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Airspace Integration Alternatives for Unmanned Aircraft

Andrew Lacher, Andrew Zeitlin, David Maroney, Kelly Markin, Duane Ludwig, and Joe Boyd
The MITRE Corporation, www.mitre.org
703-983-7182, alacher@mitre.org

The routine integration of unmanned aircraft systems (UAS) into civil airspace presents many technical, operational, and policy challenges. Foremost among these are 1) the lack of an on-board capability to see and avoid other aircraft; and 2) coping mechanisms for dealing with vulnerabilities of the UAS command and control link. This paper discusses alterative integration approaches that ensure risks are mitigated, overall system safety is not degraded, and existing flows of manned aircraft are undisrupted. Specific examples associated with small UAS, ground-based sense and avoid approaches, and UAS flying in international oceanic airspace are discussed. Trade-offs among these alternatives are explored in terms of implementation timeframes, development risks, and implications for various stakeholders.

Background

There is a rapidly growing need to operate both military and civil Unmanned Aircraft Systems (UAS) in the same airspace as manned aircraft – particularly outside of segregated* (i.e., restricted) airspace. Applications for unmanned aircraft abound from military and homeland security, to numerous envisioned research and commercial purposes. [1][2][3] For existing and potential UAS operators, the integration of unmanned and manned aircraft in the same airspace, including civil airspace, is an important capability that will enable growth in the UAS industry, expansion of applications, and greater utility for all. [4][5][1]

Today, integration of manned and unmanned aircraft in civil airspace is not routine. For decades, unmanned aircraft access to the United States National Airspace System (NAS)† has been granted on a case-by-case basis. Access involves significant operational constraints that reduce flexibility and thus also UAS mission utility. Currently, no commercial UAS operations are permitted in the United States (U.S.).

The vision of the aviation community is that UAS regularly operate in civil airspace with risks to overall system safety appropriately mitigated and existing traffic flows undisrupted. This paper summarizes airspace access challenges and discusses alternatives in the near- and long-term timeframes.

Key Challenges

The fundamental difference between manned aviation and unmanned aviation is that the pilot is not physically on-board the unmanned aircraft. The U.S. Air Force recently has begun to use the term

* Segregated Airspace can be defined as airspace which is restricted to the exclusive use of specific users, usually the military.

† The NAS is made up of a network of air navigation facilities, Air Traffic Control facilities, airports, technology, procedures, and appropriate rules and regulations that are needed to operate the system.

"Remotely Piloted Aircraft" (RPA) to emphasize that there is a pilot, but that pilot is remote from the aircraft (usually on the ground).[6][7]

While many UAS are capable to some degree of autonomous operations, human pilots still maintain operational control and interact with the on-board flight control computer from the ground as pilots of manned aircraft interact with the flight management system in today's sophisticated aircraft. With the cockpit located on the ground, a radio communications link has been inserted between the pilot and the flight control systems of the aircraft. The radio link can be provided via either line-of-sight or beyond-line-of-sight communications. In the evolution of aircraft flight control technology, we have moved from direct mechanical linkages to fly-by-wire operation.[8] With UAS, the system is essentially a *fly-by-wireless*[*] system.[9]

Although locating the UAS cockpit on the ground is a seemingly minor architecture change, it has huge implications for how unmanned aircraft operate, especially how those operations interact with the operations of manned aircraft.

1. Lack of an On-board Capability to See and Avoid

A significant issue of locating the flight deck and the pilot remotely from the aircraft itself is that there is no longer a pilot on board the aircraft capable of seeing and avoiding other aircraft (or obstacles). U.S. Code of Federal Regulations (CFR) 14, Part 91.113 states that "When weather conditions permit, regardless of whether an operation is conducted under instrument flight rules or visual flight rules, vigilance shall be maintained by each person operating an aircraft so as to see and avoid other aircraft."[10] According to CFR 14, Part 91.111, pilots also are responsible to not "operate an aircraft so close to another aircraft as to create a collision hazard." [11]

For UAS operations conducted by visual line-of-sight[†][12], the pilot or an observer on the ground can see and avoid other aircraft. This could become more challenging when weather conditions reduce visibility or after daylight hours.

The community has coined the term "*sense and avoid,*" to describe a technical capability that could be developed to mitigate the lack of a *see and avoid* capability. Recently, the Federal Aviation Administration (FAA) has sponsored workshops to more fully develop concepts associated with a UAS *sense and avoid* capability.[13] In the fall of 2009, the workshop concluded that *sense and avoid* "is the capability of a [unmanned aircraft] to remain well clear from and avoid collisions with other airborne traffic,"[13] and thus consists of two components:

- **Self-Separation:** Function that reduces the probability of a collision by ensuring aircraft remaining "well clear" of each other thereby assuring safe separation.

[*] Early aircraft (and some current aircraft) had direct mechanical linkages between the pilot's control instructions and the flight control surfaces (e.g., ailerons, elevator and rudder). As aircraft evolved, the mechanical linkages were replaced, in some designs, with an electronic interface where movements of flight controls are converted to electronic signals, and flight control computers determine how to move actuators (hydraulic or electric) at each flight control surface to provide the expected response. With fly-by-wireless, the wired link aboard the aircraft is replaced by a radio communications link.

[†] "Visual Line-of-Sight: A method of control and collision avoidance that refers to the pilot or observer directly viewing the unmanned aircraft with human eyesight. Corrective lenses (spectacles or contact lenses) may be used by the pilot or visual observer. Aids to vision, such as binoculars, field glasses, or telephoto television may be employed as long as their field of view does not adversely affect the surveillance task."

- **Collision Avoidance:** Extreme maneuvers just prior to closest point of approach to prevent collisions in cases where safe separation is lost.

These two components work together with other airspace procedures to ensure the overall collision risk is mitigated to an acceptable level. See Figure 1. These components function in a layered approach. Similar to defense-in-depth and layered information security architectures, failures would need to occur at multiple layers to cause a system failure resulting in a collision.[14]

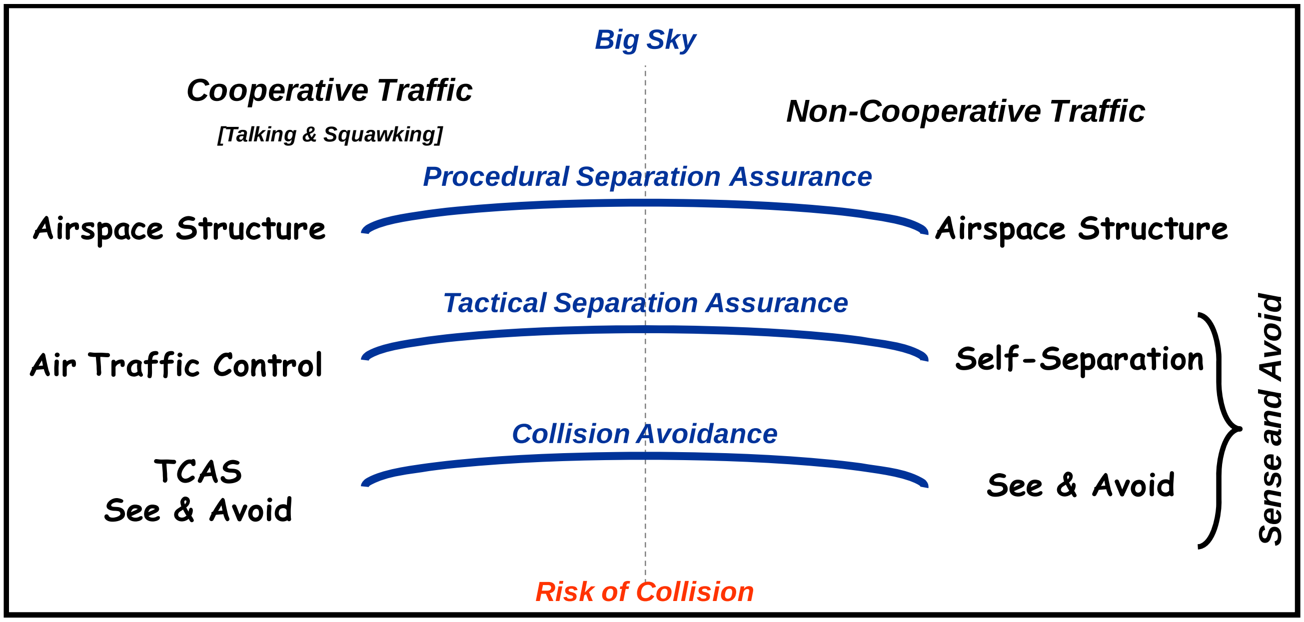

Figure 1. Layered Approach to Avoiding Collisions

2. *Command and Control Integration*

Through the insertion of a radio communications link between the pilot and the aircraft's flight control system, a number of significant issues have been introduced due to command and control (C2) link vulnerabilities and the potential latency of flight control messages.

The C2 link between pilot and aircraft in a *fly-by-wireless* system has a higher probability of interruption than the link between a pilot and aircraft control surfaces in a traditional fly-by-wire or mechanically linked system due to vulnerabilities such as radio and/or satellite system failure and radio frequency interference.[15] Mechanisms are needed to cope with these link vulnerabilities, such as autonomous flight capabilities. These mechanisms will have implications for how unmanned aircraft are managed by Air Traffic Management (ATM) and how they should be operated autonomously. Several interesting issues arise, including:

- How will flight-critical autonomous software be developed, tested, validated and verified, and then certified?
- Will alternate ATM operational concepts be required?

- Will unmanned aircraft have different separation criteria associated with their operations due to the potential for a *lost link* (loss of pilot control) and/or link latency delays associated with a pilot's control of the aircraft?
- How will the emergence of the Next Generation Air Transportation System (NextGen) impact unmanned aircraft ATM integration concepts? [16]

3. *Other Integration Challenges*

Other integration issues exist, including the certification of airframes, engines, and other aircraft components. This challenge exists because, for the most part, UAS were developed as military experiments (i.e., Advanced Concept Technology Demonstrations – ACTD) that quickly entered operational use. They generally were not developed with the typical rigor associated with military development and certification of aviation capabilities.[17] Policy decisions are needed to determine at what level of reliability unmanned aircraft need to be certified. Similarly, the certification and associated training requirements for flight crews require policy-level decisions. The aviation community knows how to build aircraft to a suitable level of reliability and knows how to determine the qualifications and training requirements of flight crews. These challenges are more of making the appropriate policy-level decisions. Thus, they are not the focus of this paper.

UAS Operations Today

Today, UAS are being operated outside segregated airspace today. There are restrictions on their operations to mitigate the above integration challenges. These restrictions include:

- **Temporary Flight Restrictions:** Temporary creation of airspace where access is either totally restricted to all other aircraft or restricted to aircraft appropriately equipped (e.g., with Mode C secondary surveillance transponders)
- **Operations Contained in Positively Controlled Airspace:** All aircraft operating in Class A airspace must be equipped with Mode C transponders, be on an IFR flight plan, and be in two-way radio communications with Air Traffic Control. These requirements enable ATC to provide separation services.[18][19]
- **Visual Observers:** Observers on the ground or in a chase aircraft provide a visual see and avoid function by scanning the airspace around the unmanned aircraft for potential intruders.[12]
- **Telephone Connection between GCS and ATC Supervisor:** In the event of a lost command and control link, air traffic controllers will be able to communicate with the pilot-in-command (PIC)* [20], who may not be in control of the aircraft due to the lost link) to learn what contingency procedure the aircraft is anticipated to execute.
- **Limitations on Operating Distance from Origin:** In case there are mechanical or other on-board problems, ensures that the UAS can safely return to base.

* "Pilot in command" means the person who: (1) Has final authority and responsibility for the operation and safety of the flight; (2) Has been designated as pilot in command before or during the flight; and (3) Holds the appropriate category, class, and type rating, if appropriate, for the conduct of the flight." [14 CFR Part 1.1]

- **Limitations on the Number of UAS which May Operate in each Air Traffic Control Facility:** Helps manage the degree of additional controller workload.
- **Low-Density Airspace:** The FAA is tending to grant waivers or Certification of Authorization (COA) for Public-use unmanned aircraft to operate in airspace with relatively low traffic densities. [12]
- **Unpopulated Areas:** Similarly, the FAA is tending to grant waivers for UAS operations that will occur over areas with relatively low population densities on the ground.

Alternative Integration Approaches

The above restrictions limit the operational effectiveness of the unmanned aircraft systems and certainly are not-scalable or extensible to accommodate the expected growth in UAS operations. Several alternatives are being explored in the community that includes changes in technology, operating procedures, and policies/regulations to more effectively integrate UAS into the non-segregated civil airspace. [9]

Alternative Integration Approaches – Lack of See and Avoid

Today, pilots on-board aircraft are able to ensure safe separation and to see and avoid other aircraft. With unmanned aircraft this is not possible; alternative means of compliance are necessary. This section discusses five alternative means of compliance to reduce the operational restrictions placed upon UAS today.

1. Small UAS Line-of-sight Regulations

The FAA initiated an effort to develop regulations for the operation of civil* small UAS which will remain within visual line-of-sight (LOS). The effort included the establishment of an Aviation Rule-making Committee (ARC) to advise the FAA on appropriate rules and regulations.[21] The ARC made their recommendations last spring [22] which the FAA currently is reviewing towards the release of a Notice for Proposed Rule-Making (NPRM) sometime next year.

The authors anticipate that the FAA could establish a final rule in as little as two years. The final rule would establish the regulations for general operations, certification of aircraft, and certification of flight crews. This rule would enable small UAS to operate for commercial purposes and could be used by public entities, such as law enforcement and the military, for routine operation of small UAS in civil airspace.

Using the Small UAS ARC recommendations as a rough framework, UAS weighing less than 25 kilograms would be able to operate within visual LOS of the pilot-in-command (PIC) or a qualified visual observer. Crew members (i.e., PIC and visual observers) will use their eyes to scan the airspace for aircraft which may pose a conflict threat and maneuver their aircraft to remain well clear and, if necessary, maneuver to avoid a collision threat. [22]

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* Civil aircraft means aircraft other than public aircraft. [14 CFR Part 1.1] Basically, this means any aircraft that is operated for commercial, recreational, and other non-governmental purposes.

To implement these regulations, the FAA needs to establish a safety case that determines conditions for which the ground-based observer is sufficient to ensure that the risks of mid-air collisions are mitigated to an acceptable level. [23] The key difference between manned aircraft's see and avoid function is that the crew member monitoring for potential traffic conflicts is on the ground, not on the aircraft. This may enable visual surveillance of broader airspace, including behind the unmanned aircraft. The influence of the different perspective of the target relative to position of own aircraft on the ability to identify a potential conflict and/or a collision threat is not fully known. There may also be a need to establish new operational procedures and modifications to existing regulations [e.g., right-of-way rules (CFR14 parts 91.113 and 91.114) so that the small unmanned aircraft will yield the right-of-way to manned aircraft].

Implementation costs for this alternative are expected to be relatively low and will center mainly on efforts associated with the following:

- **Development of regulations and standards:** The mean-time-between failures and the frequency of loss of command and control link (a.k.a. *fly-aways*[*]) for small UAS is not well understood and will have significant implications for appropriate regulations and standards. There is a need to develop standards for fly-away protection that ensures an aircraft remains within the operating area. For the most part, the appropriate technology exists and is relatively proven. Standards for lethality for people on the ground have not been determined.
- **Establishment of a safety case:** A safety case is needed that is able to extend today's *see and avoid* approach to one where the pilot and/or observer are not on-board the aircraft.

While existing airspace users in uncontrolled Class G airspace may occasionally encounter small UAS and people on the ground may experience overflights of small UAS where there are not currently any aircraft operations, the impact on these stakeholders is expected to be minimal.

2. Ground-Based Sense and Avoid (GBSAA) – Dedicated Sensor

To enable operations beyond visual line-of-sight of a pilot on the ground, a capability to sense airborne targets in the airspace in the vicinity of the UAS is needed. The community is currently focused on the feasibility of air surveillance radars to provide three-dimensional (3D) position information via a display of traffic information to the UAS flight crew. This alternative has become known as Ground-Based Sense and Avoid (GBSAA). The FAA has indicated that this may be an acceptable alternative means of compliance:

> *"If special types of radar or other sensors are utilized to mitigate risk, the applicant must provide supporting data which demonstrates that: both cooperative and non-cooperative aircraft, including targets with low radar reflectivity, such as gliders and balloons, can be consistently identified at all operational altitudes and ranges, and, the proposed system can effectively deconflict a potential collision."* [12]

[*] A fly-away is defined as an unmanned aircraft which has lost its C2 link with the pilot and is not staying within an intended operational area. A fly-away protection mechanism would either return the UAS safely to the surface, as soon as practical or keep the UAS within the intended operational area.

This alternative takes advantage of available technologies (e.g., existing 3D air surveillance radars) and may be feasible to implement in the next one to two years (assuming an appropriate safety case can be made). This alternative would involve siting and installing relatively expensive (>$3M apiece) dedicated air surveillance radars at each location where UAS are expected to operate. These radars will also need life-cycle maintenance. A single radar installation could be used to monitor operations of multiple UAS that intend to use the same airspace. Thus, the costs are per location, not per airframe.

UAS operations would need to be contained within the airspace monitored by the radar, potentially limiting operational flexibility. This alternative is likely to have value for UAS transiting from a restricted area to other segregated airspace or to Class A airspace where all aircraft are cooperative and receiving ATC separation services. It also may be a viable alternative for UAS that do not have to routinely access civil airspace to perform missions but need civil airspace access for training purposes. This avoids the installation of equipment on-board the aircraft that does not support an operational mission.

While the technology exists, the community still needs to develop appropriate operational concepts, procedures, and separation criteria to enable traffic observers and pilots to ensure aircraft remain safely separated and that they can make last-minute collision avoidance maneuvers. Appropriate decision support tools and displays will also need to be developed to enable the operations.

The community would need to prove the effectiveness of this alternative with a formal safety case that demonstrates risks are at an acceptable level by considering the following:

- Operational concept, procedures, and user interface
- Ability of sensors to detect potential hazards and the relative accuracy and integrity of the surveillance information
- Traffic density (i.e., the likelihood a UAS would encounter another aircraft that poses a conflict to safe separation or creates a collision hazard thus resulting in a proximity event)

Since the traffic situation is being monitored in the Ground Control Station (GCS) by a member of the flight crew, this alternative is highly dependent upon the use of the C2 link between the GCS and the unmanned aircraft. Implementations should probably begin with deployments in areas of low traffic density to prove effectiveness through empirical data, eventually moving into areas with higher traffic densities. It is expected that this alternative will have minimal impact on existing airspace users.

3. GBSAA – Repurposed Sensors

Some in the aviation community are looking towards existing air surveillance sensors currently deployed for air traffic control and other purposes as being potential useful for GBSAA, thereby avoiding the life-cycle cost and delay of installing dedicated sensors. This *repurposing* of existing sensors has certain additional development risks likely delaying the operational implementation by an additional one to two years.

Most of the currently deployed ATC radars (such as the terminal area surveillance radar ASR-11) have signal processing that reduces clutter on the display for primary traffic returns. Modifications to this processing may be necessary to ensure all non-cooperative aircraft are identified as primary radar returns. Primary ATC radars are two-dimensional radars and don't provide any altitude information. It may be feasible to develop some additional post-processing algorithms that may offer some altitude information with an accuracy level that will need to be determined through further analysis.

While in the long-run the life-cycle costs are likely to be reduced and the geographic area where traffic monitoring would be available may be much more extensive (adding to UAS operator flexibility), the development risks associated with the radar processing likely make this alternative less desirable than the successful implementation of the GBSAA alternative with dedicated sensors. The operational concept, procedures, separation criteria decision support system, and user display associated with the GBSAA alternative with dedicated sensors can be leveraged directly.

4. Airborne-Based Sense and Avoid (ABSAA) – Cooperative

An alternative to the traffic sensors being on the ground is to locate them on-board the aircraft itself. In the UAS community, this approach is being referred to as Airborne-Based Sense and Avoid (ABSAA).

While there is significant concern in the community about the development of the appropriate technology for sensing and detecting non-cooperative (i.e., non-transponding) traffic, if all traffic becomes cooperative, the complexity of the sense and avoid system would be greatly reduced. This section discusses a cooperative ABSAA approach; the following section discusses ABSAA for non-cooperative traffic.

In the cooperative ABSAA alternative, airborne equipment receives transmissions from other aircraft regarding their absolute or relative location. This information is either communicated to the UAS pilot on the ground or used by automation on-board the UAS to autonomously sense and avoid other aircraft.

For a cooperative alternative to be viable, all aircraft that potentially are to be operating in the same airspace as the unmanned aircraft would need to be equipped with a capability that identifies their position. Transponding or reporting aircraft are often referred to as *cooperative aircraft*. Capabilities such as Mode C transponders or Automatic Dependent Surveillance Broadcast (ADS-B) are examples.[24][25] Currently there are very few aircraft equipped with ADS-B. However, the FAA is in the process of mandating ADS-B OUT[*] to be installed on aircraft by 2020 which operate in areas that today require installation of Mode C transponders. [26][27][28] Other nations are mandating ADS-B OUT as well.[29][30]

Today, transport category commercial aircraft worldwide are equipped with a cooperative collision avoidance capability, known as Airborne Collision Avoidance System (ACAS)[†]. [31] This system makes use of Mode C transponders and alerts pilots to potential collision threats and suggests specific resolution maneuvers. While this capability may not be directly appropriate for unmanned

[*] ADS-B OUT is the capability to transmit ADS-B message. ADS-B IN is the capability to receive ADS-B messages.

[†] Known as Traffic Alert and Collision Avoidance System (TCAS) in the U.S.

aircraft, [32][33][34] a similar, but potentially adequate, capability could be developed using ADS-B as the surveillance information source. It is the belief of the authors that interrogating Mode C (a.k.a. TCAS) is not likely to have the position accuracy to enable ABSAA, thus ADS-B OUT would be necessary for cooperative ABSAA.

A sense and avoid capability built using cooperative sensors has the following advantages over a non-cooperative solution:

- Relies upon existing surveillance technology with known accuracy, integrity and failure modes
- Simplifies conflict-detection and resolution algorithms due to the known accuracy and integrity of the surveillance information
- Avoids the need for multiple sensor fusion algorithms
- Avoids the need for non-cooperative sensors (e.g., electro-optic or radar) and associated processing that could have significant implications for airframe size, weight, and power (SWAP) constraints as well as add additional implementation and maintenance costs per aircraft
- Reduces development and certification risks due to the reduced complexity of the system

The authors estimate that such a solution may be operationally viable in the next 10 years leveraging existing research [35]; synergies with the development of the Next Generation Collision Avoidance System (NextCAS) [36][37]; FAA and other aviation authorities requirements for ADS-B OUT equipage; and on-going standards development efforts such as those in RTCA.[38]

There is a major architectural trade-off with the implementation of either a cooperative or non-cooperative ABSAA system. This trade-off involves the role of the pilot in performing self-separation and collision avoidance functions as follows:

- **Pilot In-the-Loop:** While sensors will be on board the aircraft, traffic information would be directly communicated to the pilot and the pilot would need to make decisions and take action to maneuver the aircraft. Automation may alert the pilot of a conflict or collision threat and may also suggest specific maneuvers, like ACAS today. Thus, the pilot would be directly in-the-loop. Such architecture would depend heavily upon the C2 link (since the pilot must command any alterations to course) with risks added due to latency and vulnerabilities (i.e., integrity, reliability, and availability) of the link. An appropriate operational concept including procedures and separation criteria will be needed. The operational concept will need to define how traffic observers and pilots can ensure that aircraft remain safely separated and that they can make last-minute collision avoidance maneuvers. Appropriate decision support tools and displays will need to be developed to enable the operations. As with ACAS, the operational concept and specific maneuvers may be dependent upon the surveillance accuracy of the traffic position information (whether cooperative or non-cooperative).
- **Autonomous:** Again, sensors on-board the aircraft would collect traffic information that would be used by on-board automation to detect potential separation conflicts and/or collision hazards, determine the appropriate maneuver, execute the maneuver, and determine

when to return to course. The pilot on the ground may be informed of the autonomous actions and could over-ride a maneuver if necessary. However, pilot action would not be required. While this architecture is not susceptible to vulnerabilities and latencies in the C2 link, the complexity of the software and issues associated with assuring its correct functioning and certifying it for safety of life applications could add development and safety risks. See discussion of *Autonomous Operations* below.

A major implementation risk associated with Cooperative ABSAA is the policies and costs associated with requiring all aircraft to equip with ADS-B OUT or other similar capability. It does not appear that the FAA is planning to mandate ADS-B equipage for non-commercial aircraft intending to operate in Class E and G airspace.[26][27] Thus, a policy requiring such equipage at least in Class E or G airspace where UAS are flying would be needed.

While development of algorithms and their validation will be costly, the cost is likely to be less than the cost to develop a non-cooperative solution due to the added complexity of the detection and fusion algorithms; integrity monitoring; and more complex algorithms to deal with diminished accuracy and integrity of information (see below). There is an added cost associated with equipping aircraft potentially operating in the airspace in which the UAS will be operating. If every General Aviation aircraft that is not equipped with ADS-B OUT would now need to be equipped, we estimate that the cost would be an additional $58M (CY2007)[*]. This figure likely represents an upper bound due to efforts to create low-cost, portable ADS-B-OUT capabilities [35] that are compliant with published standards. [24][25]

Of course, appropriate technology, which includes the collision avoidance algorithms, would need to be developed, standards established, systems tested and certified, and then installed on every single unmanned aircraft. Thus, the implementation risks can be summarized as follows:

- Development of conflict and collision avoidance algorithms for UAS
- Development of appropriate standards
- Policy requiring equipage in specific airspace
- Development, certification, and production of low-cost, portable (i.e., non-installed) ADS-B OUT solution for manned aircraft
- If pilot-in-the loop, development of operational concept and appropriate decision-support system and user displays
- If autonomous, development and certification of appropriate tracking and avoidance algorithms

[*] According to the FAA's *Aerospace Forecasts Fiscal Years 2009-2025*, there will be an estimated 261,840 aircraft of various types in the year 2020. We assume that the ratio of aircraft equipping with ADS-B OUT in 2020 will roughly match the ratio of aircraft which are equipped with Mode C transponders in today's fleet since the FAA ADS-B rule is anticipated to roughly mirror today's transponder requirements (14 CFR Part 91.215). Using the ratio of Mode C transponder equipped aircraft by fleet type from the FAA's *General Aviation and Part 135 Activity Surveys – CY 2007* we predict that there will be a total of 25,323 aircraft which are not going to be equipped with ADS-B OUT in 2020. Using the FAA's estimate for ADS-B OUT equipage from Joint Resource Council review of the ADS-B program in August 2007 of $2,300 (CY 2007 $) per airframe we estimate that it would cost approximately $58M (CY 2007 $) to equip the remaining United States fleet of aircraft with ADS-B OUT.

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- Establishment of a safety case

Full fleet equipage with ADS-B OUT would significantly enhance the safety of the NAS by reducing the probability of mid-air collisions between aircraft not receiving ATC separation services and would further motivate the equipage with ADS-B IN. While equipping with ADS-B OUT has societal benefits beyond more routine UAS access to civil airspace and even if the Government subsidizes the cost of equipage, there may be some resistance in the user community. This is especially true if access to airspace is reduced for the failure to equip with ADS-B OUT.

Successful development of autonomous cooperative ABSAA for unmanned aircraft could lead to the technology transfer to manned aviation of an appropriate variant.

5. ABSAA – Non-cooperative

Non-cooperative ABSAA is similar in principle to cooperative ABSAA, except in addition to detecting cooperative traffic (i.e., Mode C and/or ADS-B OUT equipped) it must also work with aircraft that are not emitting any electronic signals regarding their position. There has been significant research in the area of non-cooperative ABSAA [39][40] [41][42][43][44][45][46] but much of this capability is still at relatively low technology maturity levels. It is the belief of the authors that a certifiable capability is not likely to be commercially available for 12 or more years. In addition to many of the complexities noted above with cooperative ABSAA, the non-cooperative alternative has many added complexities [33] due to the difficulty in detecting traffic with the following attributes:

- In visual- and instrument- meteorological conditions
- At all times of the day – sunlight darkness, twilight
- Masked in ground clutter
- Of varying sizes, dimensions, relative speeds, and materials
- In the air and on the ground
- At a range sufficient to avoid collisions
- With data fused from multiple sensors (e.g., TCAS/Mode A/C/S, ADS-B, Radar, Electro-optic)

In addition, the necessary sensors/processing equipment on-board the UAS are likely to create significant issues for the size, weight, and power constraints of the unmanned aircraft. The non-cooperative sensor(s) are likely to be significantly larger than cooperative sensors. Both cooperative and non-cooperative sensors will be needed.

The development of the necessary technology is also likely to be expensive. At the request of the U.S. Navy, MITRE made an initial estimate of the rough-order-of-magnitude cost for the entire aviation community of developing, validating, and certifying a non-cooperative ABSAA capability as between $2B and $3.5B. This estimate was based upon cost estimates associated with similar activities (including establishment of appropriate civil standards) associated with ACAS and ADS-B. The estimate does <u>not</u> include the cost of implementation.[47] As an example, ACAS took an estimated 15 years and the technology development, establishment of civil standards, and civil certification cost the community an estimated $400M (FY01 $).[48] The complexity of an autonomous non-cooperative solution is significantly greater, thus warranting the higher estimate.

The biggest risk to the development and implementation of such a capability is associated with the development of non-cooperative sensor technology with sufficient detection accuracy, integrity, and reliability to be certified to perform the sense and avoid function.

If such a capability could be developed and certified it may also have applicability to manned aviation potentially reducing the rate of mid-air and near-mid air collision among two non-cooperative manned aircraft.

Given the estimate of $58M to equip the remaining U.S. fleet of aircraft with ADS-B OUT, the reduced development costs and risks of cooperative ABSAA versus non-cooperative ABSAA, and the SWAP advantages of a cooperative sensor, the aviation community needs to directly address the question:

> **Would it be more effective to equip all aircraft with ADS-B OUT and develop a certified cooperative ABSAA solution than to develop certifiable non-cooperative ABSAA solution?**

Alternative Integration Approaches – Command and Control Integration

The issues created by the insertion of a radio communications link between the pilot and the flight control systems of the aircraft have resulted in operational restrictions being placed on UAS, which reduces their mission effectiveness. Alternate approaches to these restrictions are needed. This section outlines five alternatives, which individually or in combination can contribute towards reducing C2 operational risks and eliminate specific operational restrictions.

1. Standardized Lost Link & Contingency Procedures

Like all aircraft, unmanned aircraft are subject to in-flight operational issues that may require a diversion to an alternate airport or a return to the original airfield. In addition, given the vulnerabilities of the C2 link, there may be failures in the ability of the pilot on the ground to maintain operational control over the aircraft. In general, UAS designers have taken this into account when developing these systems. Given that no standards existed, developers evolved a variety of approaches for dealing with these events which occur relatively frequently.

A standardized approach for how unmanned aircraft respond to lost C2 links, prevent *fly-aways*, and respond to in-flight system failures or emergency situations would ensure that other aircraft and ATC controllers know what to expect in the event such a scenario occurs. These procedures will need to be validated through simulations to ensure that they are effective. Appropriate flight management software will need to be developed and subsequently certified.

2. UAS-specific ATM Procedures & Separation Criteria

Today unmanned aircraft operating in civil airspace are supposed to be treated like any other aircraft. As discussed above, unmanned aircraft may experience a lost C2 link and be unable to maintain their flight clearance. While a standardized approach to what the aircraft will do would be helpful, air traffic controllers may be required to clear airspace in response to notification received either from the aircraft or from the pilot that the aircraft has lost its C2 link. Controllers may need new procedures that correspond to the standardized procedures being used by the unmanned aircraft (see above). This may require the development and validation of specific ATM procedures tailored to the unique UAS operational characteristics. New ATM procedures may be associated with the following:

- Changes in emergency procedures
- Practices for providing routine separation services
- Mechanisms to deal with the differences in flight performance*
- Approaches to lost link and other flight contingencies

Field analysis and laboratory simulations will help identify specifics on what lost C2 link procedures may be needed to best address UAS operational characteristics. These new procedures will need to be validated and appropriate changes in NAS decision-support systems implemented. Appropriate controller training will need to be developed and carried out.

3. *Link Robustness*

To reduce the vulnerability of the C2 link to interference from licensed and unlicensed emitters, use of protected spectrum is desirable.[49] The International Telecommunication Union (ITU) Working Party (WP) 5B is currently working on various spectrum issues to be resolved at the 2012 World Radiocommunication Conference (WRC-12).[50] One of the issues being worked is WRC-12 Agenda Item 1.3 where the ITU will consider creating spectral allocations for highly reliable C2 links specifically to enable unmanned aircraft to begin operating in non-segregated civil airspace. The working party is focused on identifying the bandwidth requirements and candidate frequency bands.

4. *Autonomous Operations*

Unmanned aircraft that are operated in direct visual line-of-site of pilot (e.g., small UAS operated like model aircraft) tend to be the only systems that are teleoperated†. All other unmanned aircraft have some degree of autonomy where they may be under the *supervisory control*‡ of a pilot or in some situations (e.g., lost of C2 link) may operate autonomously. When operating autonomously, systems on-board the aircraft could be making critical decisions regarding flight stability, system monitoring, navigation, flight path, and hazard avoidance. More autonomy is needed in situations with the following characteristics:

- Little or no direct input from the pilot is possible (e.g., loss of C2 link)

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* Many unmanned aircraft that operate at altitudes with transport aircraft fly at much lower cruise speeds and have different climb and turn rates.

† Teleoperation: Remotely controlled by a human operator with no significant autonomy.

‡ Supervisory Control: "One or more human operators [pilots] are intermittently programming [or making control instructions] and continually receiving information [telemetry displays] from a computer [flight control computer] that itself closes an autonomous control loop through artificial effectors [flight control surfaces] and sensors to the controlled process [flight] or task environment. [Thomas Sheridan, *Telerobotics, automation, and human supervisory control*, Massachusetts Institute of Technology, 1992.]

- Pilot has limited situational awareness regarding the environment in which the aircraft is operating
- Significant time lag in the command and control link (e.g., C2 link via satellite communications)

Autonomy of unmanned aircraft may include the following capabilities:

- **Mechanism to directly communicate aircraft intent (voice or data):** to controllers and other pilots in the same airspace especially during periods of C2 link disruption
- **Machine-to-machine negotiation** among unmanned aircraft to coordinate their actions and perhaps between unmanned aircraft and air traffic control automation.
- **Auto take-off and landing**
- **Auto flight path management** to potentially include emergency management, self-separation, and collision avoidance.

There are varying degrees of autonomy for the operation of any automation-based system. Degrees of autonomy are often referred to by the ten levels shown in Figure 2.

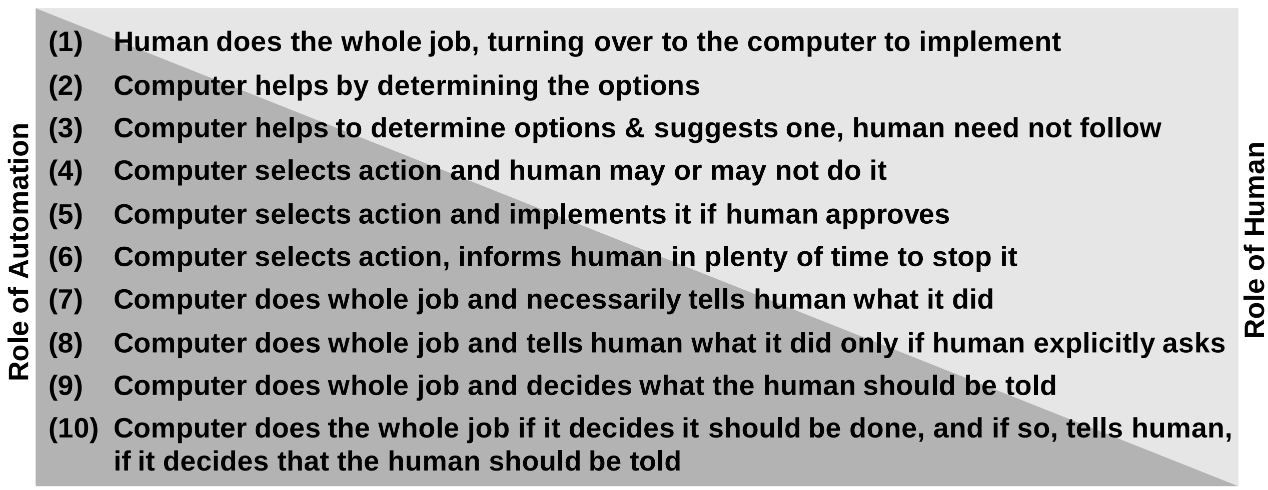

Figure 2. Degrees of Autonomy [51]

As more unmanned aircraft operational control is turned over to automation, there is an increase on the dependency of complex software-intensive systems for flight safety. These software systems must function in a multifaceted operational environment with nondeterministic input variables. Thus, these systems are becoming more difficult to design, implement, and validate ensuring that they are functioning appropriately in a range of relevant operating conditions. Basic research in new tools and techniques is needed for designing and testing software-intensive systems and for maintaining and upgrading them over time.[52][53] There are significant challenges to ensuring integrity for systems that operate <u>without</u> human monitoring or the potential for human intervention.

While the technical obstacles to these autonomous capabilities are significant, there also are challenges associated with the acceptance of such capabilities by others users of the airspace and by the public in general.

5. NextGen Operational Concepts

Many nations are anticipating tremendous growth in air travel and air traffic. In U.S., the FAA is planning for the Next Generation Air Transportation System (NextGen), which involves coordinated concepts and programs to increase capacity and efficiency, improve user access and safety, and to reduce environmental impacts. [54] In Europe, the European Commission is coordinating its Single European Sky Air Traffic Management (ATM) Research (SESAR) program to similarly improve safety and air traffic flows, to create additional capacity, and to increase efficiency.[55] While these are different emerging concepts, they share many common elements and assumptions about the air traffic system twenty years from now.

While accommodating new types of aircraft is an explicit goal of NextGen [54], so far the concepts do not directly address the integration of unmanned aircraft in the NextGen timeframe. Some specific concepts envisioned for NextGen may be particularly suited for facilitating the integration of unmanned aircraft into civil airspace, including [56]:

- **Trajectory-Based Operations (TBO):** In the TBO concept each aircraft's expected flight profile and time information (such as departure and arrival times) is the basis for air traffic management and ATC. The specificity of four-dimensional trajectories (4DTs) matches the mode of operations and the requirements of the airspace in which an aircraft operates. A major benefit of 4DT is that it enables service providers and operators to assess the effects of proposed trajectories and resource allocation plans, allowing both service providers and operators to understand the implications of demand and identify where constraints need further mitigation.
- **Equivalent Visual Operations (EVO):** Improved information availability allows aircraft to conduct operations without reliance on visibility or direct visual observation. For aircraft, this capability, in combination with position, navigation, and timing information, enables increased accessibility, both on the airport surface and during arrival and departure operations. This capability also enables those providing services at airports (such as ATM or other ramp services) to provide services in all visibility conditions, leading to more predictable and efficient operations. [16]

Work in the aviation community is needed to ensure that unmanned aircraft unique operational capabilities and integration requirements are included in the NextGen concept development and evolution.

Conclusion and Recommendations

Many challenges exist regarding the integration of UAS into the NAS. The two most daunting are:

- Lack of an On-board Capability to See and Avoid
- Coping Mechanism for Link Vulnerability and ATM Integration

Both of these challenges have implications for technology, operating procedures, and policy/regulations, as well as costs. As the aviation community examines integration approaches, a number of alternatives need to be considered. These alternatives may be implemented in a time-phased approach and may offer trade-offs in life-cycle costs and other implementation risks; see Tables 1 and 2. Some of these alternatives may be sufficient as interim integration approaches, which in turn may be stepping stones to end-state solutions. The aviation community should develop a UAS Airspace Integration Roadmap to align efforts to examine trade-offs among these and other alternatives, as well as to coordinate research, development, and implementation efforts.

Table 1. Summary of See and Avoid Alternatives

	When	Approach	Costs	Development Risks	Stakeholder Impact
Small UAS Line-of-sight Regulations	+2 yrs	Establish regulations & certification standards for aircraft and crew that would enable small UAS (<25 kgs) to operate for commercial purposes	Low	Low • Regulations & standards • Safety case	Low Glass G users may encounter small UAS
Ground-based Sense & Avoid (GBSAA) Dedicated Sensor	1-2 yrs	Deploy dedicated 3D air surveillance radars to enable UAS flight crews to monitor traffic	Medium	Medium • Installation of radar • Operational concept • Decision-support system & display • Safety Case – Highly dependent on C2 link	Low UAS operators need to remain well-within surveillance range
GBSAA Repurposed Sensors	2-3 yrs	Operate within coverage of existing ground sensors (e.g., ASR-9/11) which will enable UAS flight crews to monitor traffic	Medium	Medium • Radar post processing accuracy • Operational concept • Decision-support system & display • Safety Case – Highly dependent on C2 link	Low Broader surveillance area
Airborne-based Sense & Avoid (ABSAA) Cooperative	10+ yrs	Airborne equipment receives signals from *cooperative* aircraft (ADS-B). Traffic situation info sent to UAS pilot or used by automation on-board the UAS to autonomously sense and avoid	High	High • Avoidance algorithm development and validation • Policy requiring equipage in specific airspace • Decision-support system & display • Safety Case – Dependent upon C2 link or autonomous software	High • Reduces access for legacy airspace users unless appropriately equipped • Technology could be extended to manned aviation
ABSAA Non-cooperative	12+ yrs	Airborne equipment uses non-cooperative sensor technologies to locate other aircraft and hazards. Situation info sent to UAS pilot or used by automation on-board the UAS to autonomously sense and avoid	Very High	High • Requires the development of new non-cooperative sensor technology which is able to be certified for the purpose of Sense and avoidance • Decision-support system & display • Safety Case – Dependent upon C2 link or autonomous software	Low Technology could be extended to manned aviation

Table 2. Summary of C2 Integration Alternatives

	When	Approach	Costs	Development Risks	Impact on Stakeholders
Standardized Lost Link & Contingency Procedures	2 yrs	Procedures for all UAS platforms to follow during lost link and other flight contingencies including in-flight emergencies (e.g., engine failure, fire)	Medium	Low • Validation of procedures • SW Development • Certification	Medium Legacy users may be vectored to clear a path for a UAS following a contingency
UAS-specific ATM procedures & separation criteria	2 yrs	Specific ATM procedures tailored to unique UAS operational characteristics.	Medium	Medium • Validation of procedures • Changes in NAS systems	Medium Changes to controller functions
Link Robustness	2-4 yrs	Work with International Telecommunications Union to protect specific frequencies for UAS C2 links	Low	Low • Low risk – process in place; needs time and money	High There is a demand for spectrum for aviation and other industry applications.
Autonomous Operations	5-15+ yrs	In addition to robust software architectures for autonomous UAS operations (i.e., with limited pilot interaction) some promising technologies include: • Mechanism to communicate intent (voice or data) • Machine-to-machine negotiation • Auto-take-off and landing • Auto emergency management • Auto flight path management	High	High • Certification • Integrity monitoring without human intervention	Low There is a big public perception and acceptance hurdle to overcome
NextGen Operational Concepts	15+ yrs	Integration into future ATM framework. Most promising concepts are associated with Trajectory-Based Operations (TBO) and Equivalent Visual Operations (EVO)	Medium – High	High • Exactly how UAS will fit into emerging NextGen concepts is unclear	Unknown

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