Abstract

The two predominately challenging issues facing the development of standards for Unmanned Aircraft Systems (UAS) integration into the National Air Space (NAS) are collision avoidance and UAS command and control link integrity. This paper discusses an approach for addressing the collision avoidance issues affecting UAS and shows how advances in this area can contribute to the advancement of the Next Generation Air Transportation System (NextGen).

The approach focuses on the formation of a robust surveillance picture that maximizes the utilization of new NextGen technologies to identify and track UAS flight profile conformance and to provide that fused UAS track to all the various systems and organizations/agencies that require/desire it including FAA ATC facilities. Additionally, this will provide the UAS Operator actual tracks of all other aircraft (cooperative and non-cooperative) similar to Traffic Information service – Broadcast (TIS-B) service within the same geographic area.

This paper presents the results of a surveillance analysis based on sensors of opportunity in the NAS, and sensors anticipated to be available onboard the UAS. Given the available surveillance picture and expected traffic patterns, we show how the proposed application contributes to the safety assessment for a proposed concept of operations. Through more thorough applications of the proposed approach we hope to accelerate safe integration of UAS into the US airspace and support the development and deployment of trajectory based operations in the NAS.

Background

UAS will be playing a prominent role in accelerating the American aviation economic engine in the not-too-distant future. This fact presents a number of challenges to the various agencies within the government who, together, are responsible for American aviation safety and security in all its various elements. The Department of Defense (DOD) is responsible for defending our country on a worldwide scale; the Department of Homeland Security (DHS) is responsible for the security of the Homeland; and of course, the Federal Aviation Administration (FAA) is responsible for the safety of the aircraft operating in the National Airspace System (NAS). A key question that must be answered is: How can a UAS operate safely and securely within the NAS?

Coincidentally, at this time, planning and research is underway for developing the Next Generation (NextGen) Air Transportation System. Significant progress has been made in defining future concepts of operations, which includes elements such as Position, Navigation, and Timing (PNT) Services, and Trajectory Based Operations (TBO). NextGen needs to include provision for safe and secure UAS operation in the NAS. This point was highlighted in the May 2008 General Accounting Office (GAO) UAS Report to Congress. The report stated that “UAS development could lead to technological advances that could benefit all national airspace system (NAS) users.” The GAO Report also noted that one of current problems with determining impact of UAS operations on the NAS is that “the impact of routine access remains generally speculative” and that “the impact will depend on a number of factors that, today, are unpredictable due to a lack of data. [6]. This paper proposes a method to address the lack of data.
Currently, UAS-in-the-NAS operational safety concerns are dealt with through procedural methods such as limiting operations to restricted airspace, and other types of special use airspace or by establishing temporary flight restrictions within the NAS. In order to optimize the full potential of UAS and to enable greater optimization of the NAS, these types of restrictions need to be overcome. The DOD’s desire to more fully integrate UAS into the NAS offers an opportunity to advance the US’s aviation leadership for it not only advances the utility of UAS, but provides an opportunity to demonstrate more general NextGen capabilities. Given the potential of UAS, mechanisms are being actively sought by which to safely operate. The same concepts being considered for TBO for manned aircraft may be applicable to the dynamic allocation of airspace for UAS.

The economic and security potential of Unmanned Aircraft Systems (UAS) will not be fully realized until standards and procedures are put in place to allow for their safe operations in non-segregated airspace. The standards development process requires the analysis and specification of complex issues including multiple disciplines such as systems, algorithms, human factors, safety and extensive evaluation and testing. The current Federal Aviation Administration (FAA) roadmap shows the development and approval of a comprehensive set of standards being completed around 2017. Add the time required for manufactures and potential users to meet the standards and widespread access to the National Air Space (NAS) is not likely until after 2020. The two predominately challenging issues facing the development of these standards are the needs to provide Collision Avoidance and UAS Command & Control Link Integrity. This paper focuses on the collision avoidance.

The Collision Avoidance solution is best thought of as a layered approach consisting of airspace design, separation services, automation aided collision avoidance systems and when all else fails, the pilots’ ability to “See and Avoid”. The last two levels consists of two parts, the ability of the UAS or pilot to sense all potentially intruding aircraft, including balloons and gliders, and the ability of the system to correctly decide upon an appropriate avoidance maneuver.

For unmanned systems, the current collision avoidance environment can be summarized by the following:

- Proven technology exists to sense intruding aircraft; however, there is a trade between practical UAS implementation and reliability of the system. Where practicality is defined as cost and size, weight and power requirements.
- The sensing of cooperative aircraft is aided by transponders broadcasting a position or coded transmission that can be located with relatively small, lightweight on-board systems.
- Small non-cooperative aircraft are more difficult to detect requiring Radar or Electro-Optical systems that are currently either too large and heavy for small UAS, or do not provide adequate range and reliability to support safe separation in all conditions.
- The Joint DOD-FAA Track 1 program is working towards the collection of data to support safety analysis. A demonstration planned for October 2008 by the Army should provide a body of data to support the analysis of ground based radar potential to support collision avoidance.
- Currently there are no approved, automated avoidance algorithms for UAS comparable to Traffic Collision Avoidance Systems (TCAS) found in commercial aviation.

The MITRE Corporation and Lincoln Laboratory have described the safety analysis process for analyzing UAS collision avoidance performance. [4] Their paper describes following five steps:

1. Develop a Concept of Operations (CONOPS) which includes the expected UAS flight characteristics, surrounding air traffic, the surveillance environment, and air traffic control procedures.
2. Develop an encounter model that includes the geometries and expected frequencies of the occurrence;
3. Develop a fault tree analysis of the end-to-end collision avoidance process;
4. Compute Collision Risk; and
5. Conduct Special Analysis as necessary.

In this paper, we first summarize the reliability of available collision avoidance mechanisms. Then we define a CONOPS that includes the fusion of ground based sensors and ground based alerting that may be used in conjunction with an on-board autonomous CAS. Finally, we propose a fault tree for the system to guide further safety analysis.

**Reliability of Collision Avoidance**

Under USAF sponsorship, Northup Grumman proposed a fault tree to assess the reliability of a CAS to prevent a Near Mid-Air Collision (NMAC) or a Mid-Air Collision (MAC). [5] as shown in figure 1. In the referenced study reliability is approximated as the product of the sensor availability and the sensor coverage. The model proposed by Northrup Grumman, AND's the probability that the aircraft is on a collision course with the probability that the collision avoidance system will fail ($p_F$) to detect, sense and avoid the intruder. The $p_F$ is further decomposed into the probability of a critical processing or data bus failure OR'd with the probability that the system fails to see or detect the intruder. The research defined “Failure to See” as the ability of an onboard sensor to see, and “Failure to Detect” would cover failure of any external systems or stand alone system such as Traffic alert and Collision Avoidance System (TCAS).

Figure 1 – MAC/NMAC Fault Tree

In this version of the model, a ground based system could contribute to the reliability of the overall system by either providing the “see” capability or the “detect” capability. The “see” capability could provide tracks from a ground based surveillance fusion system into the on-board CAS, whereas the “detect: capability provides collision warnings or evasive maneuver recommendations.. In either of these cases, the fault tree model must include the reliability of ground bases system to 1) detect the intruder, 2) generate an alert or warning, and 3) provide a reliable up-link to the aircraft. The detail of the “Fail to Detect” sub-tree is shown in Figure 2.

Figure 2 – “Failure to Detect” Sub-Tree

A similar model can be generated for the likelihood of a MAC or NMAC in a system that includes both an airborne detect, sense, and avoid (DSA) system and a ground based CAS system alerting the Pilot-in-Control (PIC). The base fault tree (Figure 1) then includes an OR of the Ground-Based CAS and the Airborne CAS as shown in figure 3.

Figure 3 – Dual CAS Systems Fault Tree

We define the fault tree for the Ground Based CAS as including three variables, 1) the failure of cooperative surveillance, 2) the failure of non-cooperative surveillance, and 3) the failure of processing, communications, or data bus, as shown in Figure 4 The surveillance reliability analysis must
include four combinations - both sensor types detecting the aircraft, cooperative detection only, non-cooperative detection only, and neither detecting the intruder. The coverage analysis is discussed later in the paper in the contest of a specific CONOPS.

The automated algorithms for UAS are more complicated then those for the more homogeneous civil aircraft as it must take into account the wide range of aircraft performance such as rate-of-turn, and climb-rate. Currently, Operator pilot-in-the-loop decision making is acceptable, though communication delays of up to 1.5 seconds must be accounted for in the response cycle which requires longer detection ranges on the sensor.

Figure 4 – Ground Based CAS Fault Sub-Tree

Concept Description

By utilizing available technologies and sensor fusion capabilities it is possible to enhance UAS track/flight conformance monitoring by the FAA and enhance UAS Operator pilot situational awareness (by giving the Operator a fused air traffic picture), which will contribute to supporting UAS Detect, Sense and Avoid operational requirements within the National Airspace System (NAS).

The concept is to maximize the utilization of new NextGen technologies like Automatic Dependant Surveillance–Broadcast (ADS-B), Wide Area Multilateration (WAM), TIS-B and sensor fusion to identify and track UAS flight profile conformance. This will make use of an associated Required Navigation Performance (RNP)/Area Navigation (RNAV) route and provide that fused UAS track to all the various systems and organizations/agencies that require/desire it including FAA ATC facilities. Additionally, the concept is to provide the UAS Operator actual tracks of all other adjacent aircraft (cooperative and non-cooperative) similar to TIS-B within the same geographic area.

Current Certificate of Authorization (COA) requirements for UAS operations require “Sense and Avoid” capability to ensure separation from other aircraft. Compliance with this requirement is very logistically difficult and/or expensive to perform with today’s currently employed techniques.

Having the UAS operate on a specific flight plan and comply with a Required Navigation Performance (RNP) track would assist with meeting COA requirements. Conformance to that track can be constantly monitored by both the UAS Operator and ATC and if necessary appropriate corrections can be applied to stay within the conformance parameters.

Other aircraft traffic in the area (within proximity of the UAS track) would be provided to the UAS Operator in the Ground Control Station (GCS) via a designed Traffic Information Service (TIS) feed.

A multi-sensor fusion processor would be used to integrate target data from multiple sensors. The Multi-Sensor Tracker (MST) would filter and fuse the data from the sensor sources to provide a unified, timely, and accurate "best source" surveillance picture. Sensor sources could include ATC and Military Ground Based Sensors, Cooperative Surveillance Data (ADS-B & Multilateration), and Aircraft Sense and Avoid (SAA) Systems (radar, IR, laser and optical).

False collision warnings may result in unnecessary aircraft maneuvers, thereby potentially inducing a hazard. The fusion of multiple sensors can be used to not only increases the probability of detection, but also reduce the probability of false alarm.

The UAS Operator, like the air traffic controllers in the various ATC facilities, would then be able to “see” all of the IFR and VFR traffic which would significantly enhance common situational awareness. Additionally, this TIS, if required or desired, could be provided to a FAA Air Traffic Control (ATC) facility.

If UAS’ are ADS-B equipped, then all ADS-B [UAT] equipped aircraft would get the position of the UAS from either the FAA’s TIS-B system if it is in
the area of operation or via ADS-B air-to-air transmission.

**Ground Based CAS Model**

A prototype system for generating runway incursion alerts is used to illustrate the potential for a ground based CAS. The system is based on Sensis Corporation’s ASDE-X, which currently provides warnings of potential or actual runway incursion risks, but current commissioned systems provide alerts only to the air traffic controllers.

In 2007, Honeywell Aerospace and Sensis demonstrated a prototype system that couples - via Mode S datalink – the runway incursion warnings created by ASDE-X directly to the TCAS onboard the aircraft [1]. The associated air-side concept is shown in Figure 5. In the partnership’s prototype implementation, previously unused bits in the TCAS Mode S data field are translated by a slightly modified TCAS to yield an audible alert in the cockpits of the aircraft involved in a simulated conflict (e.g., “Runway Occupied” or “Converging Traffic”). The ground tracking and detection system (ASDE-X in the demonstration system) continues to also notify the ATC controller just as is done now. Thus, the cockpits of both potentially involved aircraft as well as the ATC controller are near simultaneously notified of the incursion gaining key seconds that can be used to resolve the pending crisis. Figures 6 illustrates a similar alert generation and communication architecture for a UAS based system.

ASDE-X safety logic predicts that, based upon the relative position of the two aircraft and their velocity and acceleration dynamics, the two aircraft will violate minimum safe separation standards within 20-30 seconds. Today’s implementations notify only the ATC controller who must then interpret what is happening and formulate and communicate a resolution action to the two aircraft where in turn the pilots interpret and take action. A significant portion of that transaction sequence timing - approximately 10 or more seconds - can be eliminated if the pilots are notified at the same time as the controller.
Syracuse Air National Guard CONOPS

The USAF has decided to locate one of its Predator/Reaper Squadrons with an Air National Guard (ANG) unit at Hancock International Airport in Syracuse, NY. This will occur in the next few years after a tactical USAF F-16 squadron currently located at Hancock is decommissioned. The transition is planned to occur in the 2009 – 2010 time period. Currently, the ANG flies out of the commercial Hancock Airport in Syracuse, NY. This location is appealing for research to advance the integration of UAS into the NAS because of the relatively light air traffic and the existing mix of military/civilian air traffic. Figure 7 shows the ambient likelihood of collision as determined by Weibel et al. The figure shows low likelihoods of collisions similar to those of other regions currently hosting UAS research operations such as New Mexico and North Dakota. [2]

![Figure 7 - Average Expected Level of Safety (collisions/hr)](image)

Proposed Region for Reaper Operations Airspace

The Syracuse ANG desires to operate in the same airspace that they currently conduct F-16 operations. It includes roughly 100 square miles that contain the Falcon and Syracuse MOA’s in addition to the restricted airspace at Ft. Drum. While the ANG would like the capability to also fly to the Misty MOAs located over Lake Ontario and to the former Griffiss Air Force Base in Rome, NY, its prime focus is to fly from Syracuse Hancock Airport to the Ft Drum restricted airspace for training.

To frame the analysis of the concept just outlined, Sensis proposed a CONOPS for flight of a UAS in this airspace for the Syracuse ANG.

An analysis of the airspace from historical ETMS data revealed two fairly distinct regions roughly distinguished by ATC Sectors ZBW09 and ZBW08 as shown in Figure 8. ZBW09 is a heavily travelled sector facilitating traffic from Boston Center to Cleveland Center. On average there are approximately 300 flights per day and an observed worst case peak of 40 flights per hour. Within this sector is also the Syracuse Class C airspace. Within this region, aircraft are required to report to ATC and operate transponders. The northern region, centered on ZBW08 handles only 30 flights per day with a worse case peak of 6 flights per hour.
Performance predictions are made using Radar surveillance in Upstate NY

- **Rensenn (Utica)**: LRR, ARSR-4 / ATCBI-5
- **Dansville, NY**: LRR, ARSR-1E / ATCBI-5
- **Rome, NY**: SRR, ASR-8 / ATCBI-4
- **Fort Drum**: SRR, ASR-11 / MSSR
- **Hancock (Syr)**: SRR, ASR-9 / MODES

**Surveillance Assessment**

**Simulation Approach**

Sensis conducted an internal assessment of the potential for ground fusion to provide the accuracies to support the proposed concept. The following analysis was performed in the context of the future Reaper deployment to the Syracuse ANG.

- Simulation of Cooperative Sensor Performance based on Multistatic Dependent Surveillance (MDS). The performance of ADS-B based surveillance will be a function of the GPS performance, but should be similar to the MDS based accuracy performance. This study simulated an MDS deployment of ten receivers covering the region of interest, a typical configuration for the terrain and coverage requirements.
- Simulation of Non-Cooperative Sensors Performance using existing primary radar systems covering the region. Secondary or beacon performance of these systems were not included in this evaluation. For the purpose of this initial analysis it was assumed that the FAA radars are maintained to meet the performance metrics shown in Table 1. Minimum detectible Radar Cross Sections (RCS) over coverage area radars were assumed to be $1 \text{ m}^2$ for terminal radars, and $2.2 \text{ m}^2$ en-route radars.
- Selection of co-operative trajectories through Upstate NY airspace from Syracuse to both Watertown, NY, and Rome, NY, at the following cruising altitudes: 500, 2000, 6000, and 10,000 feet MSL. Constant cruising altitudes were used between the Syracuse, Rome, and Watertown navigation aids.

Table 1 – Assumed Radar Sensor Performance
Simulation Results

The results of the simulation indicate that cooperative systems have the potential to provide good coverage at low flight levels and highly accurate position estimates to feed the CAS. Figure 9 shows projected coverage over the region of interest. The currently available radars in the region provide good single sensor coverage, but limited multi-sensor coverage in support of the fusion process.

<table>
<thead>
<tr>
<th>Flight Path</th>
<th>Target Speed</th>
<th>Sensor</th>
<th>Position Error (nmi)</th>
<th>Heading Error (deg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>90 degree turn (Peak RMS)</td>
<td>400 knots</td>
<td>Fused Radar</td>
<td>0.4</td>
<td>40</td>
</tr>
<tr>
<td></td>
<td></td>
<td>MLAT</td>
<td>0.03</td>
<td>10</td>
</tr>
<tr>
<td>Linear Acceleration (Peak RMS)</td>
<td>250-650-250 knots</td>
<td>Fused Radar</td>
<td>0.35</td>
<td>13</td>
</tr>
<tr>
<td></td>
<td></td>
<td>MLAT</td>
<td>0.08</td>
<td>Not Measured</td>
</tr>
<tr>
<td>Steady-State (Mean)</td>
<td>400 knots</td>
<td>Fused Radar</td>
<td>0.1</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>100 knots</td>
<td></td>
<td>0.03</td>
<td>8</td>
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<td></td>
<td>200 knots</td>
<td></td>
<td>0.03</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>400 knots</td>
<td>MLAT</td>
<td>0.03</td>
<td>4</td>
</tr>
</tbody>
</table>

Table 2 – Surveillance of Fused Radar and MLAT

Table 2 shows predicted performance of an MDS based and a radar based air fusion tracker. The results for the MDS and Radar Fusion are presented separately. The results provided for the MDS system also represent the performance in the MDS/Radar fused system because the measured performance of the MDS system dominated the overall fusion performance over the region of interest.¹

Multi-sensor coverage is essential to achieving the highly accurate and reliable surveillance performance in a fusion system. The region that experienced the best performance was the region with five overlapping sensors as indicated in Figure 10. Unfortunately, five-sensor coverage does not currently occur over any significant area until about 10,000 ft due to terrain masking at the lower altitudes. Radar fusion performance in the five sensor region is provided in Table 2.

Though the cooperative surveillance system appears to be able to support a highly reliable CAS, the available non-cooperative sensors in the region would support the detection and tracking of all aircraft in the region, namely non-cooperative, small radar cross section airplanes, ballons and gliders.

¹Footnote 1 [The coverage and performance predicted by the MDS systems is feasible because of the relatively lower cost per sensor and more scalable nature of MDS versus non-cooperative sensors]

The availability of a low-cost gap filling radar, or other modes such as electro-optic, should be investigated to improve the non-cooperative surveillance in the region. Another approach that could be investigated for non-cooperative surveillance is the fusing of airborne sensors with ground sensors. This approach would also need to analyze the reliability and availability of the communications links that would pass surveillance up to the aircraft or down to the ground.

Figure 9 – Cooperative Coverage
Summary

In this paper we have begun to address the reliability of a ground based collision avoidance system in support of UAS operations. The reliability of such a system is driven by the reliability of both cooperative and non-cooperative surveillance sensors to detect all aircraft operating in the region, and the associated reliability of the processing and communications systems.

The analysis has identified gaps in non-cooperative surveillance in support of the ANG CONOPS. The impact on overall system performance and operational safety will be dependent upon 1) additional analysis of the airspace, specifically the extent of non-cooperative traffic; and 2) the types and performance of non-cooperative sensors that can be used to augment the existing civil radar systems.

Further research and analysis is required before a compete safety assessment can be performed for the discussed CONOPS. Specific next steps should include:

1. Quantify the non-cooperative traffic in the region. The use of additional non-cooperative sensors that can provide coverage down to 500 ft and provide high probability of detection of small targets can be used to measure airspace use.

2. Refine the proposed CONOPs to include additional surveillance, human factors, and detailed operating procedures, including those for emergency conditions.

3. Define and prototype a ground based safety alert systems such as that described, and describe details of the communication methods for ensuring alerts and reducing false alarms.

4. Perform an analysis of the impact of expected false alarms (false MAC/NMAC Warnings), and assess the impact on ATC and operations.

5. Calculate an overall system reliability using a fault tree analysis based on the systems envisioned for the proposed CONOP.

6. In support of NextGen concepts and to support the recommendations of the GAO to obtain more data, assess the performance of the proposed surveillance systems against current FAA objectives and requirements for TBO.
References


Conference Identification

27th Digital Avionics Systems Conference
October 26-30, 2008