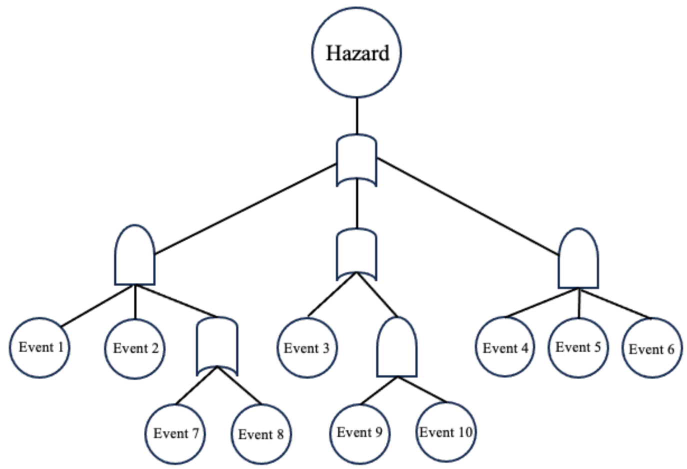

Figure 5 Structure of Tree Branches of the Fault Tree Analysis

The disadvantages of the FTA method are summarized as follows [33, 34]:

- The branches of the fault tree may become large and complicated when the causal events comprising each branch are derived from a complex system. As a result, it becomes difficult to visualize the entire tree.
- The cause splitting a sequence of events cannot be shared in fault propagation in ripple effects associated with the safety operation, i.e., it may conceal common cause failures [32, 33, 34].
- The events in each branch represent the instantaneous state of a system and it is difficult to address the temporal aspects of the hazard in the analysis.
- The dependencies can only be handled heuristically, and it is rather difficult to present temporal order of the events.
- The method limits the scope to a few specific hazardous events.

5.5 Bow-Tie Analysis

The Bow-Tie analysis method constructs a model linking the causes of a hazard and the consequences of the hazard. The Fault Tree and the Event Tree pair is employed to model the causal and consequential hierarchy linked by the common event, which is the hazard, to give a pictorial overview of how a hazard can be developed into consequences, as shown in Figure 6.

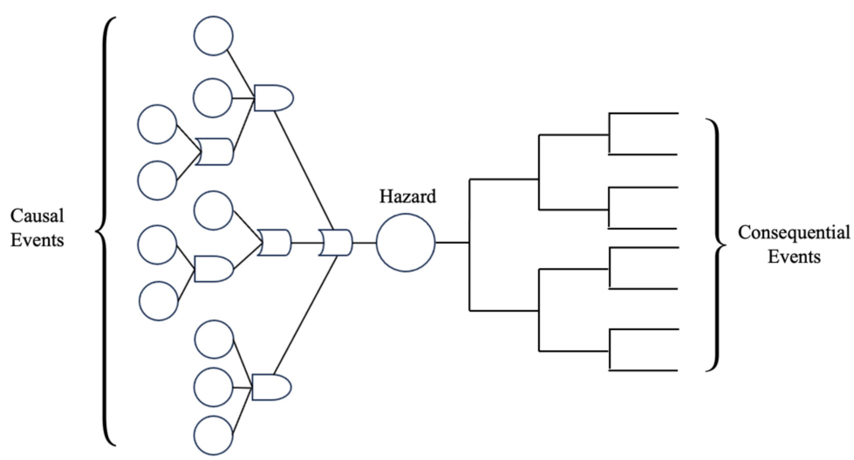

Figure 6 A Generic Description of Bow-Tie Analysis

The Bow-Tie analysis has been widely used in safety-critical operations, either explicitly or implicitly, to define the severity of the consequence of a hazard and safety targets [33]. In particular, Euro-control Safety Assessment Methodology (SAM) [34], which supports the development of the regulations for risk assessment and mitigation in Air Traffic Management, is connected to the Bow-Tie analysis. Although the Bow-Tie analysis can conceptually provide a complete list of causal and consequential events of a proposed operation, it has several drawbacks [31]:

- It assumes that there is no significant hazard is omitted, which cannot be guaranteed.
- It can be problematic when multiple events with common causes leading to the identified hazard.
- It is not always possible to identify a fixed sequence of events to define a Bow-Tie in sUAS BVLOS operations.

5.6 Formal Methods Analysis

The formal method applies principles of mathematical reasoning to ensure consistency and comprehensiveness [35]. This method connects the main functions of the operational concepts to safety through the causal links that make up safety mechanisms and to risks through the hazards that arise from issues that the functions are designed to mitigate. The process of constructing the safety mechanisms using formal methods includes the following steps:

- Identify the issues and their causal relationships with the risks derived from the proposed concept of operation.
- Identify the functions to mitigate the issues and to enables safety mechanisms as a sequence of causal links that result in operational safety.
- Define the quantifiable metrics for the safety defined in the previous step.
- Determine whether the proposed operation upholds the TLS with the metrics.

The formal method employs a bottom-up approach to develop the safety mechanism, where the sequence of causal events leading to operational safety is identified. The functions were designed to mitigate the issues and enable the safety mechanism resulting in a quantifiable safety. The pictorial causal relationships are depicted in Figure 7, showing the parallel between the risks and the safety. In summary, an issue excites hazard mechanism that results in risks, and a function mitigates an issue and enables the benefit mechanism which results in safety.

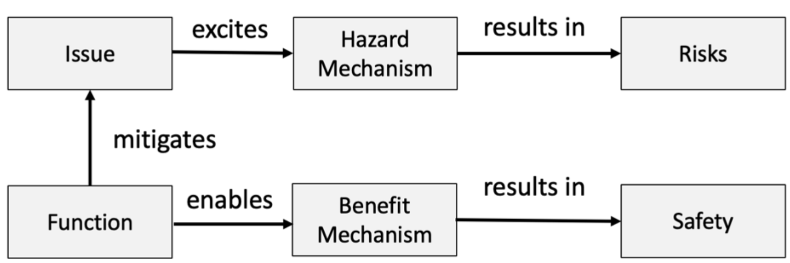

Figure 7 Safety Benefit Mechanism derived from the Formal Methods

Formal methods can be powerful; however, they have limitations summarized as follows:

- The method is not capable of representing the safety mechanism associated with functions derived from a complicated non-linear dynamical system.
- As the complexity of the operation increases, the safety mechanisms may become extremely complicated. As a result, they may be difficult to uniquely identify each risk lined by the identified issue.

6 Application of Safety Analysis Methods

This section will demonstrate how the safety analysis methodologies validate the safety assurance functions in compliance with the FAA safety requirements. The safety analysis methods discussed in the previous section are used to demonstrate the application of these methods to the analysis of the systems protecting the NAS. In particular, we will provide examples of how the safety analysis methods discussed in the previous section can be applied to systems used to detect mid-air collisions and aircraft-to-aircraft conflicts.

6.1 TCAS

The TCAS is a collision detection, communication, and resolution system used by all large air carriers and many other aircraft worldwide. There are two versions of TCAS, TCAS I provides only Traffic Alerts (TAs), and TCAS II provides both TAs and Resolution Advisories (RAs). TCAS I is required for turbine-powered, passenger-carrying aircraft with 10 to 30 seats, and TCAS II is required for commercial aircraft with more than 30 seats or a maximum takeoff weight of more than 33,000 pounds. An ICAO-complaint transponder attached to each aircraft in the nearby airspace is interrogated by TCAS, and the resulting slant ranges, altitudes, and relative bearings are tracked. Using the successive responses, TCAS calculates the slant range to the intruder and the closing rate of the slant range between the ownship and intruder. These two values are used to calculate the approximate time to the Closest Point of Approach (CPA) between the two aircraft and the time to reach co-altitude, which are the main criteria for issuing an alert. With the calculated time, two types of TCAS alerts are issued: (1) Traffic Alert (TA), which provides a visual search for an intruder, and (2) Resolution Alert (RA), which recommends evasive maneuvers to avoid mid-air collision with an intruder.

Several operational evaluations have been conducted to assist pilots in evaluating the design and performance of TCAS. The recorded flight data and the TCAS data were analyzed to determine the frequency and stability of the TAs and RAs. As part of the evaluation process, TCAS was checked for compliance with its Minimum Operational Performance Standards (MOPS), as well as engineering flight tests conducted by the FAA and manufacturers of the aircraft were also completed. The test data obtained from the industry sponsored studies, simulations, flight tests, and operational evaluations along with the data gathered by FAA are referenced by RTCA for publishing the standards, requirements, and test procedures for TCAS.

The safety analysis framework was developed in the early 1980s [36][37][38][39], and then evolved into a multi-stage process that has been accepted by RTCA and ICAO as a domestic and international standard for safety analysis [40], which is based on a comprehensive, statistically valid set of data associated with TCAS across a wide range of encounters. The steps developed to assess the performance of TCAS include:

- Develop a Concept of Operations (CONOPS) to provide flight characteristics, the operational environment in which the aircraft will operate, responsibilities of the pilot, and the communication protocols for the operation.
- Develop an encounter model defining the encounter geometries expected to occur.
- Use the Fault Tree Analysis to identify all events that lead to the hazard, Near Mid-Air Collision (NMAC), in the collision avoidance process and estimate probabilities of the risk.

The safety analysis method, Fault Tree Analysis, is used to model the branches of events ramified from the top-level event. The probability of Near Mid-Air Collision (NMAC) has been used to as the top event in the fault tree for evaluating TCAS in the fast-time Monte Carlo simulation of encounters [41], Figure 8. NMAC was defined as two aircraft coming within 100 feet in vertical separation and 500 feet horizontal separation at any point in the encounter [41]. The risk ratio defined by the ratio of the probability of

NMAC when an aircraft is equipped with TCAS divided by for the probability of NMAC without any evasive action taken (the unmitigated probability). A risk ratio greater than one would denote that TCAS causes more NMACs than it prevents, while a risk ratio less than one would show that the TCAS results in fewer NMACs to occur. The risk ratio has become the primary success metric used to evaluate the safety of TCAS in particular and airborne collision avoidance systems in general. The minimum performance of TCAS II is determined by the International Civil Aviation Organization's (ICAO) Standards and Recommended Practices (SARPS) that govern aviation worldwide.

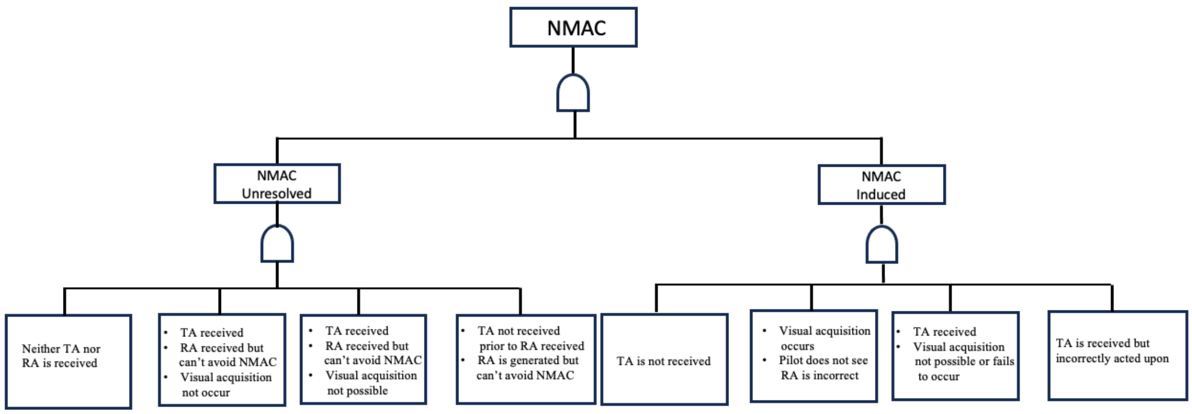

Figure 8 Example of TCAS Fault Tree Analysis

6.2 ACAS

ACAS X is a design developed by MIT Lincoln Laboratory for improvement to TCAS II and all versions of ACAS X determine collision avoidance maneuvers based on a Markov Decision Process (MDP), which is a framework for sequential decision-making problems consists of a discrete set of states, and a dynamic model that provides the probability of transitioning from one state to another based on the action that is taken, and a reward model that rewards or penalizes certain states and actions. The optimal action, i.e. policy, provides the action yielding the greatest expected reward at every state.

ACAS X consists of two primary modules, the Surveillance and Tracking Module (STM) and the Threat Resolution Module (TRM) and it models the relative position and speed of the two aircraft in the discrete state space, and the actions consist of doing nothing or issuing one of several RAs. In addition to penalizing NMACs heavily, the cost model also penalizes all RAs to a certain extent. A Partially Observable MDP (POMDP) is used since the relative position of the intruder aircraft cannot be determined perfectly. The POMDP uses observations to construct a belief state, based on which actions are taken. The belief state is determined by taking sensor measurements and using sensor error models to estimate the intruder aircraft's relative position. The optimal collision avoidance policy is calculated using dynamic programming based on the estimated states. The policy is then stored as a table, which can be uploaded to an aircraft, and the optimal action can be determined in real time by the onboard processor at any point in time.

Several variants of ACAS X are currently being developed. ACAS Xa is an ACAS X implementation designed for large manned aircraft, analogous to TCAS II. In order to provide hybrid surveillance on nearby aircraft, ACAS Xa employs both transponder interrogation and ADS-B signals. Like TCAS II, potential avoidance maneuvers given in RAs include climbs and descents at 1,500 and 2,500 fpm. The ACAS Xo system, intended to be used along with ACAS Xa, allows modified policies to be used in particular operational scenarios. For example, an aircraft flying a closely spaced parallel approach might switch from ACAS Xa to an ACAS Xo implementation that allows aircraft to fly closer parallel tracks before issuing an RA. DO-385, the MOPS for ACAS Xa/Xo, was approved by both the RTCA and the

European Organization for Civil Aviation Equipment (EUROCAE) councils in October 2018, and ICAO has adjusted standards to allow ACAS Xa to replace TCAS II from 2020 onward. As well as ACAS X, another variant known as ACAS Xu is in development for larger unmanned aircraft, such as the Global Hawk. Similar to ACAS Xa, ACAS Xu also uses information from active surveillance and ADS-B. However, ACAS Xu can also use an on-board air-to-air radar to surveil aircraft without a transponder or ADS-B equipped. TCAS II and ACAS Xa use a 1,500 and 2,500 fpm rate for avoidance information, whereas vertical RAs use a 1000 fpm rate. This is because larger unmanned aircraft often do not have the vertical maneuvering ability of larger manned aircraft. Furthermore, ACAS Xu issues horizontal RAs that command right or left turns at three degrees per second, which is a standard rate for aviation turns. The optimal logic table has been flight tested by MIT Lincoln Laboratory as part of ACAS Xu. The ACAS Xu allows sUAS under 55 pounds that operate below 400 feet to avoid collisions with manned aircraft, UAS, and other sUAS.

With the guidance provided in DO-364 [42] and ARP 4761 [43], a functional hazard analysis was performed considering the high-level functions of the safety analysis of ACAS X system. The operational effects of interest, which are primarily the unresolved and induced NMAC, are used to quantify the risk ratio in the fault tree analysis. The fault tree branch associated with the initial operational and functional safety analysis is illustrated in Figure 9. Refer to Ref. [45] For the complete fault tree branches.

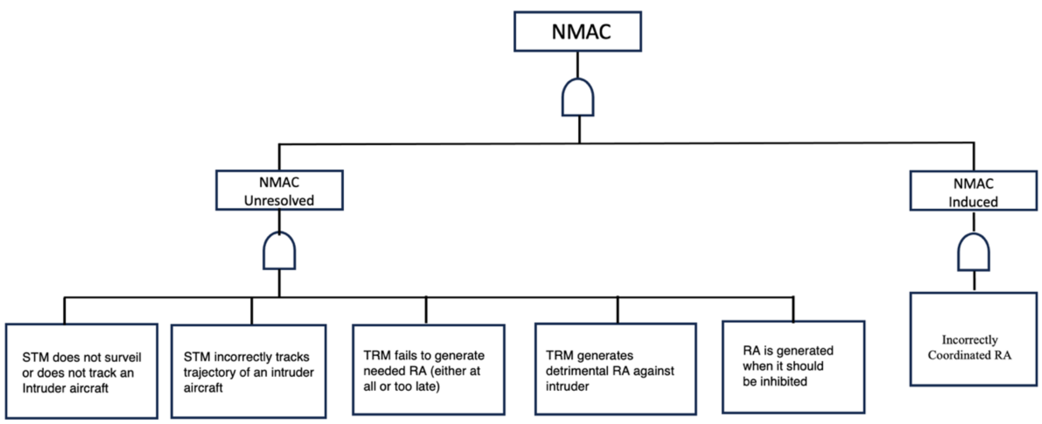

Figure 9 Fault Tree for ACAS Safety Analysis

6.3 Deconfliction of UAS BVLOS Operations

The advantageous of using Fault Trees is that it provides one way of visualizing the relationships between factors that increase safety risk and depicts cause-and-effect relationships between combinations of threats, consequences and hazards. The lack of situational awareness in the planning stage of UAS BVLOS operations often leads to two vehicles in conflict with each other. In addition, the conflict may also result from one or both of the vehicles unexpectedly deviate from planned course due to inflight emergency, unexpected weather or change of destinations. The conflict may take place in crossing/head-on routes, or one vehicle takes is taking over the other because of different cruise speeds. The fault tree branch for the cause-and -effect analysis of this hazard is illustrated in Figure 10.

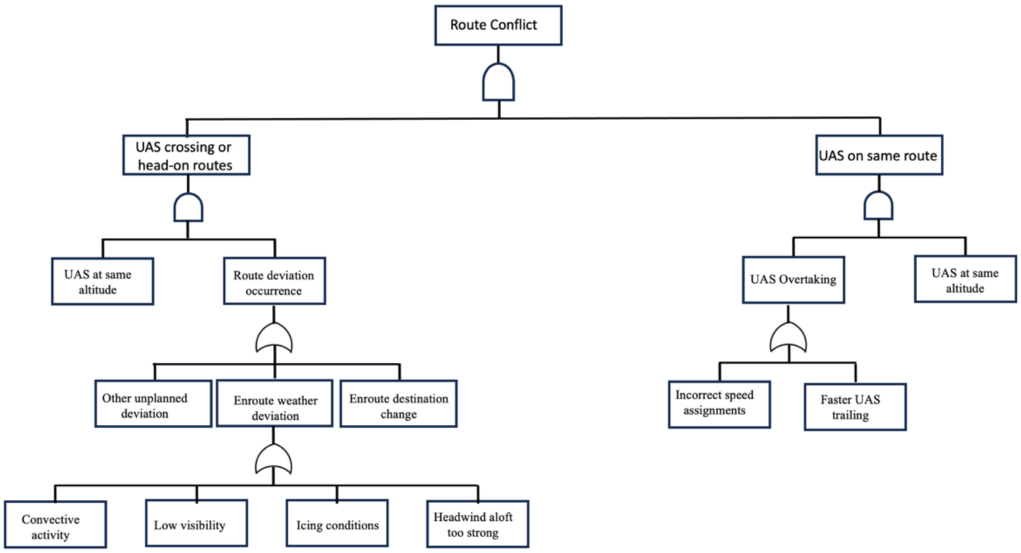

Figure 10 Route Conflict Failure Branch

6.4 Safety Analysis for UAS BVLOS Operations using the Bow-Tie Method

Specific Operations Risk Assessment (SORA) [46] provides a qualitative assessment of the safety risk associated with specific categories of UAS operations. It determines if the identified risks have been reduced to an acceptable level. In general, specific operations fall into two categories: open operations, which have very low risk, and certified operations, which require type, airworthiness, and operator certification, as well as flight crew licensing [47].

A Bow-Tie method was used in Ref. [48][49] to analyze the safety risks associated with midair collisions in UAS BVLOS operations managed by NASA UAS Traffic Management (UTM). A single Bow-Tie diagram demonstrates a single threat and consequence, with the contributing factors including the ineffectiveness of a ground-based surveillance, avoidance maneuvers, emergency procedures, and independent flight abort mechanisms. Figure 11 illustrates the Bow-Tie analysis showing the cause-and-effect relationships among causal events, the hazard, and the consequential event.

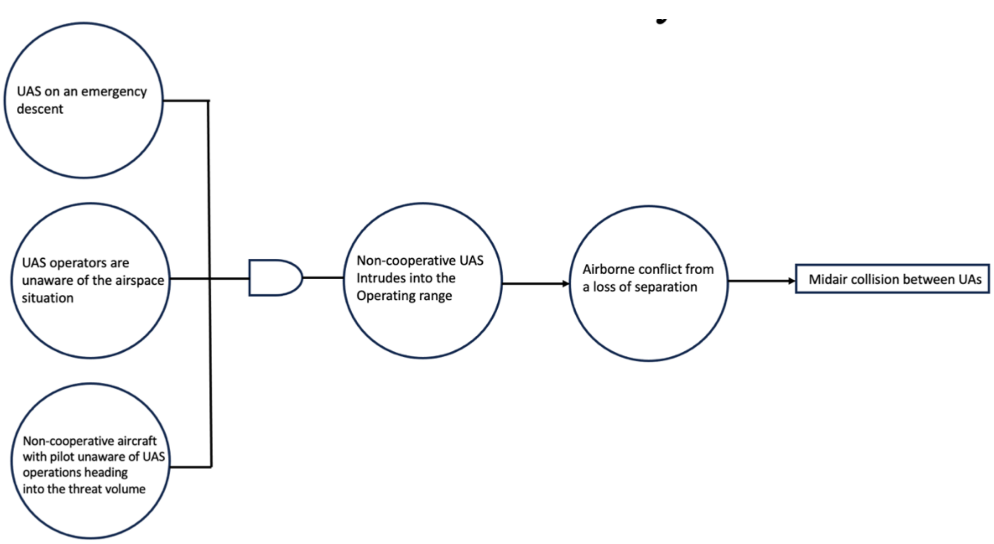

Figure 11 Fragment of a Bow-Tie Diagram showing causal events, hazard, and one single consequence

6.5 Safety Mechanism for En Route Automation Modernization (ERAM) Conflict Probe

The En Route Automation Modernization (ERAM) system is the Federal Aviation Administration's (FAA) ground automation platform used by en route controllers to manage air traffic at the twenty air route traffic control centers (ARTCC) throughout the NAS. The ERAM conflict probe (CP) is driven by the aircraft trajectory predictor (TP) and the probabilistic algorithm to predict aircraft to aircraft and aircraft to weather conflicts over the 20-minute look ahead time horizon.

The CP algorithm compares aircraft trajectories, which are generated by TP, to predict whether or not there is a conflict between the aircraft pairs over the look-ahead time horizon. The TP consists of the trajectory preparation process and the trajectory prediction process [50]. When the TP is triggered to build a trajectory driven by the flight plan, or in response to a clearance or re-conformance request, it builds the aircraft future behavior using aircraft intent modeling in the trajectory preparation process, and then predicts the aircraft trajectory using aircraft maneuver modeling in the trajectory prediction process. In addition, the effectiveness of the CP highly depends on the performance of the aircraft intent and maneuver modeling, as well as the consistency between the aircraft modeled and actual intents.

When there is error in aircraft intent entry, the TP will generate the predicted aircraft trajectory that deviates from the actual aircraft trajectory. As a result, the uncertainty in the trajectory prediction increases, and a false alert or missed alert may arise. The chance of issuing tactical maneuver increases and thus higher chance of conflicts induced by the tactical maneuver arises, thereby causing higher chances of operational error. The mechanisms derived for the safety impact for this case is presented in Figure 12. The metrics identified for this case are trajectory accuracy, number of late detections, number of missed alerts, number of tactical maneuvers, number of induced conflicts, and operational errors. The safety is expected to be enhanced if the conflict is resolved with the CRA with intent entry and the reminder that ensures the resolution being executed punctually.

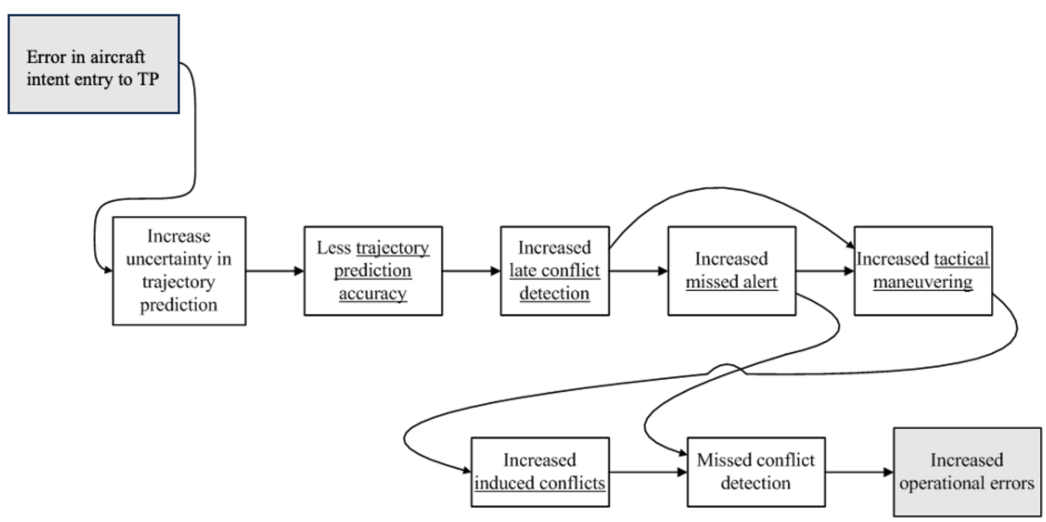

Figure 12 Safety Impact from Conflict Detection due to Missed or Incorrect Aircraft Intent Entry

7 Risk Evaluation Models

According to the categorization defined in Table 2, a risk is a measure of the likelihood and severity of the cumulative effect of a sequence of hazards. As an assessment of the safety level of proposed sUAS BVLOS operations, the risk matrix provides a means of compliance that links the likelihood of mid-air collision to the severity of the potential incident. With its mathematical convenience, the likelihood of mid-air collision, which represents an occurrence associated with the operation of an aircraft affecting the safety of operation, is used to evaluate and determine the level of safety of a sUAS BVLOS operation. Several different collision models are summarized and discussed in this section.

7.1 Reich Model

The Reich model assumes the cuboid collision zone and assumes random deviations in the velocity and position components to estimate the collision frequency per flight hour [51][52][53]. This model defines a collision as the occurrence of an overlap of two cuboids representing the aircraft. The dimensions of the cuboid are the length (S_x), width $\left(S_y\right)$, and height $(S_z\ )$ of an aircraft. The model is then established with the following assumptions:

- $x, y,$ and z represent the longitudinal, lateral, and vertical directions, respectively.
- Let $x, y,$ and z represent the longitudinal, lateral, and vertical directions, f_i is the number of aircraft passing in the i direction in one hour, where $i = x, y, z$.
- p_i is the probability density function of the aircraft overlap in the i direction at any given time
- The density function is independent in directions $x, y,$ and z.
- All the cuboids in consideration have the same sizes and the orientation of the cuboid remains constant, i.e., aircraft are flown in parallel

Then the number of longitudinal collisions per hour equals to $f_x \cdot p_y \cdot p_z$, the number of lateral collisions per hour equals to $f_y \cdot p_z \cdot p_z$, and the number of vertical collisions per hour equals to $f_z \cdot p_x \cdot p_y$. Furthermore, the number of collisions per hour in any direction equals to

$$N = f_x \cdot p_y \cdot p_z + f_y \cdot p_z \cdot p_z + f_z \cdot p_x \cdot p_y \tag{1}$$

Consider the average time in terms hour spent in pairwise overlap in direction i during a single passing to be t_i, and the average relative passing speed in the same direction to be v_i, then the number of aircraft overlap in direction i can be represented by

$$f_i = \frac{p_i}{t_i} = \frac{p_i}{\frac{2 \cdot S_i}{v_i}} = p_i \cdot \frac{v_i}{2 \cdot S_i} \tag{2}$$

Then Eq. (1) becomes

$$\begin{aligned} N &= f_x \cdot p_y \cdot p_z + f_y \cdot p_z \cdot p_z + f_z \cdot p_x \cdot p_y \\ &= p_x \cdot \tfrac{v_x}{2 \cdot S_x} \cdot p_y \cdot p_z + p_y \cdot \tfrac{v_y}{2 \cdot S_y} \cdot p_z \cdot p_z + p_z \cdot \tfrac{v_z}{2 \cdot S_z} \cdot p_x \cdot p_y \\ &= p_x \cdot p_y \cdot p_z \cdot \left(\frac{v_x}{2 \cdot S_x} + \frac{v_y}{2 \cdot S_y} + \frac{v_z}{2 \cdot S_z}\right) \end{aligned} \tag{3}$$

Hence the collision probability per flight hour is represented by

$$N = p_x \cdot p_y \cdot p_z \cdot \left(\frac{v_x}{2 \cdot S_x} + \frac{v_y}{2 \cdot S_y} + \frac{v_z}{2 \cdot S_z} \right) \quad (4)$$

It is convenient to implement the Reich model because the collision probability of each dimension can be estimated independently. The disadvantage of the Reich model is that it assumes that the operation routes are parallel, which does not apply in sUAS BVLOS operations, where the risk of collision at the crossings can be high.

7.2 Gas Model

Gas model is another model that estimates the probability of collision at the intersection of air routes by assuming aircraft behave similarly to gas molecules. This model decouples the computation of the probability of mid-air collision into the horizontal plane and the vertical plane, by assuming the horizontal and the vertical distributions are independent of each other. Moreover, the model assumes that there are N aircraft flown in the airspace volume with horizontal area A and height H, and the aircraft is represented by a cylinder with the radius g and height h. A collision is defined as an occurrence of the overlap of two cylinders, where the center of the cylinder enters the aircraft enters the cylinder. The collision ate is expressed as follows [54][55]:

$$C = F_H \cdot P_v \quad (5)$$

where

C = the rate of collisions per unit time.
F_H = the rate of horizontal overlap per unit time.
P_v = the probability density function for two aircraft overlap vertically in the presence of horizontal overlap.

Let $E(V_r)$ be the expected relative velocity, and ρ be the density of aircraft in the horizontal plane, i.e., $\frac{N}{A}$, then each aircraft encounters $2gE(V_r) \cdot \rho \cdot dt$ overlaps on average per unit time. The total number N_c of horizontal overlaps per unit time is then given by

$$N_c = 2gE(V_r) \cdot \frac{N}{A} \cdot C_2^N = \frac{g \cdot E(V_r) \cdot N^2}{A} \quad (6)$$

Let P_z be the probability density function for the aircraft flown at the altitude z, then the probability for the aircraft flown between altitude z_1 and z_2 is given by $\int_{z_1}^{z_2} P_z\,(z)dz$ and the probability of two aircraft having vertical overlap is given by

$$P_v = \int_G^{G+H} P_Z\,(z)dz \int_{z-h}^{z+h} P_z\,(u)du \quad (7)$$

where G represents the lowest level of the airspace volume in consideration.

With Eq. (6-7), the collision rate is given by

$$C = \frac{g \cdot E(V_r) \cdot N^2}{A} \cdot \int_G^{G+H} P_Z\,(z)dz \int_{z-h}^{z+h} P_z\,(u)du \quad (8)$$

The general form of $E(V_r)$ is represented by

$$E(V_r) = \int_{V_1^{min}}^{V_1^{max}} \int_{V_2^{min}}^{V_2^{max}} \int_0^{2\pi} \int_0^{2\pi} (V_1^2 + V_2^3 - 2V\,_1V_2 \cdot \cos(\theta_1 - \theta_2))^2 \cdot P_\theta(\theta_1)P_\theta(\theta_2)P_V(V_1)P_V(V_2)d\theta_1 d\theta_2 dV_1 dV_2 \tag{9}$$

where
θ_i = the aircraft i heading
V_i = magnitude of velocity of aircraft i
$P_\theta(\theta_i)$ = probability density function of θ_i
$P_V(V_i)$ = probability density function of V_i

The gas model is convenient for modelling uniform distributions of a free-flight traffic and supports crossing structures; however, the distribution cannot be mapped to aircraft with uncertainty in surveillance and communication [55].

7.3 Paielli and Erzberger Model and its Variants

The model proposed by Paielli and Erzberger estimates the aircraft conflict probability where both encounter aircraft fly straight lines at constant speed [56][57]. This model uses The Gaussian distribution for predicting errors on the predicted positions at the point of minimum separation. As a result, the errors are represented as ellipse in the horizontal plane or ellipsoids in the three-dimensional space, where the principal axes of the ellipsoids in the along-track, cross-track, and vertical directions. The relative distance between two aircraft at a given time duration is estimated by assuming the distribution of aircraft position errors being a zero mean normal distribution. With proper definition of relative distance, choice of coordinate transformation, the mathematical form of the conflict probability P_C can be written as

$$\begin{aligned} P_C &= \int_{z_0}^{z_1} \int_{y_0}^{y_1} \int_{-\infty}^{\infty} p(x,y,z)\,dxdydz \\ &= \int_{y_0}^{y_1} p(y)dy \int_{z_0}^{z_1} p(z)dz \int_{-\infty}^{\infty} p(x)dx \\ &= \int_{y_0}^{y_1} p(y)dy \int_{z_0}^{z_1} p(z)dz \\ &= P(y_0, y_1)P(z_0, z_1) = P_{hc}P_{vc} \end{aligned} \tag{10}$$

where P_{hc} represents the horizontal cumulattive normal conflict probability, and P_{vc} represents the vertical cumulative normal conflict probability.

The advantage of such approach is that a close form of analytical solution to the integral of the probability of collision can be approximated by transforming the combined error ellipse into a unit circle, where the overlap between the unit circle and ellipse is the final probability [56][57]. It should be noted that trajectory predictions are not required at the exact point of predicted minimum separation and small variation in aircraft velocity due to wind disturbances will have little effect in the immediate vicinity of an encounter.

The afore-mentioned model assumes straight trajectories of two encountering aircraft, a hybrid method that accounts for the normal distribution around a turn and therefore enhances the deficiency associated with the models for the straight trajectories. The method uses the sample points within the bending error ellipse associated with the turning trajectory and then assign a weighting parameter proportional to the frequency in normal distribution to each of the selected points for the computation of the probability of collision [58].

7.4 Bird Strike Model

The bird strike model utilizes the Poisson spatial process to determine the probability of a bird strike [59]. This method is adopted by ATSM F3548 [6] for computing the probability of the unmitigated collision.

The following assumptions are made for the model formulation:

- The aircraft frontal area is modeled as the elliptical disc formed by its height and width for the sweeping volume of space traversed by the aircraft.
- An aircraft/bird encounter within the ellipse is considered a strike.
- The number of birds in the Operations Area (AO) is constant.
- The speed of birds in the AO is negligible compared to the speed of the aircraft and can be considered stationary.
- Altitude distribution of birds follows a gamma distribution; a Poisson distribution is considered when birds are detected within an altitude band.

Assume that there are n birds flying in the bounded region A, then the encounter for n birds in the AO can be mathematically formulated as:

$$\lambda = \frac{n}{|A|} \tag{11}$$

$$P_n = e^{-\lambda \cdot |A|} \cdot \frac{(\lambda \cdot |A|)^n}{n!} \tag{12}$$

where the density λ is constant and $|A|$ represents the volume of AO.

The spatial distribution which is the intensity function in the Poisson process is defined as the ratio of the number of birds in the sweeping volume and the sweeping volume. The gamma altitude distribution along with the 2-dimensional space.

7.5 Collision Surface

The collision surface model [60] calculates the collision probability between two aircraft flying arbitrary curvilinear paths, where each of the two aircraft is represented by a bounded, closed region of airspace volume. The collision surface is defined as the locus of the center of the intruder volume. In other words, the collision surface is the center of the intruder volume touch but not penetrate the ownship volume. A collision is defined to be when an intruder encroaches the collision cross section vector which is parallel to the edge of the obstacle. This definition is rigorous yet generic for detecting the collision with an obstacle in any shape.

With the definition of a collision, this model calculates the average number of collisions, $\widetilde{N}$, over a time interval $[t_0, t_1]$ by integrating the rate of the statistical mean of the number of collisions, $\frac{d\widetilde{N}}{dt}$. Then the time rate of N can be defined as:

$$\begin{aligned} \dot{N} &\equiv u(\vec{v}_r \cdot \vec{n}) \cdot \frac{d\delta(\Delta r)}{dt} \\ &= u(\vec{v}_r \cdot \vec{n}) \cdot \frac{d\delta(\Delta r)}{dr} \cdot \frac{d\Delta r}{dt} \\ &= u(\vec{v}_r \cdot \vec{n}) \cdot \vec{v}_r \cdot \nabla\delta(\Delta r) \end{aligned} \tag{13}$$

where

$\vec{v}_r =$ the relative velocity of the encounter objects
$\vec{n} =$ the normal vector of the conflict surface pointing inward of the object
$\Delta r =$ the difference of the distance measured from the center of the ownship volume

$\delta(\Delta r)$ = the step function which is 0 for $\Delta r < 0$ and 1 for $\Delta r \geq 0$

With the mathematical establishment in Eq. (12), the ensemble average of the time rate of N can be written as

$$\tilde{\dot{N}} = \int d\vec{v}_r \int d\Delta r \cdot \mathrm{P}(\Delta r, \vec{v}_r, t) \cdot u(\vec{v}_r \cdot \vec{n}) \cdot \vec{v}_r \cdot \nabla \delta(\Delta r) \tag{14}$$

where $\mathrm{P}(\Delta r, \vec{v}_r, t)$ is joint probability density function of the relative distance and velocity.

Let $\vec{\mathrm{Z}} = \mathrm{P}(\Delta r, \vec{v}_r, t)\, u(\vec{v}_r \cdot \vec{n})\vec{v}_r$, then Eq. (13) can be rewritten as

$$\begin{aligned} \tilde{\dot{N}} &= \int d\vec{v}_r \int d\Delta r \cdot \vec{\mathbf{Z}} \cdot \nabla \delta(\Delta r) \\ &= \int d\vec{v}_r \int d\Delta r \cdot \left[\nabla \cdot \left(\delta \vec{\mathrm{Z}}\right) - \delta \nabla \cdot \vec{\mathrm{Z}}\right] \end{aligned} \tag{15}$$

By the divergence theorem, the integral of the first term $\nabla \cdot \left(\delta \vec{\mathrm{Z}}\right)$ becomes zero since it is the integral over the radius outside of the collision volume. The integral of the second term $\delta \nabla \cdot \vec{\mathrm{Z}}$ is zero outside of the collision volume and non-zero within the collision volume. Hence Eq. (15) can be written as

$$\begin{aligned} \tilde{\dot{N}} &= -\int d\vec{v}_r \int d\Delta r \cdot 1 \cdot \nabla \cdot \vec{\mathrm{Z}} \\ &= \int d\vec{v}_r \int_{S_C} (d\vec{s} \cdot \vec{v}_r)\, u(\vec{v}_r \cdot \vec{n})\, \mathrm{P}(\Delta r_c, \vec{v}_r, t) \\ &= \int d\vec{v}_r \mathrm{P}(\Delta r_c, \vec{v}_r, t) \vec{v}_r \cdot \left[\iint_{S_C} u(\vec{v}_r \cdot \vec{n}) d\vec{s}\right] \end{aligned} \tag{16}$$

Then the average number of collisions in an ensemble of encounter over $[t_0, t_1]$ can be written as

$$\tilde{N} = \int_{t_0}^{t_1} \tilde{\dot{N}}\, dt \tag{17}$$

7.6 Markov Chain

The Markov Chain model is a grid-based method for estimating the probability of the mid-air conflict occurring in a pairwise encounter by evaluating the flight plan based stochastic aircraft trajectories [61][62]. Mathematically, the aircraft stochastic is represented by

$$\dot{X}(t) = v(t) + w(X, t) + \mathrm{K}\dot{B}(X, t) \tag{18}$$

where

$X(t)$ = aircraft position at $t \in T = \left[t_o, t_f\right]$
$v(t): T \to \mathbb{R}^3$ = aircraft velocity at time $t \in T$
$w(X, t)$ = wind field representing the nominal wind speed at a position X and time t
$B(X, t)$ = time-varying random field on $\mathbb{R}^3$ modeling air turbulence perturbations to aircraft velocity and wind speed measurement errors[6]

The probability of conflict between aircraft 1 and aircraft 2 can be found with the solution to the following equation:

$$\dot{Y}(t) = \Delta v(t) + \Delta w(X, t) + KZ(t) \tag{19}$$

[6] Note that $B(X, t)$ is 3D Brownian motion whose time derivative is a white noise process, and is time increment independent.

where
X_1, X_2 = position of aircraft 1 and 2
$\Delta v(t) = v_2(t) - v_1(t)$
$\Delta w(X,t) = \Delta w(X_2,t) - \Delta w(X_1,t)$ which is assumed to be affine in X and can be represented by $\Delta w(X,t) = R(t)Y(t)$
$K = diag(\sigma_h, \sigma_h, \sigma_v)$
$Z(t) = \dot{B}(X_2,t) - \dot{B}(X_1,t)$ is assumed to be a Gaussian process and can be represented by $Z(t) \approx \sqrt{2|1-\rho Y(t)|}W(t)$

Denote Λ as the point set collecting all the points that $Y(t)$ is less than the separation minima. The Markov chain $\{\Lambda_k, k \geq 0\}$ on the state space Λ is defined on the state space such that:

1. If $0 \leq k < k_f$

$$P_{c,\delta}^{k}(q) = \begin{cases} p(q,\xi) & q \in \Lambda^0 \\ 1 & q \in \partial\Lambda \\ 0 & otherwise \end{cases} \tag{20}$$

2. If $k = k_f$

$$P_{c,\delta}^{k_f}(q) = \begin{cases} 1 & q \in \partial\Lambda \\ 0 & otherwise \end{cases} \tag{21}$$

With the probabilistic perturbation parameter ξ, this model computes the probability of pairwise conflict as $P_{c,\delta} = P_{c,\delta}^{0}(\bar{q})$ iteratively to determine whether or not there is a conflict, where $\bar{q}$ being a point in Λ closet to $Y(0)$.

7.7 Monte Carlo Simulation

Monte Carlo simulation is a method that is well received for generating multi-aircraft scenarios over a given time duration to compute the probability of aircraft-to-aircraft conflict, allowing to use the stochastic dynamic equations of aircraft motion. Moreover, the conflict rate can be obtained by dividing the probability by the time duration of the simulated scenario [63][64]. The method generates the probability of conflict as follows:

1. Generate N sample paths within a time horizon $[0,T]$, considering $k = 1, \ldots, M$ total number of aircraft in the simulation.
2. The probability of conflict between aircraft i and j within the time interval $[0,T]$ can be estimated as

$$p\big(t_{ij} \in [0,T]\big) = \frac{\sum_{k=1}^{N} 1_{\exists t_{ij,k} \in [0,T]}}{N}$$

   where $1_{\exists t_{ij,k} \in [0,T]}$ equals to 1 if there is a conflict between aircraft i and j at $t_{ij,k} \in [0,T]$ in simulation k.
3. The probability of aircraft i in conflict with other aircraft in time interval $[0,T]$ is estimated as

$$\sum_{j=1, j \neq j}^{N} p\big(t_{ij} \in [0,T]\big)$$

8 Fatality Model

Following the discussion of likelihood of mid-air collision models, the severity in the risk matrix is mostly determined by the number of human casualties caused by an operation failure, from injuries to fatalities. The cumulative factors contributing to fatalities from the mid-air collision include [66]:

- The airborne time representing a failure time interval assuming a mid-air collision occurs.
- The area of a region affected by the air vehicle impact and its population density.
- The impact probability and casualty expectation for the predicted population area.

The number of people getting impacted by the falling air vehicle from a mid-air collision can be modeled in the following equation [67]:

$$N_{casaulty} = A_{impact} \times \rho_{population} \tag{22}$$

The impact area is determined by

$$A_{impact} = \pi \cdot \left[\left(d_{impact} + d_{person} + d_{uav} \right)^2 \quad - \left(d_{impact} - d_{person} - d_{uav} \right)^2 \right] \tag{23}$$

and

$$d_{impact} = h \cdot |\tan 2\theta|$$
$$d_{person} = \text{maximaum width of a person}$$
$$d_{uav} = \text{maximum width of a UAV}$$

where h is the vehicle altitude and θ is the angle of inclination of the falling vehicle from horizon.

The impact energy is the deciding factor determines the degree of casualty an object free falling through the sky and can be represented by the following equation [68]:

$$E_{impact} = \frac{1}{2} \cdot m \cdot v^2 \tag{24}$$

where

$$v^2 = v_T^2 \left(1 - e^{-2gh/v_T^2} \right)$$

$$h = h_{collision} - h_{human}$$

$$v_T^2 = \frac{2mg}{C_D A \rho_{air}}$$

Note that the terminal velocity of a free fall air vehicle is a function of its mass, m, drag coefficient, C_D, lift coefficient, and cross-sectional area, and the density of air. Assuming the falling air vehicle hit a person's skull, the degree of injury can be summarized in Table 4.

Table 4 Relationship between Impact Energy and Skull Fracture Severity

Degree of Injury	Impact Energy Threshold
No Skull Fracture	0 – 19.8 Joules
Minor Depressed Skull Fracture	19.8 – 49.5 Joules
Major Depressed Skull Fracture	49.5 – 99 Joules
Severe Life-Threatening Fracture	> 99 Joules

The probability of casualty if a person's head is hit by the falling UAV in the head is modeled by the following equation [69]:

$$P_{casualty}\left(E \leq E_{impact}\right) = \int_{0}^{E_{impact}} \frac{1}{x\beta\sqrt{2\pi}} e^{-\frac{(lnx - ln\alpha)^2}{2\beta^2}} dx \tag{25}$$

where E represents the energy, and α and β are the scale and shape parameters of the log-normal and the values of the parameters are listed in Table 5 [70].

Table 5 Log-Normal Distribution Parameters for Different Body Parts

Body Part	Log-Normal Parameters	
	α	β
Head	55	0.2302

With the established quantities, the severity of the operation can be modeled as:

$$P_{casualty}\left(E_{impact} < E_{threshold} | impact\right) \times P_{impact} \times A_{impact} \times \rho_{population} \tag{26}$$

9 Discussion

A risk analysis methodology must be sought to determine the level of safety of a proposed sUAS BVLOS operation. The factors that lead to sUAS-level hazards and the associated risks must be considered; and they form the basis of the safety assessment with achievable TLS. The critical components of the risks are the likelihood of mid-air collision and the severity of on impact leading to casualties, where the casualties could be either fatality or injury. The International Civil Aviation Organization (ICAO) has established TLS standards for air transportation. It is expected that the overall mission TLS is one fatal accident per 10 million operations or 1.0E-07 fatal accidents per operation. The probability of collision is the essential metric measuring the risk which must be considerably lower than the overall TLS. Deviations from nominal operations could raise the overall risk of collision above the TLS; an operational objective of 1.0E-07 accidents per flight hour was chosen when no faults are present.

As a result of this survey, our findings suggest the assessment method that evaluates risks against the TLS should consist of the following stages:

- Define the proposed operation, which includes the operational requirements that depict the characteristics of the operation.
- Define the evaluation metrics for the level of safety associated with the proposed operation.
- Identify the events that collectively lead to a mid-air collision.
- Estimate the probability of mid-air collision and determine its severity.
- Estimate total risk value of mid-air collision, and compare the value against the TLS.
- Establish a safety gap analysis, in which all aspects of the safety associated with the proposed operation are analyzed through tests or simulations.

The key element in a safety assessment is the selection of safety analysis methods. The selection is subject to whether the objective of the assessment is function, hazard induced effect, or algorithmic performance centric. The qualitative risk assessment methods that are used in the academic and UTM industries, including the event-tree analysis, the fault-tree analysis, and the bow-tie diagram analysis, were investigated, and the merits were summarized. These methods begin by establishing a high-level logical model that combines the branches of the event tree and the fault tree to represent all possible hazards of the components within a system. Using the operational data at hand, we can quantify the safety assessment by computing path probabilities, which represent the combined probability of all events occurring on that path.

Simulated or field test data may underestimate, or overestimate the risk associated with the proposed sUAS BLOS operation, due to the uncertainty of the time interval during which the event occurs during simulation or testing. The probabilistic events may occur quite frequently or not at all during the data collection process. Accordingly, the confidence interval around the estimate results varies from one modeling process to another, where the confidence interval grows proportionally to uncertainty. Therefore, increased safety analysis precision is essential when making decisions regarding the operation's safety compliance.

10 Summary

In order to certify the proposed sUAS BVLOS operation, a safety compliance assessment combining hazard identification and causal analysis linking the hazards to the operation results will become increasingly important as the demand for sUAS BVLOS operations increases. Because the uncertainty of the operation can only be estimated, the risk associated with the operation becomes stochastic and varies from one operation to another. Thus, the FAA uses the TLS to determine whether an operation achieves the level of safety it expects, and this metric is generated in accordance with the agency's policies, standards, and analyses.

In this report, we identified a framework commonly used by the industry and the risk matrix as the means to estimate the level of safety of an sUAS operation. The framework includes the process of identifying operational and functional requirements, data collection, hazard identification, and safety analysis. The safety analysis in the process performs the qualitative analysis and quantifies the metrics defined in the qualitative analysis. A qualitative safety analysis identifies a causal link between failure events and the hazard by focusing on a particular aspect of the operation. The selection of techniques depends on the scope of the operation and the complexity of the system managing the operation. As part of the risk matrix, two quantities, namely the likelihood and severity, are used to represent the hazard associated with the operation. The variable likelihood represents the probability of mid-air collision, and the variable severity represents the impact on the people on the ground from the collision. The level of safety of any proposed operation can be determined exclusively with these two quantities even though the risk is itself a combination of stochastic variables changing over time.

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