Analyzing Sense and Avoid Requirements to Integrate Unmanned Aircraft Systems into Controlled Airspace

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Abstract

The rapid adoption of increasingly affordable and capable unmanned aircraft systems (UASs) has highlighted their current value and future potential in a wide variety of applications across many different industries. Most study to date has focused on the most affordable and prolific class of small UAS which are legally restricted to flight in the limited low-altitude uncontrolled portion of the National Airspace System. Larger and more capable Group 3 and 4 UASs, as defined by the U.S. Department of Defense, are capable of operating in expanded flight envelopes, but current regulations prohibit unmanned flight in controlled airspace under the more dynamic visual flight rules that require independent deconfliction referred to as "sense-and-avoid", which are required for the maturation of future civil and commercial UAS applications. This paper quantitatively analyzes the safety concerns and current mitigation efforts surrounding the proposed incorporation of larger group three and four UASs into controlled airspace under visual flight rules and concludes with recommendations for additional measures required to safely allow for future ubiquitous operation.

Keywords
Airspace, Automatic Surveillance Dependent-Broadcast (ADS-B), cooperative, controlled, Federal Aviation Administration (FAA), Unmanned Aircraft System (UAS), Visual Flight Rules (VFR)

1. Introduction
The genesis of the UAS has deep militaristic roots, but ample opportunities exist for future commercial use (Banik 2022). Much of the history of aviation has been related to its utility in transportation where the act of flying by itself is largely unimportant—a teleportation device, if available, would quickly supplant this segment. Meanwhile, significant opportunities exist that require persistent airborne presence. The lack of persons onboard means that sortie duration for a UAS is limited only by fuel load and not human factors such as fatigue (Shappell et al. 2007). A wide range of potential uses for UASs have been identified from aeromagnetic surveying to aiding search and rescue operations by locating persons lost in mountainous terrain (Cunningham et al. 2018; Karaca et al. 2018; Kerr 2020). As commercial UAS technology advances and becomes more attainable, larger airborne platforms will be required to carry the additional weight and supply adequate electrical power to more capable and complex payloads. Current UAS operations in the U.S. National Airspace System (NAS) are restricted by 14 C.F.R. § 107 to naked eye visual line-of-sight (LOS) operations in uncontrolled airspace below 400 feet above ground level (AGL), and only apply to small UAS systems weighing less than 55 pounds.

No current regulations allow for the systematic inclusion of UASs weighing more than 55 pounds, flight above 400' AGL, or beyond line-of-sight (BLOS) operations. In order to achieve better management of complex systems problems, we need to adopt a more 'systemic' approach (Nagahi et al. 2019). The vast majority of civil general aviation flights are typically conducted under flexible visual flight rules (VFR) that rely on visual navigation as the primary means of deconfliction, a concept termed by 14 CFR § 91.113 as "see and avoid". With no certifiable means to either sense conflicting aircraft or avoid them, the issue of safely integrating larger unmanned aircraft into the NAS becomes quickly evident (Melnyk et al. 2014). However, recent changes implemented as part of the Federal Aviation

Administration's (FAA's) Next Generation Air Transport System, called NextGen for short, have paved the way for UAS operators and onboard autonomous detect and avoid (DAA) systems to potentially satisfy this requirement. The backbone of NextGen is Automatic Dependent Surveillance-Broadcast (ADS-B), a decentralized, open-source datalink that allows for the acquisition of precise telemetry data from cooperative, participating aircraft. Representing a generational leap from its transponder predecessors, ADS-B allows for a complete and automatic air surveillance picture, updated in near real-time, and allows for direct aircraft-to-aircraft communication (International Civil Aviation Organization 2014). Despite its numerous advantages, ADS-B reliance presents potentially significant risk: failed message delivery referred to as 'drop-out' risk fracturing surveillance picture accuracy (Fang & Zan 2011; Tabassum & Semke 2018). In addition, detection probability of non-cooperative aircraft and lost-link logic, particularly in BLOS operations, must be carefully examined to ensure that UAS integration introduces no significant level of risk not already present in current VFR operations.

2. Literature Review

Contemporary studies relating to the safe integration of UASs into the NAS have primarily focused on small UASs weighing less than 55 lbs in uncontrolled airspace under 400' AGL. Analysis has been done to model visibility of these small UASs for the purpose of manned aircraft-initiated deconfliction and the associated risk of low-altitude mid-air collisions (MACs) (Highland et al. 2020; la Cour & Schiøler 2019). However, little study exists regarding larger UASs, likely due largely to their current prohibited operation. However, the lack of study has surely slowed the adoption of permissive regulations. The first hurdle in systematic UAS integration and regulation is proper and standardized categorization. Somewhat unsurprisingly, there is little consensus in this regard. The International Civil Aviation Organization and U.S. FAA, National Aeronautics and Space Administration, and Department of Defense (DoD) have each devised their own methodology for classifying UASs. For the sake of this discussion, the DoD's definition, as summarized in Table 1 below, will be used for continuity and its comprehensiveness (U.S. Army UAS Center of Excellence 2010).

Table 1. U.S. DoD UAS classification (U.S. Army UAS Center of Excellence 2010).

Category	Size	Maximum Gross Takeoff Weight (MGTOW) (lbs)	Normal Operating Altitude (feet)	Airspeed (knots)
Group 1	Small	0-20	< 1,200 AGL	< 100
Group 2	Medium	21-55	< 3,500	< 250
Group 3	Large	< 1320	< 18,000 MSL**	< 250
Group 4	Larger	> 1320	< 18,000 MSL	Any
Group 5	Largest	> 1320	> 18,000	Any

**MSL = Mean Sea Level
Note: Overall UAS classification is determined by its highest single category.

Group 1 and 2 UASs are those for which most existing study has been conducted. Due to their normal operation above 18,000 feet MSL, Group 5 UASs are limited to inflexible instrument flight rules designed for transportation operations. For these reasons this discussion will center around those UASs classified as Group 3 and 4.

Local ADS-B performance has been recorded and analyzed at a number of low- and high-density aerodromes in an attempt to quanitfy its reliability (Syd Ali 2013; Tabassum & Semke 2018; Hicok & Lee 1998). In their 2018 study using data collected at Grand Forks International Airport, North Dakota, Tabassum and Semke concluded that ADS-B drop-out presented a remote probability of an unacceptable risk of an intruding aircraft violating what is defined as 'well-clear', UAS separation minima defined by Special Committee-228 and the FAA and summarized in Table 2. (Radio Technical Commission for Aeronautics Incorporation, 2014; Tabassum & Semke 2018).

Table 2. UAS well-clear thresholds (Radio Technical Commission for Aeronautics Incorporation 2014).

Vertical Separation Threshold	450 feet
Horizontal Separation Threshold	4000 feet
Forward Look-Ahead Collision Threshold	35 seconds

3. Methods

The majority of events in the study fell into the category of accepted risk with mitigation, concluding that "with the provision of ATC [Air Traffic Control] interation and possible multi-sensor fusion", the risks of UAS integration could be appropriately mitigated (Tabassum & Semke 2018). Though it provides a thorough surveillance picture adaquate for UAS sense-and-avoid applications when operating as intended, ADS-B message drop-out presents a significant enough risk that complimentary sensors to detect non-cooperative aircraft are required.

4. Data Collection

Visual, acoustic, and Doppler radar-based sensor suites have been proposed to detect non-cooperative or malfunctioning aircraft and augment cooperative sensors such as ADS-B and traffic collision avoidance systems (Legowo et al. 2017). One such radar-based system, General Atomics Aeronautical's Due Regard Radar Assembly, pictured in Figure 1, illustrates how such non-cooperative sensors could be utilized (General Atomics Aeronautical Systems, Inc. 2022). Analyitical frameworks have been devised to model the effectiveness of single and multiple fused sensor networks in timely detection of intruding aircraft (Ramasamy et al. 2018). Significant study has been done to define performance standards for the algorithms required of integrated DAA systems, but little has been done to define the physical performance standards of proposed non-cooperative sensors (Du, Zhang, & Gu 2019; Fern 2017; Ghatas et al. 2017).

Figure 1. General Atomics Aeronautical Systems' developmental Due Regard Radar (DRR) Assembly (left) installed in a Predator B aircraft (right) (General Atomics Aeronautical Systems, Inc. 2022).

Non-cooperative sensor fusion requires that non-cooperative aircraft, those without a functioning transponder or ADS-B system, can be reliably detected such that the UAS has sufficient time to initiate a turn to maintain well-clear of the intruding aircraft. The most elaborate maneuver required to prevent a MAC would be a 90° turn. The minimum time required to make this maneuver is a head-on scenario when UAS azimuth to the intruding aircraft is 0°. This scenario is depicted in Figure 2.
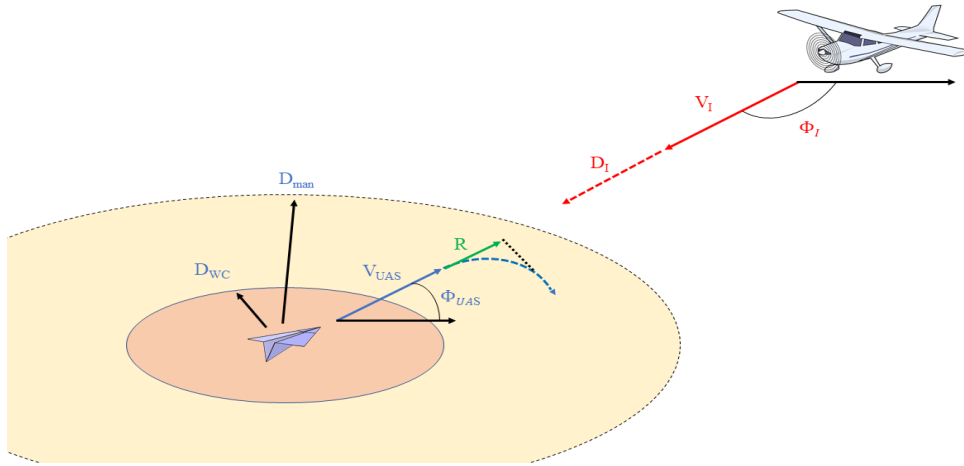
Figure 2. Head-on probable MAC scenario.

5.1 Numerical Results

The UAS and its vectors are depicted in blue and the intruding aircraft vectors in red. V_{UAS} and V_I are the speed of the UAS and intruding aircraft, respectively. Likewise, ϕ_{UAS} and ϕ_I describe the UAS and intruder aircraft headings with respect to an imagined x-axis. D_{WC} is the UAS well-clear horizontal threshold equal to 4,000 feet. D_{man} is the minimum distance which allows for the UAS to make a 90° turn away, shown here with a dotted blue line, while maintaining D_{WC}. D_{man} is a function of R, the radius of the UAS's turn, and D_I, the distance the intruding aircraft travels in the time it takes the UAS to complete its collision-avoidance maneuver and is calculated using Equations (1)-(3).

$$R_{Turn} = \frac{V^2}{11.26 \tan \theta_{Bank}} \tag{1}$$

$$\omega_{Turn} = \frac{1091 \tan \theta_{Bank}}{V} \tag{2}$$

Where R_{Turn} is the turn radius in feet, V is the aircraft's groundspeed in knots (KGS), θ_{Bank} is the bank angle of the turn, and ω_{Turn} is the angular speed in degrees per second. It is important here to recognize that due to the nature of UAS mission sets, low power-to-weight ratios, high wing loading, and low speeds are common. While a max-performance high angle-of-bank turn would help to minimize D_{man}, it is important that a UAS is able to complete this avoidance maneuver at any stage of flight without preparation.

Substituting this profile into Equations (1) and (2) gives the UAS's time to turn, t_{Turn}, in Equation (3).

$$t_{Turn} = t_{Entry} + t_{Exit} + \frac{\theta_{Turn} - \theta_{Entry} - \theta_{Exit}}{\omega_{Max\ Bank}} = 2\frac{20°}{10°/s} + \frac{90° - 4\frac{1091 \tan 10°}{V}}{\frac{1091 \tan 20°}{V}} = 4 + \frac{90V - 769.491}{397.092} \tag{3}$$

The total distance required to enact this maneuver and maintain well-clear, D_{man}, is calculated using Equation (4) where $\theta_{Avg\ Bank}$ is the time-weighted average bank angle over the duration of the maneuver. For V=100 KTAS as shown in Exhibit 2, $\theta_{Avg\ Bank}$ = 18.382°.

$$D_{man} = D_{WC} + D_I + R_{Turn} = 4000 + V_I t_{Turn} + \frac{V_{UAS}^2}{11.26 \tan \theta_{Avg\ Bank}} \tag{4}$$

A Monte Carlo simulation with 10,000 iterations was run using GNU Octave software to determine the two-dimensional lateral probability of a head-on MAC scenario inside of a 100 NM² area. The setup for this experiment is visually depicted in Exhibit 6. Two aircraft, a UAS depicted in blue, and an intruder depicted in red, are placed at y=0 NM and y=10 NM and randomly assigned a starting x-axis value between four and six nautical miles. Each aircraft is additionally randomly assigned a vector, to include speed between 50 and 250 knots and a flightpath direction within

90±45° with respect to the x-axis for the UAS and within -90±45° for the intruder; the black dotted lines portray the directional limits of the vectors. D_{WC} is held constant at 4,000 feet. D_{man} is calculated for each iteration using Equation (4). Speed and direction are assumed constant throughout each iteration. Each iteration was calculated using a maximum duration of 1018 seconds and terminated when either aircraft reached the perimeter of the 100 NM² simulation area.

5.2 Graphical Results

BLOS satellite antenna limitations typically preclude bank angles more than 30°. For these reasons and to remain conservative, a 90° turn avoidance maneuver consisting of a maximum 20° bank with 10° per second entry and exit was selected. An example profile of this turn with V=100 knots true airspeed (KTAS) is shown in Figure 3.
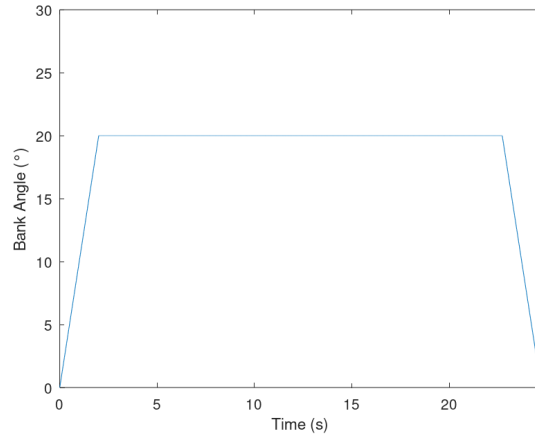

Figure 3. Theoretical avoidance maneuver profile with V = 100 KTAS.

The U.S. FAA defines a special category of aircraft known as light sport aircraft with a MGTOW of 1,320 lbs and a maximum speed in level flight of 120 knots calibrated airspeed (Federal Aviation Administration, 2004). It would be particularly unusual for a lightweight (<1,320 lb) aircraft designed for endurance to approach an airspeed of 250 knots. Even General Atomics Aeronautical Systems' prolific MQ-9A "Reaper" UAS has a published maximum airspeed of 240 knots true airspeed (KTAS) with a MGTOW of 10,500 lbs (General Atomics Aeronautical Systems, Inc., 2022). It is for this reason that 250 knots was selected as the simulation's upper airspeed limit as displayed in Figure 4.
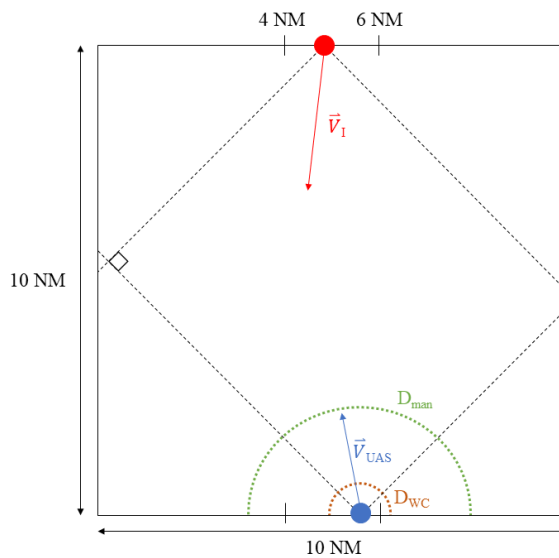

Figure 4. Graphical simulation setup.

Simulation outputs were recorded to include the following from each iteration: (1) minimum aircraft separation distance; (2) D_{man}; (3) cumulative seconds intruder aircraft existed within D_{man}; (4) cumulative seconds intruder aircraft existed within D_{WC}; (5) bearing from UAS to intruder with respect to the UAS's direction of travel, referred to henceforth as UAS azimuth, when intruder first reached D_{man}; and (6) UAS azimuth when intruder first reached D_{WC}.

5. Results and Discussion

ADS-B performance standards dictate that transmitter output power is between 75 and 500W, greatly affecting the distance at which the signal can be received (International Civil Aviation Organization 2014). One study characterizing the receipt of ADS-B signals concluded that ADS-B messages from various aircraft and equipment were reliably detected out to 200 km (Francis et al. 2011). Considering only free space path loss, a transmitted 1090MHz signal at 75W would be received 200km away at a power of approximately -90dBm. The received power levels at or near D_{man}, the average for which over the collision dataset was 3.413 NM, is on the order of -60dBm. It can therefore be reasonably concluded that failure to receive an ADS-B message in this simulated environment would not be due to signal resolution and instead attributable to equipment failure, necessitating detection via non-cooperative sensors.

Out of the simulation's 10,000 iterations, 1,276 resulted in flight paths which, if unresolved, would have violated the well-clear criteria in Table 2 and constitute the 'collision dataset'. A summary of the collision dataset is shown in Table 3.

Table 3. Summary of simulation collision dataset.

	Minimum Separation Distance (NM)	D_{man} (NM)	Time Within D_{man} (sec)	Time Within D_{wc} (sec)	UAS Azimuth at D_{man} (deg)	UAS Azimuth at D_{wc} (deg)
μ	0.3257	3.4128	79.0392	14.1638	-0.1090	0.6542
Median	0.3193	3.2768	79.0000	13.0000	-1.1979	1.1144
σ	0.1876	1.4810	16.6565	6.4379	24.2381	46.2347

To be effective, a non-cooperative sensor suite needs to be affordable enough to not preclude installation or deter use and provide a good probability of detection at ranges and azimuths that afford for appropriate avoidance maneuvers to be conducted. Though visual and acoustic-based detection systems have been proposed, the cost, complexity, and computational requirements of such systems make them less appealing as a primary non-cooperative sensor. In contrast, a pulse-Doppler radar provides for all-weather detection and computational requirements are reasonable. The preliminary metric to which a proposed non-cooperative pulse-Doppler radar should be compared is that of the human eye. The FAA's "see and avoid" requirement for flight under VFR rules has long been satisfied by the human visual field, composed of an approximately 16° arc of high-resolution vision centered within a 120° arc of peripheral vison that is useful for detecting moving objects (Hood 2013).

A proposed pulse-Doppler radar with a beamwidth of 120° would have appropriately detected all but six (99.530%) of the 1,276 simulations in the collision dataset and is comparable to the calculated normal probability density of 98.669% with x = ±60°, μ = -0.1090, and σ = 24.2381 from Exhibit 7. It can therefore be reasonably concluded that the collision dataset is approximately normal. Of the six encounters with an absolute UAS azimuth at D_{man} > 60°, the minimum and maximum absolute values were 61.262° and 67.921°, respectively. Revising the proposed radar beamwidth to 140° (±70° from center) drops the statistical probability of an intruding aircraft falling outside of the radar's beamwidth to just 0.388%.

The proposed risks associated with integrating UASs has largely been classified in absolute terms instead of relative terms that provide appropriate context within the risk already present in contemporary VFR operations. The number of near-MAC events classified as potential or critical have averaged 6.31×10^{-6} per flight hour from 2012-2020 (National Transportation Safety Board 2021). While the process of a UAS avoiding a MAC incident is composed of two steps, detection and maneuver, it is reasonable to conclude that the great majority of that risk is of failed detection,

as successful avoidance maneuvering is deterministic and verifiable in nature. In their study, Tabassum and Semke found that ADS-B message drop-out to presented a hazardous or catastrophic outcome with ≤ 120 second look-ahead time at an incidence rate of 1.7935×10^{-5} to 1.5140×10^{-6} (Tabassum & Semke, 2018). A proposed pulse-Doppler radar for detection of non-cooperative aircraft with a beamwidth of 140° would provide for a probability of failed detection of non-cooperative aircraft of 3.88×10^{-3} in a head-on scenario. It is reasonable to assume that the probability of cooperative (ADS-B) message drop-out and failure of non-cooperative detection are independent events. Therefore, the probability of a UAS equipped with a traffic avoidance system using data from both ADS-B messages and a pulse-Doppler radar for non-cooperative detection would be on the order of 10^{-8} to 10^{-9}, an improvement on the historical VFR near-MAC incident rate by two to three orders of magnitude.

5.4 Validation

Studies and simulations are critical in convincing regulators to allow for progressively permissive regulations. The development and testing of experimental mechanisms to safely integrate UASs among manned aircraft is surely a laborious and profit-scarce journey. Should regulators be convinced of their safety, however, countless market opportunities exist for a variety of technical companies who exhibit prowess in the little-explored market of large commercial UAS platforms and payloads. Business leaders need to be convinced of the largely untapped burgeoning market surrounding large commercial UASs and numerous technical challenges, as discussed in part in this paper, surely serve to occupy the professional lives of numerous engineers from many disciplines. Engineering mangers are distinctively positioned to bridge the gap between government regulators, company executives, and engineering-intensive research and development teams required to bring the large commercial UAS into safe, ubiquitous operation. Their reach into both the realm of technical and organizational uniquely situates the engineering manager to serve as a necessary catalyst for many future technological and pecuniary achievements.

6. Conclusion

As the backbone of the FAA's NextGen program, ADS-B provides a promising primary means of near-real time telemetry data for use in autonomous DAA systems in UASs. However, an avoidance system solely reliant on ADS-B data presents an unacceptably high frequency of incident due to failed or untimely message delivery. To mitigate this risk and bring the probability of incident under the historical VFR near-MAC incident rate, a pulse-Doppler radar is proposed with a beamwidth of 140° degrees for the detection of non-cooperative aircraft. This proposed dual-source DAA system would safely allow for the integration of UASs into dynamic controlled airspace under VFR with an estimated probability of incident well below historical rates.

It is important to highlight the criticality of a rigorous certification process for any UAS collision avoidance systems, analogous to current avionics certification processes. Where in a manned aircraft when all mechanical and electrical systems fail the pilot presents a final level of safety, a UAS is wholly dependent on constant successful operation of its avoidance systems and sensors to avoid other aircraft and not cause undue risk to persons or property. Redundancy is therefore vital in a UAS to ensure that any singular system or sensor failure does not cripple its ability to sense and avoid. As a last resort, standardized procedural deconfliction measures, such as having the UAS fly to a predetermined safe location and loiter indefinitely upon critical system failure, would further reduce risk.

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