Validating a Concept for Airborne Sense and Avoid*

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Abstract—Sense and avoid is the primary technical hurdle to unmanned aircraft system airspace integration. Several sense and avoid system concepts have been proposed, including numerous system architectures and technologies for aircraft surveillance, and threat detection and resolution. However, there is little evidence to support concept refinement, evaluation, requirements development, and validation. This paper introduces a methodology for evaluating, refining, and validating sense and avoid system concepts through flight testing tightly coupled to modeling and simulation safety analysis. This methodology is demonstrated through the analysis and flight testing of an airborne primary radar based sense and avoid system intended for the Department of Homeland Security Predator B variant, a medium altitude, long endurance unmanned aircraft system.

I. INTRODUCTION

Several government and commercial entities desire to operate unmanned aircraft systems (UASs) in the National Airspace System (NAS) for a variety of applications, including military training, border security, wildfire management, and agricultural monitoring. Before UASs are permitted routine access to the NAS, a certified sense and avoid (SAA) system will be required. Although only one of the many technical, operational, and regulatory challenges to UAS airspace integration, SAA is the primary technical challenge due to system and certification complexity [1]. SAA may broadly be defined as the capability of a UAS to “see, sense or detect conflicting traffic or other hazards and take the appropriate action to comply with the applicable rules of flight” [2], and is accomplished through two functions: self separation when separation is not provided by air traffic control (ATC) and collision avoidance [3]. Although SAA may include avoidance of air and ground hazards other than aircraft, this paper focuses on the sense and avoid of airborne aircraft.

The Department of Homeland Security (DHS), through the Customs and Border Protection (CBP) and U.S. Coast Guard (USCG) agencies, is one of the primary operators of UAS in the NAS, using General Atomics Predator B variants for border and maritime security [1]. The Predator B is a medium altitude, long endurance (MALE) unmanned aircraft (UA). The lack of an approved SAA system limits operational flexibility because the UA must typically remain in prearranged airspace corridors segregated from manned aircraft. The objective for this work is to develop and validate an SAA concept for the DHS fleet of Predator B unmanned aircraft, although the general process will apply to other users and systems.

A typical SAA system architecture is comprised of: a set of sensors to detect cooperative (transponding) and noncooperative aircraft; fusion and tracking logic; and threat detection and resolution logic that determines whether an intruder aircraft poses a collision threat, and how the UA should subsequently maneuver. System architectures have been proposed with various levels of automation, and conversely, pilot involvement. The SAA system may have components that reside on the aircraft, in the UAS ground control station (GCS), or external to the UAS.

SAA systems and technology have been under development for more than a decade. However, uncertainty remains in the relative benefits and drawbacks of proposed system concepts. Furthermore, the minimum technical system requirements have not been defined. One challenge is that only recently have the operational, performance, interoperability, and certification requirements begun to take form [3]. Another challenge is that there is no generally accepted and implemented methodology to objectively evaluate SAA system architectures and technologies. Flight testing has typically been used to substantiate system safety. However, flight testing is fundamentally limited in scope and realism due to cost and required flight test safety procedures.

As safety critical systems, SAA systems will be required to undergo extensive safety assessment prior to certification and operational approval. Historically, safety assessment to support the certification of the Traffic Alert and Collision Avoidance System (TCAS) included fast time Monte Carlo simulation using realistic models of the operational environment combined with other analysis techniques, including human simulation trials, fault tree models, and flight test validation [4]. Leveraging the TCAS safety assessment methodology, the SAA architecture and technology can be refined early during system concept development. Flight testing, rather than being used to evaluate the safety of the system architecture, can then be used to validate the critical concept risks, including the architecture, technology, and associated analysis. This paper presents results from such an approach where system concept candidates are identified, refined through safety assessment, and then validated through flight testing.

The remainder of this document is organized as follows: first the general methodology for concept and technology development and validation is introduced, followed by a
discussion of how this process was applied to developing and validating an SAA concept for DHS. Lastly, results are presented from this technology development, analysis, and concept validation effort.

II. METHODOLOGY

System concept and technology development aims to deliver a set of architectures and technologies that satisfy the performance and operational requirements with acceptable confidence. These products may then be used within a formal system development and acquisitions effort to certify and deploy the system. Whereas formal system development processes require verification and validation of all system components and an exhaustive certification effort (e.g., [5]), a concept and technology development effort may focus on the architecture and technology risks. This process is depicted in Fig. 1, and the remainder of this section describes the various process components.

- **System Operational Requirements.** This initiating step in the process defines the high level technology and architecture agnostic requirements and constraints, and may be in the form of a Concept of Operations document.
- **Environment Description.** Describes the operational environment context, including interfaces to external systems that may affect system operation or performance, to sufficient detail to define system and subsystem requirements.
- **System Performance Requirements.** Requirements that dictate how well a system must operate quantitatively, primarily in terms of functional performance, but also size, weight, power, and cost constraints.
- **Define Architecture Candidates.** Define the set of potential system architectures given the system requirements and environment context constraints.
- **Identify Applicable Technologies.** Typically completed in conjunction with architecture candidate identification, identify the technologies that may satisfy the requirements.
- **System Evaluation and Requirements.** The central component of the process: evaluate how well the candidate architectures and technologies are able to satisfy the requirements. Early stages may involve relatively simple evaluations, but the fidelity is enhanced as additional understanding is obtained.
- **Identify and Address Critical Technology Risks.** Leveraging the results of the system evaluation, identify the technology risks that must be addressed through verification to achieve sufficient confidence in the selected architecture, technology, and requirements. This addresses the question: is the technology able to achieve the requirements? This step typically involves designing, developing, and testing the technology and architectures.
- **Identify and Address Critical Analysis Risks.** Critical system evaluation risks associated with the assumptions, models, and tools should be identified and addressed through verification and validation. This step answers the question: is the analysis sufficient to produce the necessary confidence in the architectures and technology?

III. IMPLEMENTATION AND RESULTS

This section describes the implementation of the methodology introduced in the previous section for the development and validation of an SAA system concept for the DHS CBP and USCG Predator B variants.

A. **System Operational and Functional Requirements**

The primary SAA system operational and functional requirements largely apply to all SAA systems [2], [3]. The SAA system shall:

- Detect and maneuver to avoid cooperative and noncooperative aircraft.
- Include a self separation function, when ATC separation services are not being provided, and a collision avoidance function.
- Interoperate with other collision avoidance and separation provision systems.
- Operate under all foreseeable weather conditions, and during day and night.
- Be certified to operate in all classes of airspace.
- Be as independent as practicable from ATC separation services.
- Provide maneuver advisories to the pilot when an intruder is deemed a threat.

![General concept and technology development process.](image)

**Fig. 1.** General concept and technology development process.

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Advise ATC of any SAA maneuver if the UAS is receiving an ATC provided separation service.
Consider the UA flight envelope and size, weight, power, and cost limitations.

It is assumed that the UAS will typically operate under instrument flight rules (IFR), and receive ATC provided separation services as required by IFR aircraft under current regulations [6].

B. Environment Description

Aircraft that the SAA system is expected to act against include cooperative (transponding), noncooperative, and collision avoidance system equipped (e.g., TCAS); aircraft may also be equipped with Automatic Dependent Surveillance-Broadcast (ADS-B). In Airspace Classes D, E, and G, ATC does not provide separation services between IFR aircraft and all other aircraft [6]. Therefore, under current procedures the SAA system will need to self separate in these airspace classes when the UAS is responsible for the separation provision [3].

C. System Performance Requirements

The primary metric used to assess air traffic management (ATM) separation systems is a target level of safety (TLS), typically expressed as the rate of midair collisions per flight hour. Because the SAA system is responsible for only a component of the total ATM level of safety, the component of the TLS that is affected by the SAA system is of interest: this metric is termed the risk ratio, and measures the fraction of midair collisions that the SAA system is unable to mitigate [7].

Although the risk ratio form of the safety requirement has been recommended for SAA systems [3] and used extensively for TCAS safety assessment, acceptable risk ratio thresholds have yet to be established by the regulator. Therefore, TCAS, as a currently acceptable and operational system, may be used as a baseline performance threshold. The International Civil Aviation Organization (ICAO) in [7] has defined the risk ratio requirement to be 0.18 when the intruder is not TCAS equipped (but cooperative), and 0.04 when the intruder is TCAS equipped. Note that current TCAS performance is typically safer than these thresholds [4]; hence, they are used as a feasibility threshold, rather than a specific target.

In addition to safety, the operational suitability and pilot acceptability of an ATM system must be considered: these metrics measure the system’s impact on other ATM systems (e.g., ATC, aircraft) and on the UAS pilot, respectively. A common metric used to assess the operational suitability is the system alert or maneuver rate, but other metrics include the SAA maneuver magnitude and reversal frequency.

D. Architecture Candidates

Architectural considerations for the surveillance system include whether the surveillance is located on the UA or on the ground, and how the potentially several disparate sensors should be combined into a single intruder state estimate; the requirement for detecting both noncooperative and cooperative aircraft dictates a noncooperative sensor at a minimum.

Considerations for the threat detection and maneuver selection logic include the level of automation in the decision making process: from the pilot to the automation making all decisions on when and how to maneuver. It has been concluded through the extensive analysis of TCAS that in order to preserve safety, collision avoidance systems should coordinate their maneuver explicitly through the exchange of aircraft state and collision avoidance advisory information [3]. Therefore, the means by which the SAA system coordinates maneuvers must be considered within the architecture.

E. Applicable Technologies

Many surveillance technologies have been proposed for SAA—see [8] for an in depth discussion. The proposed surveillance technologies encompass cooperative and noncooperative, and passive and active detection, and include:

- **Cooperative Surveillance**
  - Active: TCAS surveillance is the only operational civil airborne active cooperative surveillance technology; TCAS uses transponder interrogations and replies to estimate range using the time-of-arrival, bearing using the angle-of-arrival, and barometric altitude is encoded in the transponder reply. Ground based cooperative technologies include radar (e.g., ATC radars) and multilateration.
  - Passive: ADS-B-out equipped aircraft broadcast their identity and aircraft state information, and ADS-B-out is mandated for many operations starting in 2020 (14 CFR §91.225). Traffic Information Service-Broadcast (TIS-B) provides a similar ground based means to ADS-B.

- **Noncooperative Surveillance**
  - Active: ground based ATC radar is the only noncooperative aircraft surveillance technology that is used for ATM operations. Other technologies include airborne radar (which is currently approved for weather surveillance), lidar, and sonar.
  - Passive: potential technologies include electro-optical (EO), infrared (IR), acoustic, and passive radar.

Despite a wide array of proposed surveillance technologies, there are only a small number of government efforts developing threat detection and maneuver logic. Two approaches to UAS collision avoidance are the Jointly Optimal Collision Avoidance (JOCA) algorithm that is an online, open-loop, model predictive control algorithm intended to be automatic and tightly coupled to the autopilot [9], and the unmanned aircraft Airborne Collision Avoidance System (ACAS UA) logic that leverages an offline, closed-loop, dynamic programming approach that may be automatic or provide advisories to the pilot [10].
F. System Evaluation

The architecture and technology candidates may be reduced given the operational requirements: ground based surveillance does not permit the operational flexibility required by the DHS mission, and noncooperative technologies other than airborne radar do not provide robust detection in weather and both day and night operation. Furthermore, both ground-based and airborne primary radar have been proven in the ATM system, albeit for functions other than collision avoidance. Therefore, the surveillance candidates that may satisfy the operational requirements are airborne radar, TCAS, and ADS-B.

The analyses necessary to solidify the surveillance system requirements and refine the architecture are as follows:

- Specify and validate the radar requirements, in terms of detection range and measurement metric accuracy.
- Characterize the relative benefits of the candidate surveillance technologies.
- Evaluate the requirements for pilot and communications response delay on system performance.

These objectives are evaluated in the following subsections.

The methodology used to assess the analysis objectives was realistic Monte Carlo simulation using encounter models [4]. In this process, approximately one million synthetic encounters are sampled from an encounter model, and the SAA system is exercised through these synthetic encounters to evaluate system efficacy [11]. Different encounter models are used depending on whether ATC is likely to intervene in the encounter, thus providing correlation between the two aircraft: encounter models are termed correlated if ATC intervention is likely and uncorrelated if ATC intervention is unlikely. Because the correlated encounter model includes transport category aircraft while the uncorrelated model includes primarily general aviation at low altitudes, the aircraft characteristics vary with the model—e.g., the correlated model includes higher aircraft airspeeds while the uncorrelated model includes a greater degree of aircraft maneuvering. Note that the primary focus of SAA system evaluation is the avoidance of manned aircraft such that a fatality may occur; hence, system performance is not assessed against other unmanned aircraft and obstacles—e.g., birds, weather. Because the required analyses cannot be separated from how and when the aircraft maneuvers, a preliminary version of the ACAS UA collision avoidance threat detection and maneuver advisory logic was used.

1) Radar Requirements Development: Preliminary radar requirements were developed based on airspace environment assumptions. It was initially proposed that the surveillance system would need to detect a 1 m² radar cross section (RCS) target closing head-on at 525 knots, 45 s before collision—below 10,000 ft, the maximum aircraft airspeed is 250 knots indicated airspeed and aircraft may be noncooperative. This assertion resulted in a detection requirement of 8 NM with a 0.5 detection probability. The radar was nominally designed to have a 3 s search period followed by 1 s updates once a track was established.

For angular measurement estimation, it was deemed important to resolve standard vertical separation between aircraft so as not to alert during safe operations—500 ft is standard separation between IFR and visual flight rules (VFR) aircraft. Hence, the angular uncertainty standard deviation should not exceed 1° given alert distances on the order of 3–5 NM. The initial radar configuration had minimum measurement error standard deviations of 0.24° in azimuth and 0.72° in elevation which assumed a beamsplitting ratio of 20; the uncertainty is assumed to scale with the signal-to-noise ratio (SNR) (see Fig. 6) [12]. The beamsplitting ratio is defined as the ratio of the beamwidth to the measurement error standard deviation. An extended Kalman filter (EKF) was used to form the radar measurements into smoothed tracks. The initial radar configuration was specified to have a field of regard (FOR) of ±110° in azimuth and ±20° with respect to the aircraft body reference frame. This FOR limit resulted in not detecting aircraft on a collision course in 3.1% of uncorrelated and in 2.6% of correlated encounters.

The effect of measurement accuracy on system performance is shown in Fig. 2. Note that all results assume no pilot or communications system response delay unless otherwise noted. Recall that the risk ratio represents the fraction of collisions that remain after equipping with SAA.

The risk ratio is only sensitive to the elevation uncertainty; this is the result of the collision avoidance maneuver logic issuing advisories only in the vertical dimension. The difference between correlated and uncorrelated encounters is caused by lower relative airspeeds in uncorrelated encounters, such that the collision avoidance system alerts at smaller ranges—smaller ranges result in reduced uncertainty in the Cartesian reference frame. For correlated encounters, performance begins to degrade significantly with twice the nominal elevation standard deviation (by 51.5%), but does not improve significantly with half the standard deviation (by 9.6%).

The sensitivity of system performance to the RCS and detection range is shown in Fig. 3. The results are largely

![Risk Ratio vs. Accuracy Multiplier](image-url)
insensitive to the RCS, and degrade by no more than 10.6% when compared to the initial assumption of 1 m². This insensitivity is caused by the collision avoidance system not alerting near the maximum detection range; if the system alerts near the detection range, then the detection range sensitivity may be greater. Given the safety insensitivity to RCS, there is little value in increasing the detection range requirement and the current RCS assumptions pose a low risk. Due to the system performance sensitivity to the radar parameters and the several radar modeling assumptions, the radar model characteristics and the radar’s ability to satisfy the derived requirements must be validated through flight test; this is the focus of Sec. III-G.

2) Surveillance Technology Evaluation: TCAS and ADS-B provide an existing and certified means for detecting cooperative aircraft, but their relative performance compared to an airborne radar is not known. The TCAS surveillance model exercised here assumes Gaussian white noise sensor error with standard deviations of 10° in azimuth and 50 ft in range [7]. The ADS-B position error model is based on the minimum performance requirement (14 CFR §91.227)—an error with a standard deviation of 155 ft in both horizontal dimensions [13]. Both ADS-B and TCAS use the aircraft reported barometric altitude.

Table I presents the system performance given each surveillance technology for cases where the intruder aircraft is TCAS equipped (coordinating), and unequipped. TCAS and ADS-B were only evaluated in correlated encounters because these surveillance systems are typically only available in correlated encounters. ADS-B and TCAS provide enhanced safety performance and should therefore be used when available. Furthermore, maneuver coordination using the existing TCAS coordination mechanism reduces the collision risk significantly. Because the TCAS coordination and reply mechanism is the only method for coordinating maneuvers with existing TCAS equipped aircraft, and is thus a required architecture component, TCAS surveillance data is also available when the intruder is cooperative. However, it must be determined if the benefit provided by ADS-B warrants its inclusion in the SAA architecture; note that horizontal maneuvers will likely be much more effective with ADS-B than TCAS due to the poor TCAS bearing accuracy. Furthermore, the safety of both the ATC separation and SAA systems using the same ADS-B data should be assessed for single point failures.

3) Response Delay Requirements: The impact of response delay on system efficacy dictates whether the pilot can be included within the decision making process. Response delay is the aggregate of the pilot response and communications link latency. Fig. 4 shows this sensitivity. Correlated encounters are more sensitive to response delay than uncorrelated encounters because of the higher relative airspeeds for correlated encounters; this greater airspeed gives the system less time to react. Therefore, a pilot should only be included in the decision making process if the response delay is less than about 5 s. Note however, that this analysis did not consider the possible benefits of having a pilot in the decision making process—e.g., providing enhanced situation awareness that would reduce false alarms. Furthermore, the maneuver algorithms may be further optimized to account for large response delays if the delay is anticipated.

G. Addressing Analysis and Technology Risks

A radar prototype was developed and flight tested to validate the technology and radar modeling assumptions [14]. Through a design analysis considering detection range, measurement uncertainty, clutter rejection, platform limitations, interference constraints, and cost, it was determined that the radar should consist of a phased array and operate at X or Ku...
band (8–18 GHz): specifically, the prototype was developed in the 13.25–13.4 GHz band. The prototype was flight tested on a DeHavilland Twin Otter that has similar operating characteristics (i.e., airspeeds and operating altitudes that will affect radar system performance) to a General Atomics Predator B against an instrumented Cessna Stationair 206 which is a small general aviation aircraft that may be likely to operate without a transponder.

Radar detection results from the flight testing are compared with the prototype model in Fig. 5; note that the prototype was not designed to satisfy the full detection range requirement. The prototype’s empirical detection range lagged the initial model by the range equivalent of approximately 3 dB which was caused by deficiencies of the target RCS modeling assumptions. The 3 dB can be added to the radar power output in order to satisfy the required 8 NM detection range, or a reduced detection range can be used with limited impact on collision avoidance performance as presented in Fig. 3. Fig. 6 shows the comparison between the empirical monopulse angular beamsplitting performance and the modeled. The model tends to overestimate performance at low SNR, but underestimate at high SNR where the collision avoidance system is likely to alert.

The radar prototype flight test results demonstrate that a radar of this design can achieve the requirements, and that the radar model used in simulation is representative. This validation is sufficient to address the critical technology and analysis risks, however further verification and validation will be needed as system development progresses and additional confidence is required.

IV. CONCLUSIONS

This paper introduced a methodology for developing and validating an airborne sense and avoid system concept, including architectures and technologies. Preliminary requirements were derived through realistic safety simulation, and the radar requirements and model were verified and validated through flight test. As system development progresses, required future efforts include incorporating the other system components, including the self separation system, into the system safety assessment and flight testing.

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