2013 International Conference on Unmanned Aircraft Systems (ICUAS)
May 28-31, 2013, Grand Hyatt Atlanta, Atlanta, GA

ADS-B for Small Unmanned Aerial Systems: Case Study and Regulatory Practices

Brandon Stark, *Student Member, IEEE,* Brennan Stevenson, *Student Member, IEEE,* and YangQuan Chen, *Senior Member, IEEE*

***Abstract*—Sense and Avoid Systems (SAASs) are one of the last technical challenges for the safe integration of Unmanned Aerial Systems (UASs) into the U.S. National Airspace System (NAS). While military applications still dominate UAS use, civilian UAS usage is expected to grow dramatically over the next several years. However with this growth, there are significant air safety concerns. SAASs have been proposed as potential solutions for air traffic collisions and obstacle avoidance, but the technical implementations have been largely unsatisfactory. The development of the Next Generation Air Transportation System (NextGen) surveillance tracking technology known as Automatic Dependent Surveillance-Broadcast (ADS-B) has been proposed as one of the potential solutions. This technology, mandated to be in all aircraft by 2020, is designed to improve situational awareness for pilots and improve air traffic management but may also be utilized by UASs. However there remains implementation issues and regulatory issues, especially for small UASs (SUASs) that are expected to be used significantly by civilian operators. This paper examines the use of ADS-B in future SAASs and their implementations in SUAS for domestic use.**

***Index Terms*—Unmanned Aerial System, Sense and Avoid, Air Safety, National Airspace System Integration, ADS-B**

I. Introduction

THE demand for civilian Unmanned Aerial Systems (UASs) has dramatically increased in the past several years. In the U.S., there has been significant pressure on the Federal Aviation Agency (FAA) to develop and finalize the regulations for the management of domestic UAS operations. However, this is not a simple task. The safe integration of UASs into the National Airspace System (NAS) has been the subject of numerous exploratory reports and research. Dr. Wilson Felder, the Director of the William J. Hughes Technical Center of the FAA, identified five challenges of UAS integration as procedural, technical, aircraft safety, crew credentials and public acceptance in his keynote address to the International Conference on Unmanned Aircraft Systems in 2012 [1]. While all of these are significant challenges, of the remaining technical challenges, Sense and Avoid Systems (SAASs) remain one of the largest hurdle towards safe integration. This key element is routinely singled out as the limiting factor in UAS to NAS integration [2], [3], [4].

MESA Lab, School of Engineering, University of California, Merced, Merced, CA, USA, e-mail: bstark2@ucmerced.edu
MESA Lab, School of Engineering, University of California, Merced, Merced, CA, USA, e-mail: bstevenson@ucmerced.edu
MESA Lab, School of Engineering, University of California, Merced, Merced, CA, USA, e-mail: ychen53@ucmerced.edu

However, the development of a single all-purpose solution is not only counter to the FAA's layered approach towards safety [4], [5], but is generally seen as infeasible in the near term. Instead, recent efforts have been in the improvement of the individual layers towards safety. Any UAS designed for the NAS must conform to existing NAS regulations regarding collision detection and resolution efforts. The Next Generation Air Transportation System (NextGen) surveillance tracking technology, Automatic Dependent Surveillance-Broadcast (ADS-B) has been under development for several years before its recent adoption [6]. While this technology was developed for improving situational awareness for manned aircraft, it has also appeared as a potential solution for the sense and avoid issue in UASs [7].

ADS-B has been touted as the most important technology to transform air traffic control away from radar based systems and to the more reliable satellite systems by the FAA [8]. The FAA envisions that the complete ADS-B system will enable pilots to see and avoid weather disturbances, air traffic, and terrain with the most up-to-date flight information, providing an unparalleled level of situational awareness. As a result of this significant overhaul, the FAA anticipates compulsory compliance in ADS-B to be complete by 2020 for the majority of aircraft in the NAS [6]. In its ubiquitous state, ADS-B appears as a practical requirement for UASs for use in SAASs. However, there remains significant challenges [7].

Current regulations and proposals have addressed UASs in general, but have largely explicitly excluded small UASs (SUASs) in many discussions, especially on the topic of SAASs. While larger UASs perform similarly to other manned aircraft and have similar requirements and characteristics, SUASs have a very distinct set of challenges that warrant special consideration [9].

SUASs for domestic operations are one of the expected major areas of growth in the UAS market according to the FAA [2]. These versatile platforms can be utilized in a myriad of ways. Aside from obvious applications in law enforcement and search and rescue operations, SUASs can be effectively utilized in monitoring applications such as agriculture, fire detection, and infrastructure (oil/gas lines, power lines and pipelines). Scientific and research applications of SUASs are equally numerous, ranging from remote sensing of soil moisture, invasive weed control, wildlife monitoring and geological surveys. However, unlike most manned aircraft and larger UASs, the cost of entry is significantly affordable. While this is a boon towards their rapid adoption and usage, it also poses significant challenges for regulations, especially in the need to enforce air safety.

In this paper, the integration of ADS-B in future SAASs is addressed, specifically for SUASs. The implementation challenges and regulatory issues are outlined and addressed. The rest of this paper is organized as follows. The next section, Conflict Detection and Resolution Strategies, introduces the strategies associated with safety, sensing and conflict resolution. In Section III, Sense and Avoid Systems, a survey of existing SAASs and their implementations is presented with an emphasis on ADS-B. Regulations regarding SUASs, SAASs and ADS-B are discussed in Section IV, Regulations and Limitations. Implementation strategies for the use of ADS-B in future SAASs is presented in Section 5, Integration of ADS-B in SUASs.

II. Conflict Detection and Resolution Principles

Sense and Avoid Systems are designed to deliver an analogous capability to 'see and avoid' requirements of manned aircraft. Their capability has been identified by the FAA as being comprised of two major aspects: self separation and collision avoidance [4]. Each of these aspects have specific requirements and are a necessity for safe UAS integration into the NAS. In the following section, the existing strategies and approaches towards air safety, sensing and conflict resolution are introduced.

A. Air Safety Strategies

Air safety is a critical foundation for aviation operations in the NAS. In the U.S., the FAA has been tasked by a federal mandate to develop plans and policies for the use of the NAS to ensure the safety of all aircraft and efficient use of airspace. The FAA's authority reaches to all aspects of aviation, including the certification of all aircraft, airmen, airspace, air traffic, and facilities [5].

When it comes to in flight collision avoidance, the FAA relies on the eyesight of its human pilots as the primary method of detection, utilizing other systems such as ADS-B as secondary systems. These responsibilities are defined within the Federal Aviation Regulations (FARs) and the Aeronautic Information Manual [10]. However, even with experienced pilots, seeing and avoiding is an often challenging task when coupled with other pilot responsibilities. Most mid-air collisions, in fact, occur not in dangerous weather conditions, but rather in daylight hours, in satisfactory weather conditions and on warm weekend afternoons. Studies have identified that the majority of in-flight collisions are the result of a faster aircraft overtaking and striking a slower one [11]. According to the FAA, the failure of the pilot to see other aircraft is the leading cause of mid-air collisions. Recent technology has significantly aided in air safety, but the exponential increase in air traffic has made the problem more difficult. To address air safety concerns, the FAA utilizes a layered approach for collision avoidance (Fig. 1) [4], [12].

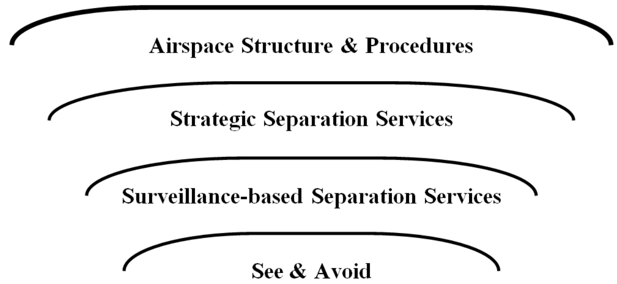


Figure 1. Layered Approach for Collision Avoidance [4], [12]

Airspace structure and the proper operating procedures provide the first layer of protection. Through the use of regulations and standard operation procedures, the FAA attempts to keep the airspace segregated to limit encounters of disparate flight characteristics, especially airspeed differences. Airspace classification acts as a significant mechanism for defining operations and flight rules, depending on flight altitude, and airport size and location. Other mechanisms, such as altitude levels and approach and departure procedures, provide additional levels of built-in separation.

The next two layers of separation services refer to Air Traffic Control (ATC) management of the NAS. The management of separation done in these layers is dependent on the airspace and the flight plan specific operating rules. Strategic separation services include additional management aids to balance air traffic controller workload [4] while the surveillance-based separation services rely on surveillance data and decision support tools.

The final layer of collision avoidance relies on the ability to 'see and avoid' other aircraft as defined by the FAA to remain all clear from other aircraft [13]. Accomplishment of this is done primarily with visual observation and confirmation. Under current regulations, ADS-B traffic information is not sufficient justification for avoidance maneuvers and are intended only to assist in visual acquisition of other aircraft [10].

B. Sensing and Awareness Strategies for Manned Aircraft

While the first three layers of the collision avoidance approach requires coordination with ground support, the final level of 'See and Avoid' relies solely on the pilots. Pilots of manned aircrafts are required to rely on visual acquisition for avoidance maneuvers, with an exception to ATC instructions. This places the responsibilities of the final layer of collision avoidance sensing fully upon the human pilot. The FAA, through their education agency, teaches the use of various visual scanning techniques to keep pilots constantly alert of their surroundings. Scan patterns based on the 'block' system have been proven effective in covering the necessary scan range of 60° to the left and right, and 10° up and down with occasional glances to either side beyond the ±60°.

Despite all the technological improvements in recent years, the human factors still play the primary role in 'See and Avoid' collision detection and resolution strategies as the the standard model of performance. The challenge for UASs integration is the development of a system capable of meeting these requirements of sensing and procedures to enhance being sensed by other aircraft. A survey of existing sensing technology is presented in Section III.

C. *Conflict Detection and Resolution Strategies*

For a pilot, the process for Conflict Detection and Resolution (CDR) consumes valuable time. The process may take on average 10-15 seconds from aircraft detection to the correct avoidance maneuver. Recently, a panel of experts from the FAA and the Department of Defense described the eight stages of CDR that are expected to be required for UAS SAASs [14].

1) **Detect** - The first stage is to detect any obstacle or hazard to initiate the CDR process.
2) **Track** - The motion of the detected object must next be tracked. This involves the confirmation of the existence of an object and the determination of accurate position and trajectory information.
3) **Evaluate -** The evaluate stage of CDR evaluates the confidence of the previous two stages and the necessity of an avoidance maneuver. The confidence level of the previous stages are highly effected by uncertainties, such as the object has changed trajectories or has just been detected.
4) **Prioritize -** This stage prioritizes the tracked objects based on their evaluated parameters from the previous stage, including distance or hazard type. This may be utilized as a method for handling multiple conflicts or utilizing more advanced autonomy in UASs.
5) **Declare -** The point at which a prioritized conflict is determined to need resolution occurs at the declaration stage. Separate declarations may be utilized for different levels of conflicts depending on the evaluated parameters.
6) **Determine -** The determination of the correct conflict resolution maneuver is calculated at this stage.
7) **Command -** Once an appropriate maneuver has been determined, the aircraft can be commanded to perform it.
8) **Execute -** Finally, the commanded maneuver is executed.

The first several stages are related to the classification and identification of threats. A generalized classification volume approach was presented by the same panel of experts to discretize the threat classification thresholds (Fig. 2) [14].

The figure depicts the different danger zones and the threat classification thresholds. These volumes are assumed to take into consideration the aircraft's velocity as well as any uncertainty in position broadcast. In the outermost layer is the ATC separation volume, where other aircraft may exist but are not currently regarded as a threat. The ATC has sufficient time and situational awareness to manage and prevent encounters, satisfying the first three layers of the layered approach in Fig. 1.

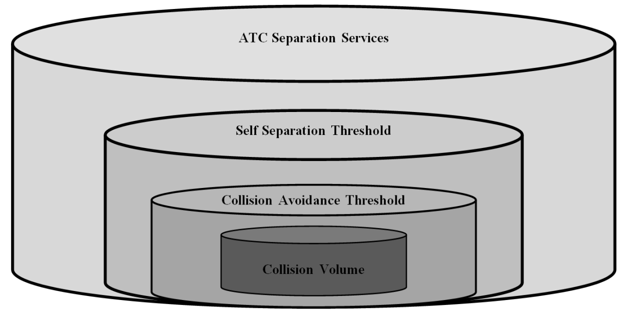


Figure 2. UAS ATC Separation, Self Separation and Collision Avoidance [14]

Entry into the second volume indicates that the invading aircraft may be a threat. However, there is sufficient time for the aircraft to engage in self separation maneuvers, without ATC management, to avoid last-moment avoidance maneuvers.

The final threshold volume indicates the point at which the only remaining safe course of action is an immediate collision avoidance maneuver.

The final volume represents the estimated volume of the aircraft to be avoided. The typical definition of this volume aligns with the 'critical near-midair collision' definition as outlined by Traffic Collision Avoidance System (TCAS) II 7.1 [15], a mandatory collision avoidance system for passenger aircraft. This definition equates the volume to a cylinder of ±100 ft in height and a radius of 500 ft. The volume is considerable larger than the actual size of the aircraft to account for the uncertainties in the aircrafts position and the invading hazards uncertainty. Any conflict resolution maneuver must be sufficient to overcome these variations and sources of error.

III. SENSE AND AVOID SYSTEMS

Sense and avoid systems have been a significant target for improvement and development in recent years as technology has advanced and matured. In an attempt to replace or augment the human vision, numerous approaches and techniques have been developed. In this section, some of the common approaches are presented.

A. *Sense and Avoid System Classifications and Metrics*

Sensing functionalities vary widely across approaches, however there are several general sensing classifications and metrics that serve as the necessary parameters for sense and avoid system quantification and analysis. A short description of these classifications and metric follows.

Sense and avoid systems can be divided into two major classifications: cooperative and non-cooperative systems.

Table I
COMMON SENSE AND AVOID SYSTEMS (ADAPTED FROM [16] AND MODIFIED)

Technology	Non-Coop	Airborne	Active	In IMC	Discern Range	Range (NM)	SUAS Capable
Human Visual	Yes	No	No	No	No	< 2	Yes
HD Live Video [17]	Yes	Yes	No	No	No	< 1	Yes
Electro-Optical [18]	Yes	Yes	No	No	No	< 4	No
IR Search & Track [19]	Yes	Yes	No	No	Yes	> 20	No
Passive IR	Yes	Yes	No	No	No	< 4	Yes
Laser [20]	Yes	Yes	Yes	Yes	Yes	< 2	No
GB Radar [21]	Yes	No	Yes	Yes	Yes	> 20	Yes
AB Radar [22]	Yes	Yes	Yes	Yes	Yes	> 20	No
TCAS/ACAS	No	Yes	Yes	Yes	Yes	> 20	No
ADS-B [23]	No	Yes	Yes	Yes	Yes	> 20	Yes [24]
ADS-B Radar[25]	Yes	Yes	Yes	Yes	Yes	< 1	Yes

Cooperative systems, such as ADS-B and other air traffic transponder based systems rely on all other aircraft to operate openly and transmit their information freely. The range and capabilities of these systems typically make them ideal for self separation conflict resolution with other aircraft. Non-cooperative technologies such as radar and vision systems are capable of monitoring the sky for other air traffic and hazards, but suffer from difficult implementations and limited capabilities.

A second major classification of sense and avoid systems is based on the installation location of the sensing technology [16]. Ground based sense and avoid systems seek to satisfy the necessary air traffic management and conflict resolution requirements without burdening the aircraft with an extra subsystem. These systems are common on testing and proving grounds and can serve as a valuable role in establishing UAS requirements, collecting data and airworthiness appraisals. Airborne based sense and avoid systems are intended for deployment on an aircraft for the most accurate and up-to-date information to ensure appropriate level of air safety.

The method of data collection constitutes a third major classification. Active systems transmit a signal to detect hazards while passive systems rely on their ability to detect signals and information emanating from the hazard. In general active systems, such as laser based range finding, consume greater amounts of power, though provide a better performance than passive systems.

The operational limits of the sense and avoid system provides a further classification. In particular, many optical systems are prohibited in Instrumental Meteorological Conditions (IMC), an aviation specific set of weather conditions that are used for determining when visual flight rules (VFR) are not allowed.

The ability to discern the distance of the hazard from the aircraft is another key classification to analyze the appropriateness of the sense and avoid system. This is also a common limitation of optical and passive systems.

More technical metrics include the total effective detection range, field of view, latency and resolution. The necessary requirements for these technical metrics depend on the type of sensor and its overall utilization. All of these technical qualities have strong implications on performance. Detection ranges must be sufficient for avoidance maneuvers. Field of view must meet the requirements to be equitable to a manned aircraft pilot or greater. Latency and update rate must also be sufficient to provide accurate information to allow for avoidance maneuvers while taking into account sensor uncertainty. Resolution, an important metric in optical and radar systems must be sufficient to detect an appropriate percentage of hazards. Weight classifications are critical in airborne systems, especially in considering the applicability of its integration into a SUAS.

A table of common sense and avoid systems and their classifications can be found in Tab. I.

B. Automatic Dependent Surveillance - Broadcast

ADS-B is a surveillance tracking system that can be split into two subsystems, ADS-B In and ADS-B Out. Currently, only the ADS-B out portion of the system has been mandated by the FAA to be installed in all aircraft by 2020 [6].

ADS-B Out is a transmitter that broadcasts the positional location and directional velocity of the ADS-B equipped vehicle as well as being capable of transmitting additional data such as the vehicles planned route and identity [26]. The output broadcasts sent by the ADS-B system are transmitted periodically without any required external action.

Though the ADS-B In portion of the system has not yet been mandated by the FAA, it can provide a method to display the information of nearby ADS-B Out equipped vehicles to the pilot or ATC. This provides real time information to pilots about all nearby ADS-B equipped aircraft as being capable of receiving Traffic Information Service - Broadcast (TIS-B) from ground stations when using a UAT [10].

ADS-B standards mandate a minimum range of 40 NM air-to-air even in poor environmental conditions, and the capacity of above 200 NM in clear skies. This allows for pilots to be aware of other aircraft even in environments where visibility and radar would not prevail [8]. This long range detection of aircraft would allow pilots equipped with ADS-B In to engage in self-separation maneuvers far before see and avoid techniques would take place and would help to reduce air-to-air collisions caused by low visibility conditions.

IV. Regulations and Limitations

The development of UASs has significantly outpaced their legislation. A quick overview of the existing legislation and recommendations of UASs is presented followed by an introduction to the policies that govern ADS-B development and use.

In the U.S., the FAA is the official agency that governs the use of the National Airspace System (NAS). Utilizing Federal Aviation Regulations (FARs), standards and policies, the FAA develops and enforces strategies and rules that promotes air safety and an efficient use of the NAS. However, there are few officially sanctioned options for UAS use.

In early 2013, the FAA released National Policy N 8900.207 that standardizes many of the practices introduced by previous reports such as AFS-400 UAS Policy 05-01 and Interim Operational Approval Guidance 08-01 report. These include the offering of a Certificate of Waiver or Authorization (COA) to military or public agencies for U.S. government purposes such as military training operations and research and development purposes. This national policy marks one of the first major policies released by the FAA regarding domestic UAS usage.

A Concept of Operations (ConOps) for Unmanned Aircraft Systems report by the FAA, first issued in 2011 and updated in 2012, proposes the necessary requirements that a UAS must meet to be worthy of integration into the NAS [4]. In this report, the FAA shares their view of a UAS operating safely and efficiently with other air traffic by utilizing a 'file-and-fly' approach; filing a flight plan similar to existing Instrument Flight Rules (IFR) flight plans before receiving flight authorization, without the need for creating a segregated airspace specifically for UASs [4]. However, as with many of the other mentioned reports, the FAA ConOps for UASs specifically excludes describing operations for SUASs as not fitting within their concept narrative.

One specific report, published in 2009, attempts to address the rules and operations for SUASs. The 'Comprehensive Set of Recommendations for sUAS Regulatory Development,' written by the Small Unmanned Aircraft System Aviation Rule Making Committee (SUAS ARC) proposed similar operations as its predecessors, but stricter limitations and regulations on use. In this report, SUASs are proposed to strict altitude and lateral distances of 400 ft and 1200 ft respectively while utilizing visual line of sight (VLOS) as the primary method of mitigation for mid-air collisions [12]. Limitations on flight altitude and lateral distance, 400 ft and 1200 ft, were recommended due to the limited capability of visual observers for conflict detection and resolution services. The report does not consider any other method of SAA such as real-time video links or real-time air traffic monitors to aid in situational awareness to allow extended flights in terms of distance, altitude and duration. The recommendations by the SUAS ARC also includes a primary means of collision avoidance by recommending that a UAS dives to a lower altitude and yield right-of-way, as a pilot would expect a similarly sized bird would do as a manned aircraft approaches [12]. Due to the visibility challenges of a SUAS, it was decided that the a vertical evasive maneuver would prove to be the optimal maneuver to avoid the collision volume. In addition to the operational bounds, the recommendations posed by the SUAS ARC include additional qualifications for operation in each available class of airspace. SUAS operations are assumed to typically occur in uncontrolled airspace (Class E or G), where air traffic is sparse and where Visual Flight Rules (VFR) are allowed during Visual Meteorological Conditions (VMC), a common aviation term that quantifies the safe operational weather and visibility. Other airspace classes may be used, but the altitude limitations keep this usage to a minimum, applicable only when near Class C and D airspace that extends to the surface around airports. Operation near these airports are recommended to be prohibited unless special authorization is given from the local ATC and ATC contact is maintained [12].

The operation of the ADS-B system is defined in §91.225 of 14 CFR 91 [13]. At the 1090 MHz band, the equipment minimum performance standard is defined by TSO 166b, whereas the 978MHz band equipment is regulated by TSO-C154c. Additional guidance for the operation of ADS-B systems was provided by the FAA in AC 90-114 [27]. Additional minimum performance standards for ADS-B systems are specified in TSO-116b and TSO-C195a. These systems must meet functionality conditions such as upholding the reception of the Flight Information Services- Broadcast. UAT subsystems must also uphold various classes of failure conditions, including providing applications with faulty reports no more than once in 10^3 flight hours [28], [29]. Important equipment needs to be marked as outlined in TSO C154a. An outline for the process for airworthiness approval of ADS-B Out is laid out in AC 20-165 [30]. ADS-B out is currently only available for registered aircraft [10], which many SUASs are currently not. ADS-B In receivers may be purchased and used, but will not receive the full spectrum of information without an ADS-B Out transmitter as TIS-B information is only available to registered aircraft. Ground-based ADS-B In systems are commercially available as well, but they are not subjected to existing standards which limits the FAA ability to sanction their use.

V. Integration of ADS-B into SUASs

The possibility of integration of an ADS-B system into a UAS has been proposed on several occasions, however, these discussions have been focused on the capabilities and challenges of full-size UASs [7]. The approaches for these integration plans are not always applicable or appropriate for SUASs which face several unique challenges. In this section, a specific look into the challenges and operations of ADS-B integration into SUASs are presented.

A. SUAS Specific Remarks and Observations

Based on the previous sections of SAAS solutions, ADS-B operations, SUAS standard operating procedures and UAS regulations, the following set of observations can be made.

- SUAS operations are a moderate risk to air traffic because they are atypical of manned aircraft operations.
- SUASs typically operate at low airspeed and are more likely to be hit rather than to hit other air traffic. Limited airspeed results in insufficient lateral avoidance maneuvers.
- SUASs are typically several magnitudes smaller than manned aircraft.
- SUAS ARC recommends vertical avoidance maneuvers.
- Current proposed regulations limit SUAS operations to VLOS, low flight altitudes and short lateral distances.
- Current proposed regulations require the use of visual observers as the primary method of SAA.
- Visual observers have limited detection and recognition range and thus provide limited situational awareness.
- Aircraft flying in Class G airspace must operate under VFR, ensuring operation only under VMC with specific requirements for visibility. Aircraft flying in Class E airspace may operate under either VFR or IFR. VFR operations in Class E requires greater visibility range than Class G, but must remain below cloud cover due to potential for collision with aircraft flying under IFR.
- FAA ConOps address UAS operations, but exclude SUAS operations.
- FAA ConOps recommends ADS-B requirements for UAS operations.
- FAA currently does not authorize ADS-B In as a suitable collision avoidance system, but is intended for future use.
- Standards for visual integration of ADS-B In data into ground control station must be consistent with existing standards.

B. ADS-B Implementation Capabilities for SUAS

Sense and Avoid Systems for SUASs pose a significant challenge. The strict size and weight constraints limit the airborne capabilities, and maintaining the low cost of entry constrains the use of ground-based SAAS. The common practice of maintaining visual contact with an observer has limitations on operating environments and unsatisfactory results for all but the closest SUAS missions. Cooperative technologies, such as ADS-B provide significant advantages to range, but will not be commonly adopted in the expected SUAS operational airspace. Visual and other optical systems can be utilized for an approximation of a manned pilots point of view, but pixel resolutions and bandwidth issues limit hazard identification range.

While not all aspects of a SAAS can be addressed with current technology, the use of ADS-B in SUAS is the currently a capable solution. The range, resolution, accuracy and update rate are all superior from other existing technology. The challenges to overcome with an ADS-B based system are not negligible however. Cooperative technology suffers from a reliance on widespread adoption and implementation costs. While ADS-B Out is currently scheduled for adoption by 2020 through legislative mandates, it adoption is not currently widespread and not required for aircraft flying at the low altitudes expected for SUAS operations. However, as the technology improves and the integration of ADS-B into the NextGen Airspace System completes, the adoption of ADS-B based SAASs will improve a UAS operators situational awareness in regards to other air traffic. Specifically, it addresses a current weakness in the proposed operating procedures for SUAS operation.

Visual observers are the current primary source of situational awareness in the proposed standard operating procedures for SUAS operations. While satisfactory for many operations, it has significant blind spots in its deployment. A SUAS operating in Class G airspace is subject to the same VFRs as manned aircraft. Manned aircraft flying in this airspace and these low altitudes are typically slow moving. Combined with the limited altitude of Class G airspace (under 700 ft or 1250 ft), a SUAS is capable of diving to a safer altitude (under the minimum 500 ft altitude as per FAR) in a sufficient time to complete a self-separation or collision avoidance maneuver. However, this arrangement is only sufficient if the visual observer is able to detect, track and evaluate invading aircraft as per the eight stages of CDR. This requirement significantly affects the operational bounds which is limited by the capability of the visual observer. The overall performance can be furthered improved with on-board visual or optical systems, either autonomous or human-in-the-loop, for terrain and structure hazards. The addition of ADS-B into this setup would enable a UAS operator to detect cooperative aircraft before they reach visual range.

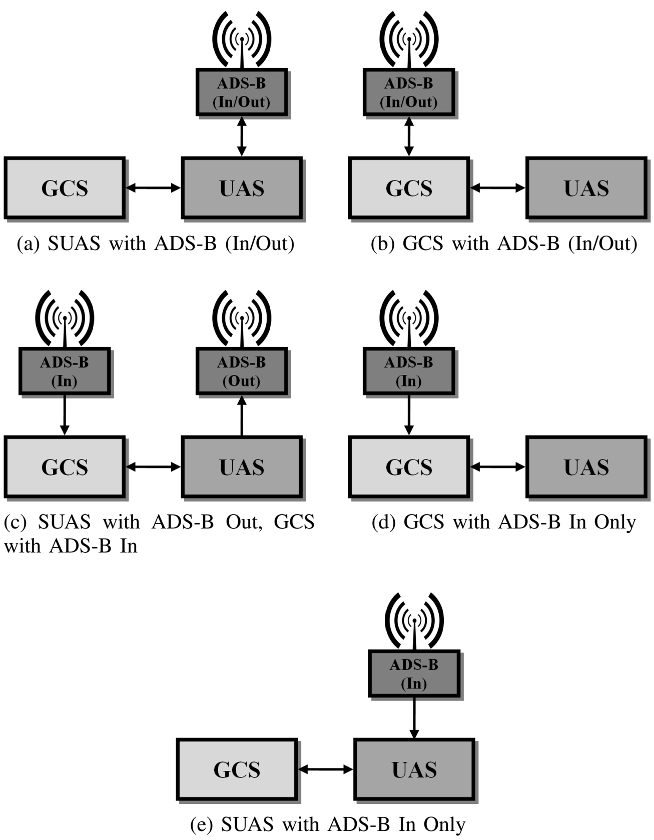
However, a greater benefit of the addition of ADS-B is found in larger operations and at higher altitudes. Increased range and endurance introduces additional dangers, but may be necessary for many SUAS missions. Aircraft flying under VFR are still subject to favorable conditions for visual observations and the use of visual optical SAAS. However, class E airspace also permits the use of IFR for aircraft. The combination of VFR and IFR aircraft increases the danger of mid-air collisions. An aircraft flying IFR may descend through a cloud layer only to find themselves in a collision course with an aircraft flying in VFR below the clouds. Neither the visual observer or the use of vision or optical SAASs is capable of detecting the invading aircraft in this situation. The situation may be further worsened by the mismatch of airspeed of the two aircraft. The implementation of an ADS-B SAAS would enable the first three stages of CDR to be accomplished sooner and would allow a UAS operator sufficient time to complete a self separation or conflict avoidance maneuver.

In some cases, a SUAS may be tasked to operate in a more congested airspace class, with permission of a local ATC. In these situations, ADS-B integration is a necessity to gain sufficient situational awareness. SUAS operation in high air traffic areas require a heightened attention to air space management and control. This can be achieved by addressing all levels of conflict resolution strategies. By utilizing ADS-B as required by FAA laws, the outer levels of ATC management and self separation layers are addressed.

Additional discussion is warranted to the topic of the effects of introducing a new and likely heavily utilized class of aircraft to the ADS-B frequencies. The increased utilization of the two ADS-B frequency bands may result in an overly crowded system, especially in airspace segments where ADS-B information is most critical. Additional management from ATC would be required for the oversight of these operations as well.

C. Potential Implementations

There are five configurations for implementing an ADS-B SAAS for a SUAS (Fig. 3). Each implementation has its advantages and challenges, but each may be a preferred implementation for a specific architecture depending on the technical challenges.



(a) SUAS with ADS-B (In/Out)

(b) GCS with ADS-B (In/Out)

(c) SUAS with ADS-B Out, GCS with ADS-B In

(d) GCS with ADS-B In Only

(e) SUAS with ADS-B In Only

Figure 3. Potential ADS-B Integration Configurations

In Fig. 3a an implementation that is most similar to a manned aircraft implementation is depicted, placing a full system ADS-B In/Out system on the SUAS. This implementation would require the least technical challenges, requiring only that the ADS-B In situational awareness information is passed down from the UAS in the air to the ground station. However, this setup places the additional weight cost airborne, a limitation that may be too costly for many of the lighter SUASs. The advantage of this setup is that it allows for autonomous self separation algorithms to be conducted autonomously, a potentially valuable capability in lost-link situations. Situational awareness relaying may additionally increase system latency, however, with the long range capabilities of ADS-B, it may be tolerable for all but the closest calls.

Alternatively, the entire ADS-B SAAS may be attached to the ground control station (Fig. 3b). This removes the weight of the ADS-B system off the aircraft, and onto the ground where weight and size are not significant constraints. ADS-B Out messages can be constructed from the real-time telemetry link from the UAS to the GCS. However, this implementation may be incompatible with ADS-B standards regarding message accuracy and message latency. In this situation, the implementation acceptance would be autopilot system specific and may be too challenging to regulate by the FAA. Another alternative using this same setup would have the ADS-B Out message broadcast an uncertain range of the aircraft's position, trajectory and velocity. Given the relatively small size of a SUAS compared to most manned aircraft, a sufficient uncertain bound could be broadcast without effecting safety.

A more complex setup places the ADS-B Out transmission on the aircraft while collecting ADS-B In messages on the GCS (Fig. 3c). The necessary ADS-B Out message accuracy can be obtained without concern for latency on the aircraft, enhancing the ability for self separation for other air traffic. ADS-B In messages for situational awareness can be directly viewed on the GCS display. Low latency ensures a better experience for the UAS operator and allows for a quicker human response to air traffic hazards. However, in the prescience of telemetry disruptions and interference, the activation of self separation or collision avoidance maneuvers may be delayed or lost.

The final two implementations utilize only ADS-B In on either the GCS (Fig. 3d) or the unmanned aircraft (Fig. 3e). In consideration of the increased usage of the ADS-B frequencies, it may be prudent to consider using ADS-B for only increasing the UAS operator's situational awareness. In many situations, while a manned aircraft may be capable of spotting the UAS, it may lack the maneuverability to conduct self separation maneuvers. In these situations, the SUAS should always yield right of way to larger aircraft and is expected to get out of the way rather than conducting a co-operative self separation. In the case where immediate action is necessary, the SUAS may be tasked to perform beyond its safe operational bounds. While the loss of a SUAS may be unfortunate, the loss of a human life would be unacceptable. Additionally, in an ADS-B In only implementation, manned aircraft can be alerted to a UAS operation through other means such as Notices to Airmen (NOTAM) or through the ATC. Current regulations prevent ADS-B Out systems to be installed on unregistered systems, a category that currently includes the vast majority of UASs. This makes the use of an ADS-B In system currently more feasible legally and addressing the concerns of frequency crowding.

Utilizing only ADS-B Out is not a viable option as it removes the ability for the UAS operator to gain situational awareness and places the burden of avoidance using ADS-B on the manned aircraft.

VI. Conclusion

While little discussion has been directed towards SUASs on the topic of ADS-B integration, its use would significantly aid sense and avoid operations. There remains several challenges left to overcome before its use becomes common. Several of these remain legislative and regulatory prohibitions that will likely be adjusted as the technology matures. Current implementations should focus on ADS-B In integration, a setup that currently has less regulatory issues and standard requirements. However, if ADS-B In is to be utilized for SUAS operations, standards must be developed specifically for this new application. Regulations also currently prohibits the use of ADS-B as a primary self separation and collision avoidance system for manned aircraft. The FAA is expected to address these issues, and potentially as the technology continues to mature, these prohibitions will subside.

There is no single solution for sense and avoid for SUASs; the most effective solutions are the ones that address each and every level of threats from multiple approaches. It is foreseeable that SUAS operations will become common place and the augmenting of visual observers and optical sensors with ADS-B SAAS will keep the air safe for all who wish to utilize it.

Acknowledgment

This project is supported in part by Utah Water Research Laboratory MLF 2006-2012 and by NASA UAS2NAS program (Grant Number NNX11AO77A). Part of the work was also supported by NSF REU Site program (Award # 0851709).

The authors would like to thank all OSAM UAV team members in CSOIS, all the researchers in the MESA Lab and the Paparazzi UAV community for providing the wonderful paparazzi project to work on.

References

[1] W. Felder, *Unmanned System Integration into the National Airspace System*. Philadelphia, PA, USA: Keynote Presented at ICUAS 2012, June 2012.

[2] Federal Aviation Administration, *Fact Sheet - Unmanned Aircraft Systems (UAS)*. 2010.

[3] Department of Defense, "Unmanned Aircraft System Airspace Integration Plan," Tech. Rep. March, Department of Defense, 2011.

[4] Federal Aviation Administration, *Integration of Unmanned Aircraft Systems into the National Airspace System Concept of Operations*. 2012.

[5] Federal Aviation Administration, "System Safety Handbook," 2000.

[6] "Automatic Dependent Surveillance - Broadcast (ADS-B) Out Performance Requirements to Support Air Traffic (ATC) Service; Final Rule," *Federal Register*, vol. 75, p. 30159, May 2010.

[7] Unmanned Aircraft Systems Study Group, *The Use of Displayed ADS-B Data for a Collision Avoidance Capability in an Unmanned Aircraft System*. Montreal, Canada: International Civil Aviation Organization, 2012.

[8] Federal Aviation Administration, *Fact Sheet - Automatic Dependent Surveillance-Broadcast (ADS-B)*. 2010.

[9] B. Stark, C. Coopmans, and Y. Chen, "Concept of Operations for Personal Remote Sensing Unmanned Aerial Systems," *Journal of Intelligent & Robotic Systems*, vol. 69, no. 1-4, pp. 5–20, 2013.

[10] Federal Aviation Administration, *Aeronautical Information Manual*. 2012.

[11] P-8740-51, *How to Avoid a Mid Air Collision*. Federal Aviation Administration, 2012.

[12] Small Unmanned Aircraft System Aviation Rulemaking Committee, *Comprehensive Set of Recommendations for sUAS Regulatory Development*. Federal Aviation Administration, 2009.

[13] 14 CFR 91, *General Operating and Flight Rules*. Code of Federal Regulations, 2013.

[14] FAA-Sponsored SAA Workshop, *Final Report*. Federal Aviation Administration, 2009.

[15] HQ-111358, *Introduction to TCAS II Version 7.1*. Federal Aviation Administration, 2011.

[16] R. Barnhart, S. Hottman, D. Marshall, and E. Shappee, *Introduction to Unmanned Aircraft Systems*. Boca Raton, Fl: CRC Press, Taylor & Francis Group, 2012.

[17] R. J. Kephart and M. S. Braasch, "See-and-Avoid Comparison of Performance in Manned and Remotely Piloted Aircraft," *Electronics*, no. May, pp. 36–42, 2010.

[18] J. D. Griffith, M. J. Kochenderfer, and J. K. Kuchar, "Electro-Optical System Analysis for Sense and Avoid," in *Proc of AIAA Guidance, Navigation and Control Conference and Exhibit*, (Minneapolis, Minnesota), pp. 18–21, Aug. 2008.

[19] H. Srivastava and Y. Limbu, "Airborne Infrared Search and Track Systems," *Defence Science Journal*, vol. 57, no. 5, pp. 739–753, 2007.

[20] G. Euliss, A. Christiansen, and R. Athale, "Analysis of Laser-Ranging Technology for Sense and Avoid Operation of Unmanned Aircraft Systems: The tradeoff between resolution and power," in *SPIE Defense and Security Symposium* (G. R. Gerhart, D. W. Gage, and C. M. Shoemaker, eds.), vol. 6962, pp. 696208–1 – 696208–10, International Society for Optics and Photonics, Apr. 2008.

[21] P. Angelov, *Sense and Avoid in UAS: Research and Applications*. Hoboken, New Jersey: John Wiley & Sons, Ltd, 2012.

[22] B. Korn and C. Edinger, "UAS in civil airspace: Demonstrating Sense and Avoid capabilities in flight trials," in *Proc of IEEE/AIAA 27th Digital Avionics Systems Conference, 2008*, pp. 4.D.1–1–4.D.1–7, Ieee, Oct. 2008.

[23] R. Clothier and R. Walker, "The Smart Skies Project," *Aerospace and Electronic Systems Magazine, IEEE*, vol. 26, pp. 14–23, June 2011.

[24] R. Strain, M. DeGarmo, and J. Moody, "A Lightweight, Low-Cost ADS-B System for UAS Applications," *MITRE Technical Papers and Presentations, Case Number: 07-0634*, pp. 1–9, May 2007.

[25] C. Lai, Y. Ren, and C. Lin, "ADS-B based collision avoidance radar for unmanned aerial vehicles," in *Proc of IEEE MTT-S International Microwave Symposium Digest, 2009. MTT'09.*, pp. 85–88, 2009.

[26] D. Hicok and D. Lee, "Application of ADS-B for airport surface surveillance," in *Proc. of the AIAA/IEEE/SAE Digital Avionics System Conference*, vol. 2, (Alexandria, VA), pp. F34/1 – F34/8, 1998.

[27] AC 90-114, *Automatic Dependent Surveillance-Broadcast (ADS-B) Operations*. Federal Aviation Administration, 2012.

[28] TSO-C154c, *Universal Access Transceiver (UAT) Automatic Dependent Surveillance-Broadcast (ADS-B) Equipment Operating on Frequency of 978 MHz*. Federal Aviation Administration, 2009.

[29] TSO-C166b, *Extended Squitter Automatic Dependent Surveillance - Broadcast (ADS-B) and Traffic Information Service - Broadcast (TIS-B) Equipment Operating on the Radio Frequency of 1090 MHz*. No. 1, Federal Aviation Administration, 2009.

[30] AC 20-165A, *Airworthiness Approval of Automatic Dependent Surveillance - Broadcast (ADS-B) Out Systems*. Federal Aviation Administration, 2012.