Progress on Requirements and Standards for Sense & Avoid

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Standards leading to certification of UAS could enable broader operations in civil airspace. This paper describes the standards development process underway in the Sense & Avoid (S&A) working group of RTCA SC-203. Some issues that affect requirements exhibit complexity due to the great variety of systems and architectures. Considerations of size, weight, power and cost must be balanced against safety requirements. Requirements could be determined in part by a UAS's size, or by the type of airspace to be used. Requirements also must make provision for alternative architectures, such as pilot-in-the-loop or autonomous S&A.

Significant issues affecting sensors, algorithms and human factors are reviewed. These areas are far from mature, particularly for performing S&A against non-cooperative targets. A comprehensive modeling and simulation program is indispensable for developing performance requirements, but first requires the creation of models for sensing, airspace encounter statistics, and communication and pilot response characteristics.

INTRODUCTION

Considerable attention within the Unmanned Aircraft System (UAS) community is focused upon gaining broad access to civil airspace without the encumbrances of restrictions imposed today. It is generally recognized that one prerequisite to such broad access would be a Sense and Avoid (S&A) system, in order to meet statutory requirements[1,2]. The first part of this paper discusses some of the major issues remaining for S&A certification and implementation, as well as some of the complex tradeoffs to be made in the design of each UAS implementation. The second part of the paper describes the S&A standards process underway within the RTCA SC-203 committee, and discusses the present status of that work.

S&A ISSUES AND TRADEOFFS

S&A needs to replace a set of functions traditionally performed by an onboard pilot. There are many candidate technologies and architectures for the function. This section discusses some of the key issues.

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Hazards to Safe Flight

The UAS must avoid a variety of hazards. Traffic encompasses aircraft, gliders, balloons, and even other UAS. Some traffic support “cooperative” surveillance by carrying equipment that provides electronic information supporting their detection. This can include ATC transponders or Automatic Dependent Surveillance - Broadcast (ADS-B). The latter is being featured in FAA’s NextGen architecture, and has been mandated for future operation in some classes of airspace. Hazards also include terrain and obstacles (e.g., buildings, towers, power lines). A system trade must determine whether to avoid each of these types of hazards by sensing them, or instead to use navigation input in conjunction with a terrain or obstacle map so as to procedurally remain clear of these threats. Some UAS will need to avoid hazardous weather simply for the safe operation of their flight, and those flying a VFR-like operation will need to remain clear of clouds, to remain visible to other aircraft. If an optical technology is used by their own surveillance systems, clear airspace also may be needed for sensing other aircraft or terrain.

Surveillance System

The surveillance system that detects hazards can be implemented in various forms. Some technologies could be carried onboard the UAS, while another approach is to exploit sensing on the ground, such as a radar. These choices have extremely different capabilities, ranging from their coverage volume to the types of measurements made and the respective accuracies, update rates, and probabilities of false detection. For onboard use, it may be desirable to combine several technologies. Cooperative technologies should be superior in target detection and track association, but these only detect suitably equipped traffic. In airspace where non-cooperative traffic is allowed, other technologies would be needed. For smaller UAS, the size, weight and power of multiple sensors may be prohibitive. Ground-based sensing may be attractive for these UAS, although these sensors also have limitations, such as their accuracy and update rate, which may be reflected in the use of more conservative separation measures. Their field of view also could preclude long-range, low-altitude coverage.

Since the sensor technologies vary in their range and surveillance coverage, a system trade needs to determine these requirements to meet required safety levels, considering also the timeline for detection and avoidance maneuvering (Figure 1) and the likelihood that a target initially outside the sensor’s range or field of view would not be detected or avoided in time (or at all).

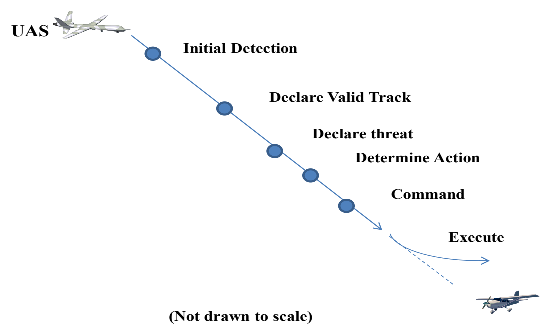

Figure 1. Sense & Avoid Timeline

Decision Process

Experience with TCAS has shown that it is difficult to design an algorithm that adapts to every operational situation. While safety remains the highest priority for collision avoidance, the S&A system also needs to minimize the frequency of "nuisance" maneuvering when no danger exists. A design choice involves the degree of human decision-making, which could be argued is more adaptable to the immediate context, such as the Air Traffic Control situation, or local constraints such as nearby terrain or restricted airspace. However, human performance is difficult to quantify and prove to high levels of reliability. An algorithmic approach can be tested and refined, and its performance is predictable. The time and cost of algorithm development and certification is a key factor in making this tradeoff. However, the pilot displays and automation aids likewise need to be assessed and certified, especially where pilot decisions play a large role in S&A.

Communications Link or Autonomous Decision

UAS are flown in several ways, such as by following commands from a pilot not onboard, or by following programmed waypoints. Since S&A is designed to resolve unplanned hazards, a real-time reaction capability must be provided. This also could involve the UAS pilot, or could be performed by the aircraft alone, as an autonomous maneuver. The link reliability and latency become important in this tradeoff. Even if the time line were sufficient for routine operational or clearance corrections, more stringent times likely will apply to collision avoidance.

Aircraft Capabilities and Maneuverability

UAS traditionally have been designed for characteristics other than tactical maneuverability. Long flight endurance qualities and missions such as persistent surveillance may conflict with the abrupt maneuver needs of S&A. This does not preclude using the S&A function, but does necessitate a design that accounts for feasible maneuvers by the UAS and decisions that allow for realistic time delays and accelerations. A side effect of requiring earlier maneuvers is the potentially longer range to the threat when the decision must be made. Some sensor technologies are quite sensitive to range, making this a significant tradeoff.

PLANS AND PROGRESS TOWARD S&A STANDARDS

Standards are expected to play an important role in the certification of UAS to enable operations in civil airspace without the extreme restrictions imposed today. The Sense & Avoid (S&A) function is a primary area where the use of an approved standard can provide fundamental support to an applicant's safety case, since the function would replace one or more functions performed by the human pilot aboard manned aircraft. While a human's performance is extremely difficult to quantify, the UAS version will need to meet safety targets yet to be prescribed.

RTCA SC-203 has been directed to develop standards for UAS. These include Minimum Aviation System Performance Standards (MASPS) for the UAS System, and for two subsystems: Communications and Control (C2) and Sense & Avoid (S&A). The latter two products are being developed respectively by the committee's Working Groups (WG) 2 and 3.

RTCA customarily develops standards for the civil aviation community, although defense services often participate and take a close interest in the product. In the case of UAS, the Department of Defense and other public users such as the Department of Homeland Security have near-term needs for airspace access. While these may be met on an interim basis with other approaches, compliance with the eventual standards may be in the best interest of the broad community.

Standards typically provide system developers with direction toward achieving system certification and operational approvals, and by demonstrating conformance to the standard's requirements, much of the work towards the safety case would be accomplished. Therefore, the standard must provide a comprehensive set of requirements that would demonstrate safety and operational compatibility, as well as a prescribed "test suite" for demonstrating the requirements were met.

The SC-203 standards process draws heavily from elements of the standard RTCA/EUROCAE system engineering process[3]. Its steps are tailored to best serve the standards development and account for the complexities of UAS. Unlike smaller systems that are standardized, a UAS contains many distributed functions. Moreover, the aircraft are quite varied in their sizes, flight dynamics and capabilities. A variety of system architectures are under consideration and the standard should accommodate all those that are desired and feasible. The committee has progressed its work to the point of publishing an Operational Services and Environment Definition (OSED) which enumerates much of this information. Some further detail on architecture is required to define S&A configurations.

Requirements for S&A

Recent activity in WG-3 has emphasized the development of a stable set of requirements for S&A. These draw heavily from the report of the Sense & Avoid Workshops[4], a series of meetings involving all the Department of Defense services, the FAA, the Joint UAS Center of Excellence, and several other experts in aircraft collision avoidance. One key result is that S&A needs to provide two main services:

a. A "Self-separation" service that would act when normal (e.g. Air Traffic Control) separation is lost, and could support earlier, gentler maneuvers than those used for last-moment collision avoidance
b. The collision avoidance service that attempts to protect a small "collision zone"

The requirements are further categorized by sub-functions, again derived from the Workshop. These are:

1. **Detect** any of various types of hazards, such as traffic, terrain, or weather. At this step, it is merely an indication that something is there.
2. **Track** the motion of the detected object. This requires gaining sufficient confidence that the object is valid, and making a determination of its position and trajectory.
3. **Evaluate** each tracked object, first to decide if its track may be predicted with sufficient confidence, and second, to test the track against criteria which would indicate that a maneuver is needed.
4. **Prioritize** the tracked objects based on their track parameters and the tests performed during the evaluation step. In some implementations, this may help to deal with limited S&A system capacity, while in others, prioritization might be combined with the evaluation or declaration steps.
5. **Declare** that the paths of own aircraft and the tracked object and the available avoidance time do indeed require maneuvering to begin.
6. **Determine** the specific maneuver, based on the particular geometry of the encounter, the maneuver capabilities of own aircraft, and all relevant constraints (e.g. airspace rules, or the other aircraft's maneuver).
7. **Command** own aircraft to perform the chosen maneuver. Depending upon the implementation of the S&A, this might require communications to the aircraft, or if the maneuver determination was performed on-board, merely internal communication among the aircraft's sub-systems.
8. **Execute** the commanded maneuver.

It should not be assumed that each of these sub-functions is performed only once. They typically will need to be repeated as long as the object can be seen. The first choice of maneuver may need to be modified, for reasons such as prediction errors, delays in maneuvering, or adverse maneuvers by the other aircraft. Therefore, the tracking and evaluation steps must keep assessing the effectiveness of the first choice. Research will determine the potential roles for the human in this process.

To date, the emphasis of the work has been on describing the operational and functional needs of S&A. While there are opinions concerning quantitative performance values, these will mature once subsequent analysis steps are performed. A related issue is whether the functional requirements for each sub-function should be developed to state a corresponding performance requirement for each. In S&A, the performance metrics tend to refer to end-to-end operation, and specifying performance at that level would allow each designer greater latitude in performing tradeoffs between sub-functions.

Architecture for S&A

The system engineering process includes documenting functions and data flows in a functional architecture. The Department of Defense Architectural Framework (DoDAF) provides a number of formats, or “views” which capture various aspects of this topic. At a high level, the UAS Architecture places the aircraft and its control station within the airspace and ATM framework. One of the scenarios or “Use Cases” under development is entitled “Avoid Hazards.” A S&A architecture would develop details of the functions and data flows that are required to perform the S&A function. Defining these elements will be essential for the later provision of performance requirements, as well as the associated analyses such as Hazard Assessment and Interoperability.

Research into UAS has already developed several variations of UAS architectures, and these will have corresponding impact on the S&A architecture in that a single instantiation would not cover all desired uses. A notable example concerns the issue of whether the UAS pilot would be “in the loop” for S&A activity. One version would measure some surveillance data onboard the aircraft, communicate it to the pilot, who would make decisions such as when and how to avoid a threat, and the resulting avoidance maneuver would be communicated to the aircraft for implementation. There could be subsequent communication to confirm that the maneuver was performed. A different version would perform the decision function onboard using automation, and no communication with a pilot would be involved (until perhaps after the fact). Another example is the aforementioned distinction between airborne and ground-based sensing for S&A, again affecting the presence or absence of aircraft-to-ground communications of sensor data.

Safety Assessment

A critical step towards developing performance requirements will be performing safety assessment of S&A. This will involve the determination of operational hazards – an example would be a midair collision – that could arise from the failure or incorrect performance of each function or data flow constituting S&A.

Examples of failure events could include:

Aircraft not detected by surveillance sub-function
Aircraft detected late by surveillance sub-function
Aircraft detected with incorrect position or velocity

The latter two of these involve complex analysis, since a “late” or “incorrect” detection may not cause a hazardous outcome with certainty, but only increase its likelihood. The relationship between the cause and the effect might depend on the design or technology involved, and the committee needs to devise a method to deal with this aspect in order to support a performance requirement decoupled from the design.

Even further complexity could be involved in the combinations of less-than-perfect performance of several sub-functions. For example, if the measurement contained some error, the pilot provided some delay in making a decision, and the communication link provided additional delay, the total effect on safe performance would be some function of these components. This complexity gives strong motivation for performing end-to-end simulation (discussed below).

Trades and Allocation between Sub-functions

There are multiple levels of trades that can be made in the S&A system design, and a challenge for standards-writing is how much of this can be allowed while still assuring safety and other requirements are met. One example of a tradeoff is the interaction of the sensing system and the maneuver decision. Various sensor technologies exhibit different detection probabilities, accuracies, and other parameters. The maneuver decision could attempt to provide just the required distances to avoid collisions, or they might seek extra distance in order to compensate for possible errors in measurement and trajectory prediction. This trade is difficult to make in a generic fashion since sensor capabilities vary so widely; it is challenging even when the sensor choice is known.

Another trade reflects the impact of communications between aircraft and the control station. Most communication links will have some latency and less-than-perfect availability. It could be difficult to assure a very high level of system performance unless the timeline for threat detection and resolution allowed for realistic delays and outages. One way to do this is to attempt to declare a threat and maneuver earlier than absolutely necessary, providing a margin for delay. There is a cost to do this, in that the sensing system then needs to detect those threats at longer ranges (see Figure 2).

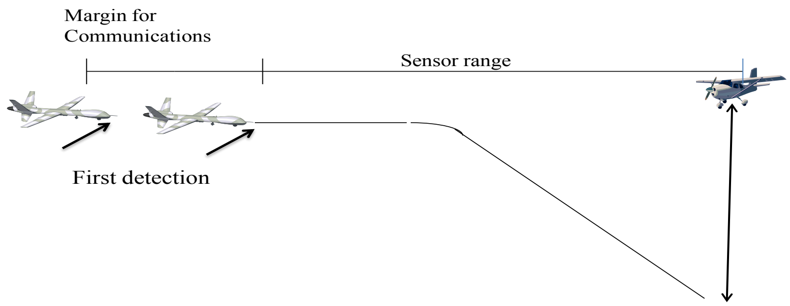

Figure 2. Relation between S&A time line and sensor range

Another class of tradeoffs involves human factors. One extreme is to provide the UAS pilot with greatly detailed information to support decision-making. The other extreme is to provide only basic information and a course of action decided by automation. Between these extremes lies a broad range of choice in designing data and advisory information for the pilot. One of the factors in making the tradeoff is the pilot's training and experience. Another is his workload, which would affect the time and attention available for assimilating information.

Nearly every event contributing to a safety analysis is treated probabilistically, rather than succeeding or failing with certainty. Since S&A would contain a number of sub-functions and their respective components contributing to its operation, the design could trade off performance, or alternatively allocate its risk budget, among the various parts. Some examples typical of many system designs are choices between making one function more accurate or reliable versus providing some mitigation for failure elsewhere in the system. These choices might have great significance with regard to feasibility or cost.

S&A Algorithms

The S&A system needs to determine when a potential threat has progressed to the point of requiring an avoidance maneuver, and then deciding upon a specific maneuver. Although it is premature to preclude human decisions performing either or both of these functions, the standard surely must accommodate an automated approach (i.e., the system declares a threat and/or decides the maneuver).

The collision avoidance system for manned aircraft, TCAS II, uses a precisely specified algorithm. This was done for a variety of reasons: it assured interoperability in conflicts between two TCAS-equipped aircraft; it provided a specific design that could be evaluated; and it was a known entity for which the FAA was willing to accept responsibility. Further, TCAS II was intended only for air carrier aircraft, and was designed for a specified amount of maneuverability which seemed reasonable across that fleet.

In contrast, the UAS population represents a very diverse set of aircraft which differ in their flight characteristics and maneuverability. Other aspects of the UAS S&A system also vary in ways that could make a single, standard algorithm impractical. These include the use of communication links, which could be line-of-sight, satellite relay, or even no link at all for autonomous S&A. When the pilot is in the S&A loop, human delay may be different and far more variable than that expected within an air carrier cockpit.

Taking these differences into account, as well as the broad variety of approaches among research into conflict and collision avoidance[5] the SC-203 S&A WG is considering an alternative approach to specifying a single algorithm. This would require development of a comprehensive set of requirements that the S&A sub-functions must meet to operate safely and compatibly. New approaches to interoperability are under investigation, as UAS S&A would need to interact with TCAS-equipped aircraft whose equipments expect explicit maneuver coordination; with non-TCAS aircraft who would presumably execute avoidance maneuvers according to standard Rules of the Air; and possibly with other UAS which could be equipped with different S&A implementations. Interoperability would need to be assured without knowing how many different implementation types might appear.

Modeling & Simulation

A comprehensive end-to-end simulation program will be needed to fully exercise the encounter geometries, sensor measurement characteristics, algorithmic or pilot decision making, air-ground link (if used), and aircraft maneuvering that all play a role in effective collision avoidance[6]. These elements have distinct stochastic variations, and need to be modeled accurately and exercised in concert with a large number of simulation trials. The results should give a great deal of insight into overall performance as well as the sensitivities of individual components, thus aiding the allocation process.

For the standards work, the committee would need to determine how many configurations and levels of sub-system performance to evaluate. The goal would be to determine the minimum performance levels that would support the overall requirements, and write standards requirements accordingly.

Standards for S&A

When allocation between functions and validation of performance requirements are completed, the writing of the standard should be straightforward. Still, the task of completing algorithmic requirements, if that approach remains acceptable, could be complex in its own right.

The first standard to be written is a MASPS, which is expected to avoid requiring specific technology (although some exceptions may be necessary to assure interoperability with other systems). RTCA and the FAA then must determine whether additional standards, such as Minimum Operational Performance Standards (MOPS) would be needed to develop requirements specific to certain technologies, architectures, or algorithms. The key decision would be whether those further standards would be useful or needed to support equipment certification.

CONCLUSION

UAS S&A involves a number of sub-systems whose characteristics need to be carefully considered in light of the aircraft and system characteristics, safety requirements, and available technology. This paper has discussed issues and tradeoffs that add to the complexity of design decisions. The standards process for S&A will follow traditional system engineering methods; however the approach for S&A algorithms may attempt a new focus on requirements rather than specifying one algorithm for all users. The committee currently is maturing its operational and functional requirements. The important steps of safety analysis, modeling and simulation, and design trades to allocate risk among functions still lie ahead.

REFERENCES

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