A Framework to Develop Sense and Avoid Requirements for Unmanned Aircraft Systems

Using a Target Level of Safety Approach

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1.0 Introduction:

Full integration of Unmanned Aircraft Systems (UAS) into the National Airspace System (NAS) is the goal of many stakeholders in the Aerospace community in addition to being mandated by law as of February, 2012 [1]. The Department of Defense seeks greater access to training sites, other public users would like to use UAS for operations such as law enforcement and disaster relief, and the civil sector wants to unleash the potential of UAS to generate revenue [2, 3].

However, the reality of the situation remains that UAS operations in the NAS have remain limited to military operations in Restricted airspace and limited public / civil usage under restrictive Certificates of Authorization or Waiver (COAs). One of the most often cited obstacles to integration is the inherent lack of a See or Sense and Avoid (SAA) capability on UAS to comply with Code of Federal Regulations (CFR) 14 Part 91.113 [4]. There have been several efforts to develop and test a SAA capability for UAS including a ground-based system tested by the U.S. Army and an air-based one tested by the U.S. Air Force.

The purpose of this article is to propose a method to develop effectiveness standards for SAA systems developed for UAS. Effectiveness, in this context is defined as the combination of reliability and efficacy that indicates to what extent a system performs its intended function and is not prevented from doing so due to either system failures or insufficient performance standards

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In order to develop minimum effectiveness standards for SAA, the authors propose utilizing a framework that includes a Target Level of Safety (TLS) approach to the problem and an Event Tree format model.

2.0 Background

It is impossible to design a SAA sub-system for UAS, or for any aircraft for that matter, without specific performance and reliability standards. These standards should include parameters such as the minimum intruder detection distance based on closure rates and the ability to maneuver to avoid collisions. They should also include a reliability or availability standard to ensure that the system maintains functionality. The parameters would also likely include the number of potential intruders the system must track, the accuracy of any positioning system, and a maximum number of false alerts.

It was the opinion of the FAA’s Sense and Avoid workshop that the foundation for these performance standards be a TLS approach [6]. The Target Level of Safety has been defined as a “top-down approach which focuses on safety critical issues which could affect achievement of the safety target” by Haddon and Whittaker [7]. The metric used to define the TLS in the framework for this article is a midair or second-party casualty rate, or fatalities per UAS flight hour. This metric was chosen because it mirrors the statistics already in use by the FAA for the NAS and it also matches the metrics used by the Range Commander’s Council (RCC) [8], the Nuclear Regulatory Commission (NRC) [9] and other agencies concerned with safety such as the National Transportation Safety Board [10].

The real purpose behind using the TLS approach to this problem is to link the effectiveness of any SAA sub-system to a metric that matters most to the FAA, stakeholders and
the public. That metric should be safety-related, which is why the fatality rate is suggested. Without linking SAA standards to safety, any design choices and trade-offs made on the subsystem will not necessarily lead to safer skies.

Event trees (ET) are established reliability tools first used by the NRC in the 1970s [11]. The authors chose to use an Event Tree format to model UAS operations in the NAS for several reasons. First, they provide a means to visually trace both the probability and impact of events which can be either failures or normal operating events [5]. Second, fatalities in the NAS are extremely rare events. To properly identify and analyze events that only occur sometimes on the order of $1 \times 10^{-8}$, a model that replicates the behavior of the NAS like an agent-based model, would require $1 \times 10^9$ simulations, at a minimum [12]. Event trees combined with Monte Carlo simulation, on the other hand can still capture the effects of improbable events because even unlikely events can be featured in a branch of the tree.

3.0 Framework Details

The model for this framework consisted of four major components. First, the authors developed characteristics of the air environment to include the density of aircraft in the airspace in question, the type of aircraft in the environment [13, 14], and the type of airspace control or architecture of the environment [15]. Aircraft density was obtained through statistics on aircraft flights in the NAS [16-19] and definitions of the airspace types from the FAA [20, 21].

Second, each event tree started with an initiating event. In this case, the initiating event was an encounter or near midair collision between a UAS and a manned aircraft. Values for the probability of an encounter were based on a gas particle model which treated aircraft in a specified volume of airspace as randomly moving gas particles [22-26]. Other aircraft in the
airspace were treated as motionless particles, while the UAS was treated as a cylinder sweeping out volume at a rate based on the size of the encounter cylinder and the relative velocities between the UAS and manned aircraft. The dimensions of that cylinder were based on physical dimensions of the UAS and not a larger separation volume. That decision was based on the focus and purpose of this study. Previous uses of gas particle models were primarily for air traffic or collision avoidance purposes. Thus, the goal of those studies was to determine the likelihood of two aircraft requiring additional separation measures either from a controller or collision avoidance system. However, given the safety-related focus in this study on casualty rates, the primary concern was actual collisions and not near midair collisions. If the study was expanded to determine the impact of UAS operations on air traffic and separation, then the larger separation volume could be used.

The unstructured nature in which the gas particle model portrays aircraft in the airspace is not entirely indicative of the measures of control inherent in the NAS. However, for the purpose of this research, given its overall statistical nature, the random motion of particles replicated by this model was favored. While this model is less realistic around airports or along airways, it provides a good statistical representation of overall activity in the NAS. In fact, with the advent of trajectory-based operations (TBO) in the near future under NextGEN, aircraft behavior will actually more closely resemble random trajectories and rely less on more ordered trajectories focused on ground-based navigational aids \[27\]. Finally, this approach provides a more conservative estimate of encounters which can then be made more realistic by applying separation and avoidance standards.

The third feature of the event tree model was risk mitigation or collision avoidance. The probability of avoiding a collision was based on a combination of factors to include whether or
not the airspace was under positive control by Air Traffic Management (ATM), and the closure rates of the manned aircraft and UAS. The success rate in avoiding collisions through ATM control was based on statistics of the NAS [12, 28], while avoidance rates for the aircraft in the environment were based on a combination of studies that detailed avoidance rates by both visual and electronic means [23, 29-32].

The fourth piece of the air risk event tree were the effects that would occur if a midair collision did occur. This segment consisted of determining the probability that a midair collision between a UAS and a manned aircraft would cause fatalities and if so, how many. The probability that a midair collision would result in a catastrophic event and therefore casualties, was based on studies of both bird strikes on aircraft from CFR14 Part 25.631 and the European Aviation Safety Agency (EASA) Part CS-25 [4, 33], and the risk to aircraft from falling debris from the RCC [34]. If a catastrophic collision did occur, the number of casualties caused was based on the type of aircraft in the NAS, their passenger capacity [21], and load factor statistics [35].

The actual event tree used to model the risk of fatalities from UAS operations appears in Figure 1, while a more detailed description of the logic used to determine the effects, or fatalities, in the event of a collision appears in Figure 2. The ET is a series of branches that detail different options for the air environment, mitigation and event outcomes based on the probability of each of the branches occurring. Since the probability of many of the branches were not deterministic values, the software tool @Risk™ was used to model the branches as probability distributions. The resulting casualty rate results were also distributions based on Monte Carlo simulations conducted typically with more than 5,000 iterations.
Figure 1: Event Tree for Air Risk
Information about the representative UAS in the model was obtained by examining the current characteristics of the most common UAS in use at the time of writing this effort. The values for the UAS characteristics appear in Table 1.

Table 1: UAS Parameters for Model

<table>
<thead>
<tr>
<th>Information</th>
<th>Value</th>
<th>Units</th>
<th>Source</th>
<th>Citation</th>
</tr>
</thead>
<tbody>
<tr>
<td>UAS Weights</td>
<td>Lognormal: Mean: 2582.44 Std Dev: 20,994.3</td>
<td>lbs</td>
<td>Survey of Vehicles</td>
<td>[36]</td>
</tr>
<tr>
<td>Speed</td>
<td>$88.18 + 0.0279 \times \text{Weight}$</td>
<td>ft/s</td>
<td>Regression</td>
<td>[37]</td>
</tr>
<tr>
<td>Wingspan</td>
<td>$12.015368 + 0.0140653 \times \text{Weight} - 4.6313e-7 \times (\text{Weight}-1807.6)^2$</td>
<td>ft</td>
<td>Regression Based on Weight</td>
<td>[36]</td>
</tr>
<tr>
<td>Fuel Load</td>
<td>$-42.1565 + 0.5073 \times \text{Weight}$</td>
<td>lbs</td>
<td></td>
<td>[38]</td>
</tr>
<tr>
<td>Endurance</td>
<td>$6.0627732 + 0.0079073 \times \text{Weight}$</td>
<td>hrs</td>
<td></td>
<td>[38, 39]</td>
</tr>
</tbody>
</table>
The model was validated by using historical data for General Aviation (GA) midair collisions and fatalities. Data for a 20 year period was used and the UAS characteristics were replaced by characteristics representative of the GA aircraft involved in the midair collisions during that period. The data used to validate the model appears in Table 2.

<table>
<thead>
<tr>
<th>Information</th>
<th>Value</th>
<th>Units</th>
<th>Source</th>
<th>Citation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Traffic Speeds</td>
<td>Triangular Distribution: Min: 50.36 Peak: 100.72 Max: 302.17</td>
<td>knots</td>
<td>Average of Radar Reports</td>
<td>[40]</td>
</tr>
<tr>
<td>General Aviation Velocity</td>
<td>173</td>
<td></td>
<td>Waggoner Study</td>
<td>[41]</td>
</tr>
<tr>
<td>Vertical Cylinder Height (V)</td>
<td>36</td>
<td>Ft</td>
<td>Average of Studies and Information on GA Aircraft</td>
<td>N/A</td>
</tr>
<tr>
<td>Horizontal Radius of Cylinder (H)</td>
<td>36</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Midair Collision (MAC) Rate for GA</td>
<td>$5.9 \times 10^{-7}$</td>
<td>Midair per flight hour</td>
<td>NTSB Data</td>
<td>[42]</td>
</tr>
<tr>
<td>MAC Rate for All Aircraft</td>
<td>$3.74 \times 10^{-7}$</td>
<td>Midair per flight hour</td>
<td>NTSB Data</td>
<td>[42]</td>
</tr>
<tr>
<td>Fatality Rate for Midair Collisions</td>
<td>$6.82 \times 10^{-7}$</td>
<td>Fatality per flight hour</td>
<td>NTSB Data</td>
<td>[42]</td>
</tr>
<tr>
<td>Casualties per Midair Collisions</td>
<td>1.76</td>
<td>Fatality per midair</td>
<td>NTSB Data</td>
<td>[42]</td>
</tr>
</tbody>
</table>

After implementing the data from Table 2 in the model, the difference between the predicted casualty rate and the historical casualty rate was less than 1%. Hypothesis testing of the results did not provide statistical evidence to reject the null hypothesis that the hypothetical mean of the casualty rate and the historical casualty rate were different.

A sensitivity analysis of the air risk model revealed that the three parameters that had the most impact on the variability of the casualty rate were the size or wingspan of the UAS, the
density of the airspace, and the percentage of time that the UAS operated in controlled airspace. An example of the findings from the sensitivity analysis appears in Figure 3, in the form of a tornado plot of regression coefficients. The tornado plot displays the input parameters of the air risk model in order of how much they affected the variability of the outcome. These findings became the basis for the categorization featured in section 4.0.

![Tornado plot of regression coefficients](image)

Figure 3: Sensitivity Analysis for Air Risk Model

### 4.0 Results and Discussion

In order to set effectiveness standards for the SAA sub-system, potentially for certification purposes, it is helpful to create UAS categories for consideration. While is possible to generate a continuous range of effectiveness standards using the air risk model, linking the standards to specified categories is less confusing and creates a system similar to the current manned aircraft categories for certification. The delineating parameter for the factors was chosen as the air vehicle weight. While there are arguments in the literature to use other
parameters such as size, kinetic energy, maximum altitude, or operating endurance, all of these parameters are highly correlated to vehicle weight, thereby allowing one parameter to effectively take many different aspects of UAS risk into account. The relationship between several parameters and vehicle weight was determined by performing a regression analysis on existing UAS, the results of which appear in Table 1.

The categories recommended from this study appear in Table 3. They were selected because they conform as closely as possible to existing categories from various agencies. The rationale was that recommending these categories would cause the least amount of administrative burden to adopt because many of the weight values already compare to an existing legal or administrative category.

<table>
<thead>
<tr>
<th>Group</th>
<th>Weight (lbs)</th>
<th>Source</th>
<th>Citation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Group 1 (Micro)</td>
<td>&lt; 1</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Group 2 (Mini)</td>
<td>1.1 - 4.4</td>
<td>FAA Law</td>
<td>[1]</td>
</tr>
<tr>
<td>Group 3 (Small)</td>
<td>4.5 - 55</td>
<td>FAA Law, DoD, EASA Drafts</td>
<td>[1, 2, 43]</td>
</tr>
<tr>
<td>Group 4 (Tactical)</td>
<td>56 - 351</td>
<td>ICAT Study, EASA Drafts</td>
<td>[44, 45]</td>
</tr>
<tr>
<td>Group 5 (Medium)</td>
<td>352 - 1320</td>
<td>DoD</td>
<td>[2]</td>
</tr>
<tr>
<td>Group 6 (Large)</td>
<td>1,321 - 10,000</td>
<td>Based on Predator C</td>
<td>[36]</td>
</tr>
<tr>
<td>Group 7 (Heavy)</td>
<td>10,001 – 25,000</td>
<td>Based on Global Hawk</td>
<td></td>
</tr>
</tbody>
</table>
In addition to the UAS vehicle categories, it was helpful to categorize the environment based on airspace classes for several reasons. First, the airspace classes are already in use by the aerospace community and would not require additional categories or rules to govern SAA effectiveness. In addition, the existing airspace classes combine elements of airspace density and airspace control, by definition. Both of these parameters were identified as important factors in air risk by a sensitivity analysis. As a result, the airspace density values associated with each airspace class is shown in Table 4.

Table 4: Airspace Densities by Class

<table>
<thead>
<tr>
<th>Information</th>
<th>Acft / nm²</th>
<th>Source</th>
<th>Citation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Class A</td>
<td>0.0012</td>
<td>Based on Calculations from Air Validation</td>
<td>N/A</td>
</tr>
<tr>
<td>Class B</td>
<td>2.55</td>
<td>Derived from Statistics on ATL Airport</td>
<td>[21]</td>
</tr>
<tr>
<td>Class C</td>
<td>1.76</td>
<td>Derived from Definition of Airspace Classes</td>
<td>[20]</td>
</tr>
<tr>
<td>Class D/E</td>
<td>0.73</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Class G</td>
<td>0.0012</td>
<td>Based on Calculations from Air Validation</td>
<td>N/A</td>
</tr>
</tbody>
</table>

The minimum effectiveness standards were calculated by conducting Monte Carlo simulations in the air risk model for each of the seven UAS categories in each of the five airspace classes. The airspace classes are characterized by the airspace density values in Table 4, in addition to architecture parameters such as airspace control and flight rules. The TLS used to set the standards was $2.56 \times 10^{-5}$ fatalities per flight hour. This value was based on the fatality rate for all categories of manned aircraft in the NAS for a period from 1990 to 2009 [10].
reason this value was chosen instead of a third-party fatality rate was because midair collisions involve second-party individuals or other airspace users. Since they have accepted the risk of engaging in flight activities, the expectation is that UAS operations should at least be as safe as manned aviation already is.

For each UAS and airspace combination, the simulation was used to determine the minimum SAA effectiveness that would be required to meet the TLS. The model took airspace density, the level of airspace control, and assumed that manned aircraft would be able to participate in conflict resolution with a UAS by means of visual and/or instrument means. The results for each combination appear in Table 5. The areas in black do not represent likely combinations based on the small size of these UAS and the minimum altitude for Class A airspace.

In review, the effectiveness percentage is the combination of availability and efficacy of the SAA system. This value is obtained by determining the unmodified encounter rate from the gas particle model, applying the risk mitigation in the event trees to account for air traffic management and avoidance by the manned aircraft, then calculating the number of remaining collisions that need to be avoided to remain below the TLS threshold.

The green blocks with an asterisk are interesting because they represent combinations where no SAA on the UAS is required to meet the specified TLS. Due to the the airspace density values inherent in the airspace in question and the size of the UAS, the casualties caused by UAS operations under these circumstances do not exceed the TLS despite the lack of SAA systems on the UAS. Yellow boxes indicate combinations where the required SAA effectiveness was either near or below previously published Traffic Alert and Collision Avoidance System
(TCAS) effectiveness values, which are approximately 75% for TCAS without altitude encoding equipment and as high as 95% for aircraft with such equipment [46]. Finally, the red boxes required a SAA system better than published TCAS effectiveness values to meet the TLS and would require additional risk mitigation.

<table>
<thead>
<tr>
<th>Group</th>
<th>Class A</th>
<th>Class B</th>
<th>Class C</th>
<th>Class D/E</th>
<th>Class G</th>
</tr>
</thead>
<tbody>
<tr>
<td>Group 1 (Micro)</td>
<td>80.2</td>
<td>71.4</td>
<td>30.9</td>
<td>*</td>
<td></td>
</tr>
<tr>
<td>Group 2 (Mini)</td>
<td>80.3</td>
<td>71.5</td>
<td>31.0</td>
<td>*</td>
<td></td>
</tr>
<tr>
<td>Group 3 (Small)</td>
<td>90.8</td>
<td>86.7</td>
<td>68.1</td>
<td>*</td>
<td></td>
</tr>
<tr>
<td>Group 4 (Tactical)</td>
<td>91.1</td>
<td>87.1</td>
<td>68.9</td>
<td>*</td>
<td></td>
</tr>
<tr>
<td>Group 5 (Medium)</td>
<td>91.7</td>
<td>88.1</td>
<td>71.3</td>
<td>71.0</td>
<td></td>
</tr>
<tr>
<td>Group 6 (Large)</td>
<td>*</td>
<td>99.8</td>
<td>99.7%</td>
<td>99.3</td>
<td>99.6</td>
</tr>
<tr>
<td>Group 7 (Heavy)</td>
<td>*</td>
<td>99.9</td>
<td>99.9%</td>
<td>99.7</td>
<td>99.9</td>
</tr>
</tbody>
</table>

5.0 Conclusions

Sense and Avoid has been identified by stakeholders as one of the major challenges to overcome before achieving full UAS integration. Clearly no system is perfect and trying to design a system as close to perfection as possible is expensive. What is required for this problem are realistic standards that designers can use when developing any potential SAA sub-system. It is the authors’ assertion that these standards should be linked to quantifiable, safety-related metrics for two reasons. If not, any SAA system design requirements could either create
conditions where SAA is not as effective as desired and UAS cause more casualties that acceptable. The other possibility is that inordinate amount of time and resources are spent to create a system that is not necessary in the case of the vehicle and airspace combinations described above in the green boxes. This will only delay the full integration of UAS further.

The air risk model developed for this effort is a transparent, flexible and credible way to predict casualty rates from UAS operations that takes UAS characteristics, the characteristics of other airspace users, and aspects of the operating environment such as airspace density and architecture into account. Based on the results of experiments, several combinations of UAS and airspace classes could operate now with no SAA capability and still not pose any more risk to airspace users than current manned operations do. Other combinations will require a SAA capability at least as effective as proven TCAS capabilities while other combinations will require more effective avoidance means or other risk mitigation steps.

This knowledge can be used to focus SAA development efforts and testing to ensure that the proper time and effort is spent on the type of air vehicles and operational missions that most require an avoidance capability. The effectiveness requirements can also be used by the potential UAS test centers to help determine whether proposes SAA systems can avoid collisions at a required rate. Tests can be done that replicate the appropriate airspace density and architecture associated with each airspace class to determine if the combination of SAA parameters such as detection distance, navigation accuracy, and turn rates are sufficient to avoid the necessary percentage of midair collisions.

The test centers could also be used to verify the assumptions used in this model about the ability of a pilot to visually acquire and subsequently avoid a collision with a UAS.
trees developed for this study incorporated visual avoidance data from previous studies that were based on manned aircraft only. UAS can be significantly smaller than manned aircraft and thus present a reduced visual signature.

In addition to being used to develop SAA effectiveness standards for system certification, the model can be used to further explore other areas of UAS integration such as the potential casualties caused by midair collisions under a lost-link condition, or the difference in midair casualties caused under lost-link conditions if using a ground-based SAA system instead of an air-based one.

UAS integration is an important and relevant topic for the aerospace industry and the country as a whole. Safety is the foremost concern and most significant challenge to overcome before full integration can be achieved. One of the most important technical challenges prohibiting full integration is the ability to achieve the requirements in CFR14 Part 91.113 to be able to ‘see and avoid’ other aircraft. It would be both unadvisable and potentially dangerous to develop requirements and standards for any potential SAA system without a direct link to safety in the form of quantifiable casualty rate metrics.
6.0 References

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