A6 Surveillance Criticality

Literature Review

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PROJECT A6: SURVEILLANCE CRITICALITY

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1 Scope

1.1 SCOPE

The Literature Review for the ASSURE A6 Surveillance Criticality Project validates the need for research while also providing context for the scenarios and ConOps assumptions that will be used to generate the evaluation system performance results. The Literature Review includes product descriptions for surveillance equipment and solutions, published standards, TSOs, and AC's for transponders, ADS-B, and TCAS II integration. Reference research for surveillance system performance and monitoring, maintenance and recertification requirements, and effectiveness of controller and pilot procedure is also included.

1.2 PURPOSE

The Literature Review for this project has three primary objectives:

1) Review background, prior research related to UAS Detect and Avoid System performance analysis, air traffic surveillance system performance, UAS DAA requirements, standards, and operating scenarios, and pilot performance using air traffic surveillance systems.
2) Provide the context for designing the performance assessment system to evaluate design assurance of select surveillance technology solutions.
3) Identify stakeholders and participants for research workshops and potential users for results from this project research.

1.3 APPLICABILITY

This Literature Review is focused on research related to the Alliance for System Safety of UAS through Research Excellence (ASSURE) team consisting of North Carolina State University, The Ohio State University, Embry-Riddle Aeronautical University, University of North Dakota, Oregon State University, and Mississippi State University for the A6 Surveillance Criticality Research Project.

The Literature Review is shared with the university research team, the FAA, and industry partners for research context and reference. The Literature Review is a "living document" that will expand throughout the A6 Project Period of Performance as new reference materials and research is discovered and included in system design and development.

2 Definitions and Acronyms

AC	Advisory Circular
ADS-B	Automatic Dependent Surveillance-Broadcast
ASSURE	Alliance for System Safety of UAS through Research Excellence
ATC	Air Traffic Control
AUVSI	Association of Unmanned Vehicle Systems International
C2	Command and Control
CFR	Code of Federal Regulations
CoE	Center of Excellence
DAA	Detect and Avoid
ERAU	Embry Riddle Aeronautical University
FAAO	FAA Order
FHA	Functional Hazards Analysis
FMECA	Failure Modes, Effects and Criticality Analysis
GNC	Guidance, Navigation, and Control
KSN	Knowledge Services Network
LD-CAP	Limited Deployment- Cooperative Airspace Project
MSU	Mississippi State University
MOPS	Minimum Operational Performance Standards
NASA	National Aeronautics and Space Administration
NCSU	North Carolina State University
NPRM	Notice of Proposed Rule Making
OHSt	The Ohio State University
ORSt	Oregon State University
RA	Resolution Advisory
RTCA	Radio Technical Commission for Aeronautics
SAA	Sense and Avoid
SC	Special Committee
SOW	Statement(s) of Work
sUAS	Small Unmanned Aircraft System
TA	Traffic Alert

DEFINITIONS AND ACRONYMS

TCAS	Traffic Collision Avoidance System
TIM	Technical Interchange Meeting
UAS	Unmanned Aircraft System
UND	University of North Dakota
UTM	UAS Traffic Management

3 Overview

The Literature Review is divided into four primary sections. Each of these sections focuses on a different segment of the background research for this project. The four sections are:

1- Detect and Avoid Research and Standards: DAA literature including flight testing, algorithm development, published standards, and system performance analysis.
2- ADS-B: Literature specifically about ADS-B technology development, performance, and characterizations.
3- TCAS: Literature specifically about TCAS technology development, performance, and characterizations.
4- Miscellaneous: covering topics such as the research into "well-clear" definitions, airspace integration research, UAS component system performance and analysis, and other areas of interest that were explored during the literature background review.

The format for the Literature Review is to present an introduction into each research topic, then list the specific literature reference that was reviewed, followed by a brief description of its relevance or potential applicability to this project. Additional comments from the research team are included with reference that provide additional value.

4 Detect and Avoid (DAA)

Overview of DAA performance research, algorithm development, and standards.

4.1 ALGORITHM DEVELOPMENT

1. **Kochenderfer, M. J., J. P. Chryssanthacopoulos, L. P. Kaelbling, and T. Lozano-Perez. "Model-Based Optimization of Airborne Collision Avoidance Logic." (2010): 1-129. Web. 20 Mar. 2016.**

   A project report illustrates the development of a particular conflict resolution Algorithm and establishes connection with existing model-based optimization.

2. **Munoz, Cesar, Anthony Narkawicz, and James Chamberlain. "A TCAS-II Resolution Advisory Detection Algorithm." AIAA Guidance, Navigation, and Control (GNC) Conference (2013): 1-12. Web. 20 Mar. 2016.**

   The paper represents the development of mathematical model of TCAS II Resolution Advisory (RA) logic and the design of RA detection algorithm. The algorithm can also be used for TA resolution as TCAS II logic for traffic advisories and the logic for resolution advisories mainly differ in the values of the time and distance threshold parameters and the use of a horizontal miss distance filter. This RA detection algorithm proposed in this paper is a fundamental component of a NASA sense and avoid concept for the integration of Unmanned Aircraft Systems in civil airspace.

4.2 EVALUATION STANDARDS

1. ***Airborne Collision Avoidance System (ACAS) Manual*. 1st ed. Montréal: International Civil Aviation Organization, 2006. International Civil Aviation Organization, 2006. Web. 10 Apr. 2016.**

   This manual was developed by the Surveillance and Conflict Resolution Systems Panel. The guide provides a detailed description of ACAS and associated technical and operational issues to facilitate proper operation and monitoring.

2. **Air Traffic Organization, "Safety Management System", 2014**

This document provides a wide range of information on hazard identification techniques and safety level descriptions. It gives a base of set of processes that allow for a disciplined approach to failure mode evaluations such as the task of A6. Additionally, it provides a set of definitions of criticalities and begins to define likelihoods of specific events. This wealth of knowledge will serve as a general base that can be molded and adjusted appropriately for the case of TCAS and ADS-B failure analysis. It was especially important to find prior work from a reputable source that could spell out this framework and provide direction, as well as help identify a repeatable process for extension to future, similar, research.

3. **SC-186. "RTCA DO-260B: Minimum Operational Performance Standards (MOPS) for 1090 MHz Extended Squitter Automatic Dependent Surveillance – Broadcast (ADS-B) and Traffic Information Services – Broadcast (TIS-B)." RTCA, Inc., 2 Dec. 2009. Web. 22 Feb. 2016.**

The MOPS for 1090 MHz Extended Squitter ADS-B and TIS-B were outlined with great detail. The document was prepared by RTCA.

4. **SC-209. "RTCA DO-181E: Minimum Operational Performance Standards for Air Traffic Control Radar Beacon System / Mode Select (ATCRBS / Mode S) Airborne Equipment." RTCA, Inc., 17 Mar. 2011. Web. 22 Feb. 2016.**

The MOPS for ATCRBS and Mode S equipment were outlined in this document. The document was prepared by RTCA.

5. **SC-228. "Detect and Avoid (DAA) Minimum Operational Performance Standards (MOPS) for Verification and Validation." RTCA, Inc., 24 Nov. 2015. Web. 15 Feb. 2016.**

This is a draft which establishes Minimum Operational Performance Standards for verification and validation of UAS DAA equipment in the specified Operational Environment. The document was prepared by RTCA.

Includes Appendix A: Detect and Avoid Operational Services and Environment Description (OSED).

6. **SAE Aerospace Recommended Practice 4754a, 2010**

A set of guidelines for performing failure based analysis as well as design criteria assurance levels. Includes examples of development processes and failure tree construction as well as their classification and risk assignment.

4.3 PAST DAA ANALYSIS

1. **Billingsley, Thomas B. "Safety Analysis of TCAS on Global Hawk Using Airspace Encounter Models." Massachusetts Institute of Technology, 26 May 2006. Web. 21 Mar. 2016.**

TCAS collision avoidance effectiveness was evaluated on the U.S Air Force's RQ-4 Global Hawk using a fast-time simulation tool at MIT Lincoln laboratory. The risk ratio was determined comparing Global Hawks with and without TCAS. Encounter models reflecting the Global hawk's actual performance were also developed.

2. **Galati, G., M. Leonardi, I.a. Mantilla-Gaviria, and M. Tosti. "Lower Bounds of Accuracy for Enhanced Mode-S Distributed Sensor Networks." *IET Radar, Sonar & Navigation IET Radar Sonar Navig.* 6.3 (2012): 190-201. Web. 02 Apr. 2016.**

A study was done to analyze the accuracy of passive location systems using the Cramer-Rao lower bound (CRLB). The focus was on sensor networks derived from Multilateration systems. The CRLB was used to define basic limitations and advantages of different architectures, as well as optimizing certain architectures by adding new measurement capabilities.

3. **Haissig, Christine, and Eric Euteneuer. "ADS-B Position Validation Criteria Using TCAS or Radar for UAS Detect and Avoid." N.p., n.d. Web. 01 Mar. 2016.**

This paper justified the proposed position validation criteria to enable the use of ADS-B position data for UAS Detect and Avoid (DAA). Position validation can be done with active TCAS data or with DAA on-board radar.

DETECT AND AVOID (DAA)

4. **Kochenderfer, Mykel J., Jessica E. Holland, and James P. Chryssanthacopoulos. "Next-Generation Airborne Aircraft Collision Avoidance System."** ***Lincoln Laboratory Journal*** **19.1 (2012): 17-33. Print.**

   The Traffic Alert and Collision Avoidance System (TCAS) is mandated worldwide in all large aircraft. Major changes to the airspace are planned over the coming years. Lincoln Laboratories has been developing a new approach to collision avoidance which is outlined in this paper.

5. **Kuchar, James K., and Ann C. Drumm. "The Traffic Alert and Collision Avoidance System." Lincoln Laboratory Journal 16 (2007): 277-96. Web. 7 Mar. 2016.**

   This paper deals with RA reversal problems with an example of accident. It also discusses possible solutions and future corrections for the RA reversal issue.

6. **Kuchar, James K. "Update on the Analysis of ACAS Performance on Global Hawk."** ***Aeronautical Surveillance Panel*** **(2006): 1-9. Web.**

   UAV airspace encounter models have been developed, along with fast-time Monte Carlos simulations during the encounters. ACAS performance was examined comparing conventional aircraft vs. conventional aircraft, conventional aircraft vs. non-ACAS Global Hawks, and conventional aircraft vs. ACAS-equipped Global Hawks.

7. **S. Hottman; K. Hansen; D. Bawcom; J. Mcdonald; D. Bawcom; M. Berry; L. Kirk; G. Frushour. "Literature Review on Detect, Sense, and Avoid Technology for Unmanned Aircraft Systems." (2009): 1-88. FAA. Web. 2 Mar. 2016.**

   This review paper elaborates different types of detect, sense and avoidance technologies over past years, discusses the present situations and recommendations for future developments.

DETECT AND AVOID (DAA)

8. **Strohmeier, Martin, Matthias Schafer, Vincent Lenders, and Ivan Martinovic. "Realities and Challenges of Nextgen Air Traffic Management: The Case of ADS-B."** ***IEEE Communications Magazine*** **52.5 (2014): 111-18. Web.**

   Important issues regarding ADS-B are discussed. Researchers used the OpenSky sensor network to analyze the current state and behavior under increased traffic load. Security challenges with ADS-B are also visited, with recommendations for the future.

9. **Temizer, S., M. J. Kochenderfer, L. P. Kaelbling, T. Lozano-Perez, and J. K. Kuchar. "Unmanned Aircraft Collision Avoidance Using Partially Observable Markov Decision Processes." Lincoln Laboratory. Massachusetts Institute of Technology, 22 Sept. 2009. Web. 21 Mar. 2016.**

   This paper investigated the use of an automatic collision avoidance logic given information such as: aircraft dynamics, sensor performance, and intruder behavior. Developing this logic will prevent custom making every collision avoidance algorithm by hand for every aircraft and sensor combination. Using a partially-observable Markov decision process (POMDP), a generic POMDP solver can be used to create a generic avoidance strategy.

10. **Zeitlin, Andrew D., and Michael P. McLaughlin. "Modeling for UAS Collision Avoidance." (n.d.): 1-13. MITRE Corporation. Web. 22 Mar. 2016.**

    Several methods and tools are discussed for modeling and evaluating the safety of collision for manned aircraft. The problem with applying these methodologies to unmanned aircraft is also discussed.

11. **Wehner, Paul J., Jonathan Schwartz, Deihim Hashemi, Charles Howell III, Harry Verstynen, Cathy Buttrill, Mark Askelson, and William Semke. "Evaluating Prototype Sense and Avoid Alternatives in Simulation and Flight." AUVSI Unmanned Systems 2013, Aug 2013.**

    Review of the integrated MITRE-NASA LaRC test capability by a joint team of investigators from UND, NASA LaRC, and MITRE to evaluate the technical and operational feasibility of using ADS-B technology as a cooperative surveillance source for on-board, automatic SAA alternatives. Provides data results and lessons learned from the LD-CAP project for integration into test scenarios and system characterization in the A6 research.

5 Automatic Dependent Surveillance-Broadcast (ADS-B)

These publications on ADS-B were reviewed as part of the Literature Review for the A6 background research.

1. **Cook, E., "ADS-B, Friend or Foe: ADS-B Message Authentication for NextGen Aircraft," in *High Performance Computing and Communications (HPCC), 2015 IEEE 7th International Symposium on Cyberspace Safety and Security (CSS), 2015 IEEE 12th International Conference on Embedded Software and Systems (ICESS), 2015 IEEE 17th International Conference on* , vol., no., pp.1256-1261, 24-26 Aug. 2015.**

   This paper outlines the lack of security measures in place within current ADS-B devices to provide authenticity and integrity as well as presents a method for ADS-B message authentication. A public key infrastructure to verify all ADS-B signals from FAA registered aircraft that uses an asymmetric cryptography to exchange a session key to validate data authenticity is suggested as a means of securing ADS-B devices in the NAS.

   The evaluation of the current security issues that makes ADS-B open to spoofing as well as a possible methodology to provide integrity and authenticity to ADS-B messages provides insight into possible failure modes of ADS-B in terms of external spoofing.

2. **Costin, Andrei, and Aurélien Francillon. "Ghost in the Air (Traffic): On insecurity of ADS-B protocol and practical attacks on ADS-B devices."*Black Hat USA* (2012).**

   This paper analyzes the security of ADS-B in regards to both passive (eavesdropping) and active (message jamming) attacks on the system. By using a commercial off the shelf software defined radio (SDR) to transmit attacker controlled messages to an ADS-B receiver Costin, Andrei, and Francillon were able show various types and severities of ADS-B attacks. This study outlines some of the fundamental architecture and design problems of ADS-B that have not been addressed in prior security experiments in an attempt to raise awareness to the liability of current ADS-B systems.

   The results of this paper on ADS-B insecurity provides viable research into the possibilities of ADS-B attacks as well as outlines some of the security concerns and design flaws within the architecture of ADS-B. These flaws could provide useful to input into the simulations to provoke system failures.

3. **Jeon, D.; Yeonju Eun; Hyounkyoung Kim, "Estimation fusion with radar and ADS-B for air traffic surveillance," in *Information Fusion (FUSION), 2013 16th International Conference on* , vol., no., pp.1328-1335, 9-12 July 2013.**

This article presents a practical system for the estimation fusion with radar and ADS-B for air traffic surveillance and control. Validation processes and methods are also presented for ADS-B data which are dependent on individual aircraft. The simulation results show that the current fusion system can provide a plausible solution within the ATC environment.

The fusion of multiple sensors including ADS-B and radar provides insight into the future of ATC management as well as possibilities for detect and avoid collaboration.

4. **Kovell, Brandon, et al. "Comparative analysis of ADS-B verification techniques." *The University of Colorado, Boulder* 4 (2012).**

This paper analyzes Kalman Filtering and Group Validation techniques in order to determine which provides a better verification method for ADS-B signals. In addition to the verification analysis this paper outlines some of the key vulnerabilities within ADS-B security.

Reviewing this paper provides a detailed look into ADS-B security vulnerabilities as well as two proposed solutions.

5. **Krozel, Jimmy, and Dominick Andrisani. "Independent ADS-B verification and validation." *AIAA Aviation, Technology, Integration, and Operations Conference Proceedings*. 2005.**

The paper on Independent ADS-B Verification and Validation discusses both the possibility of ADS-B being spoofed as well as the verification and validation techniques used to analyze ADS-B systems to ensure continuous uninterrupted service in the NAS. Two applications were addressed by this study, ADS-B in ground based applications (used as a multilateration system) and airborne ADS-B applications.

This paper provides additional background on some of the faults and security questions concerning ADS-B and its use in the NAS.

6. **Lester, Edward A. *Benefits and incentives for ADS-B equipage in the national airspace system*. Diss. Massachusetts Institute of Technology, 2007.**

This thesis presents research into the applications of ADS-B with the strongest benefit to possible users. In order for ADS-B equipage to be universal and voluntary in some sectors the benefits need to outweigh the cost. This research concludes that ADS-B should be implemented in non-radar airspace as well as busy terminal areas.

A student at MIT presented this thesis in 2007 before the ADS-B equipage ruling was released by the FAA. However, this research does highlight many of the benefits of ADS-B equipage by outlining survey answers from various stakeholders

7. **Li, Tianyuan; Sun, Qibo; Li, Jinglin, "A Research on the Applicability of ADS-B Data Links in Near Space Environment," in *Connected Vehicles and Expo (ICCVE), 2012 International Conference on* , vol., no., pp.1-5, 12-16 Dec. 2012.**

This paper focuses on the applicability of ADS-B data links in a near space environment. The study simulated the channel transmission performance of both 1090 MHz and UAT data links with a High Altitude Performance System (HAPS) as well as analyzed the simulation results in terms of path loss, signal to noise ratio, and bit error rate. The paper concludes that both 1090 MHz and UAT data links are applicable and that aircraft in high-altitude the performance is better than in a ground environment.

The simulations run in this study provide a framework of understanding for future simulations as well as an additional metric for ADS-B applicability.

AUTOMATIC DEPENDENT SURVEILLANCE-BROADCAST (ADS-B)

8. **Martel, Florent, et al. "Unmanned aircraft systems sense and avoid avionics utilizing ADS-B transceiver."** ***AIAA Infotech@ Aerospace Conference*****. 2009.**

   In a study done by the University of North Dakota, the results of modeling collision avoidance algorithms using ADS-B derived information within a software-in-the-loop (SWIL) environment were tested. Simulated flights were conducted in an SWIL environment with an ADS-B equipped simulated aircraft. The results found a preliminary validation of the detect and avoid algorithms for ADS-B.

   This study outlines an earlier attempt to evaluate the safety criticality of ADS-B equipage on unmanned aircraft systems. This paper indicates the need for future work with hardware-in-the-system testing within a Monte Carlo simulation. The future work of this paper is very similar to how the problem is being approached by the ASSURE A6 team.

9. **Mozdzanowska, Aleksandra, et al. "Dynamics of air transportation system transition and implications for ADS-B equipage."** ***Proceedings of the 7th American Institute of Aeronautics and Astronautics Aviation Technology, Integration, and Operations Conference, Belfast*****. 2007.**

   This paper uses a feedback model to describe the stakeholder barriers to ADS-B integration as well discusses ensuring a efficient safety approval and certification process for the implementation of ADS-B. Additionally the criticality levels and the target level of safety of ADS-B are addressed by this paper in that by increasing the desired application of ADS-B in the NAS, increased standards and criticality levels may be necessary to validate equipage.

10. **Orefice, M.; Di Vito, V.; Corraro, F.; Fasano, G.; Accardo, D., "Aircraft conflict detection based on ADS-B surveillance data," in** ***Metrology for Aerospace (MetroAeroSpace), 2014 IEEE*** **, vol., no., pp.277-282, 29-30 May 2014.**

    This paper focuses on the application of ADS-B surveillance data as inputs for conflict detection algorithms, in order to support future self-separation as well as collision avoidance systems. The architecture and the main implemented software modules of the proposed conflict detection system are outlined in the paper and it is concluded that the intended system is applicable for both manned and unmanned aircraft systems.

The work outlined in this paper provides an avenue for future testing of ADS-B IN using real world surveillance data to validate the results obtained. This is meaningful to ASSURE in that it provides a possible method to determine ADS-B design assurance.

11. Pourvoyeur, K.; Heidger, R., "Secure ADS-B usage in ATC tracking," in *Digital Communications - Enhanced Surveillance of Aircraft and Vehicles (TIWDC/ESAV), 2014 Tyrrhenian International Workshop on* , vol., no., pp.35-40, 15-16 Sept. 2014.

This paper discusses the safety of ADS-B data for ATC purposes and concludes that current security is not sufficient to rely on the accuracy information provided from ADS-B. Furthermore this paper concludes that the usage of ADS-B can be made safe and reliable if proper security mechanisms are set in place. For example, this paper specifically shows the usage of the PHOENIX multi sensor data fusion system provides increased security layers for ADS-B.

12. Powell, J. David, Chad Jennings, and Wendy Holforty. "Use of ADS-B and perspective displays to enhance airport capacity." *Digital Avionics Systems Conference, 2005. DASC 2005. The 24th*. Vol. 1. IEEE, 2005.

This study outlines research done to show the use of ADS-B to reduce the impact from wake vortex turbulence in parallel runway spacing. The reduction of wake vortex turbulence from ADS-B could decrease the necessary airport spacing and as such increase the capacity of airports without increasing the land area.

Overall this study provided a solid example on the possible use of ADS-B to increase safety in the NAS as well as provided some of the complications faced in mass implementation of ADS-B.

13. Strohmeier, Martin, et al. "Realities and challenges of NextGen air traffic management: The case of ADS-B." *Communications Magazine, IEEE* 52.5 (2014): 111-118.

This article discusses important issues with the current state of ADS-B (as of 2014) by evaluating reports from the OpenSky network in Central Europe. Using OpenSky the 1090 MHz communication channel of ADS-B is analyzed to understand the current state of its behavior under the increasing traffic loads. Additionally the article considers some of the security challenges faced by ADS-B. From looking into reports from central Europe commercial aviation, two primary concerns dealing with ADS-B were noticed. The first being the serious message loss caused by increased traffic loads on the 1090 MHz channel and the open security concerns caused by cheap and easy availability of software radios.

Overall this article was helpful in understanding some of the design flaws inherent in current ADS-B systems as well as providing a framework of analysis done on sense and avoid system currently in use throughout commercial aircraft in central Europe.*******

14. **Syd Ali, Busyairah, et al. "ADS-B System Failure Modes and Models." *The Journal of Navigation* 67.6 (2014): 995-1017. *ProQuest.* Web. 13 Apr. 2016.**

This paper outlines the high level failure modes and models of an ADS-B system. Specifically the paper identifies the failure modes associated with ADS-B out from avionics, ADS-B out from ground station, ADS-B in, human error, and environmental effects. The descriptions of each failure mode are outlined as well as their impacts on ATC operations and aircraft navigation. Finally potential mitigation for each failure mode is presented.

This study is critical for the design assurance of ADS-B systems as they pertain to UAS and will be used to develop bow-tie analysis of an ADS-B system to run through a Monte Carlo simulation.

15. **Yucong Lin; Saripalli, S., "Sense and avoid for Unmanned Aerial Vehicles using ADS-B," in *Robotics and Automation (ICRA), 2015 IEEE International Conference on* , vol., no., pp.6402-6407, 26-30 May 2015.**

This paper outlines the experimental testing and development of a path planning algorithm for UAV collision avoidance. The testing was done in a software-in-the-loop system in which the UAV was able to avoid collisions with aircraft of different numbers, speeds, and approaching directions.

The experimentation on SITL collision avoidance as well as the development of an path planning algorithm for UAV collision avoidance provides framework for future verification and validation of ADS-B systems as equipped on hardware enabled UAV's.

16. Zeitlin, D., et al. "Achieving early CDTI capability with ADS-B." *USA/Europe ATM R&D Seminar*. 1998.

The paper on the early Cockpit Display of Traffic Information (CDTI) with ADS-B is an early study on the necessary technical requirements, developmental work, and standards for ADS-B. This study is an overview of some of the initial work done by RTCA SC-186 and discusses the initial standard developed called the MASPS. In this study MITRE used a simulation test bed focused on a generic mid-fidelity transport aircraft on approach to Seattle-Tacoma International Airport.

Reviewing the earlier work done by MITRE and RTCA SC-186 gives insight into the historical attempts to classify the design assurance level of ADS-B for widespread use in manned aircraft; however, as this study does not concern unmanned aircraft and because it deals with airports it is not relevant to the current study other than gaining historical perspective.

17. Zhang Kexi; Zhang Jun; Zhang Xuejun, "Research on ADS-B geometric height information for height keeping performance surveillance," in *Advanced Computer Theory and Engineering (ICACTE), 2010 3rd International Conference on* , vol.2, no., pp.V2-328-V2-331, 20-22 Aug. 2010.

This study analyzes the feasibility of ADS-B (both UAT and 1090) geometric altitude data meeting the requirement for altitude keeping performance surveillance. In order to properly maintain altitude levels in controlled airspace the Air Traffic Controller must receive accurate altitude readings from ADS-B. This study provides analysis on the precision of ADS-B for altitude surveillance.

Analyzing the precision of altitude accuracy in ADS-B systems provides an example of a possible failure mode in detect and avoid systems as well as improves understanding of ADS-B function.

AUTOMATIC DEPENDENT SURVEILLANCE-BROADCAST (ADS-B)

6 Traffic Collision Avoidance System (TCAS)

These reports and publications provide the overview for TCAS and ACAS (airborne collision avoidance system) performance, analysis, and related research.

1. **Asmar, Dylan Mitchell. *Airborne collision avoidance in mixed equipage environments*. Diss. Massachusetts Institute of Technology, 2013.**

   This thesis looks at recent research on coordination, interoperability, and multiple threat encounters. This paper investigates different methods to extend ACAS X beyond single unequipped intruders to coordinated encounter and multiple equipped intruders.

   This research provides insight into future avoidance system equipage as well as the extended capabilities of ACAS X. Overall this paper could lend a framework for TCAS testing and simulation.

2. **Bai, Haoyu, et al. "Unmanned aircraft collision avoidance using continuous-state POMDPs." *Robotics: Science and Systems VII* 1 (2012).**

   This paper discusses the modeling of unmanned aircraft collision avoidance and generated the threat resolution logic by solving the developed models in a Monte Carlo Iteration. Simulation results showed that the continuous state models developed reduced the risk of collision by up to seventy times.

   The analysis of the paper provides an example of a Monte Carlo simulation run with TCAS architecture. This could provide a framework for future TCAS simulation.

3. **"Concept of Operations for the Next Generation Air Transportation System. Version 3.0." N.p., 2010. Web. 25 Feb. 2016.**

   This version of the ConOps provides an overall, integrated view of NextGen operations for the 2025 time-frame, including key transformations from today's operations.

TRAFFIC COLLISION AVOIDANCE SYSTEM (TCAS)

4. **De, D.; Chattoraj, N., "A review : Theoretical analysis of TCAS antenna : Traffic collision avoidance system for aircrafts," in *Green Computing Communication and Electrical Engineering (ICGCCEE), 2014 International Conference on* , vol., no., pp.1-7, 6-8 March 2014**.

   This paper describes a theoretical model of a TCAS antenna installed on an aircraft. The theoretical analysis was developed to study the overall effect on the aircraft due to the performance of TCAS antenna. This paper also contains a new proposed idea for a TCAS antenna which might be more beneficial than the existing system. By analyzing a TCAS antenna to determine the overall effect on an aircraft it provides an example of a possible failure mode on a system as well as an understanding of the structure of a TCAS platform.

5. **Gariel, M.; Kunzi, F.; Hansman, R.J., "An algorithm for conflict detection in dense traffic using ADS-B," in *Digital Avionics Systems Conference (DASC), 2011 IEEE/AIAA 30th* , vol., no., pp.4E3-1-4E3-12, 16-20 Oct. 2011.**

   This paper presented a novel algorithm for traffic situation awareness with alerts. The algorithm alerts pilots of potential incoming collision or hazardous situations. The algorithm uses a constant turn trajectory prediction. This trajectory prediction outperforms the classic constant velocity propagation.

6. **Gottstein, J.; Form, P., "ACAS-monitoring of 1 000 000 flight hours in the North German Airspace," in *Digital Communications - Enhanced Surveillance of Aircraft and Vehicles, 2008. TIWDC/ESAV 2008. Tyrrhenian International Workshop on* , vol., no., pp.1-6, 3-5 Sept. 2008.**

   This paper discusses a developed ACAS Monitor Station which receives 1030/1090 MHz Secondary Surveillance Radar and ACAS Communications. The monitoring software keeps track of the status of all Mode S-Aircraft in range and automatically compiles reports on Resolution Advisories by ACAS in the North German Airspace. This paper indicates that over twelve months of continuous recordings covered more than 1 000 000 flight hours of ACAS-Equipped Aircraft were recorded. On average one ACAS indicated collision threat was reported per day. The analysis also showed that only 6 of 7 Resolution Advisories were followed by proper escape maneuvers.

This study of ACAS flight hours in Northern Germany provides valuable real world data on the average number of threats and the percentage of pilot error in following escape maneuvers.

7. **Holland, Jessica E., Mykel J. Kochenderfer, and Wesley A. Olson. "Optimizing the next generation collision avoidance system for safe, suitable, and acceptable operational performance." *Air Traffic Control Quarterly* 36 (2014).**

   This paper summarizes a fifteen month study on iteratively tuning ACAS X in order to meet operational suitability and pilot acceptability performance metrics. The tuning process reduced the operational impact on the air traffic system and improved the acceptability of alerts. This paper demonstrates the safer logic that is more operationally suitable than currently existing TCAS.

8. **Horio, B.; DeCicco, A.; Hemm, R.; Stouffer, V., "Safety risk assessment case study using Airspace Conflict Analysis Simulation," in *Integrated Communications, Navigation and Surveillance Conference (ICNS), 2012* , vol., no., pp.D2-1-D2-8, 24-26 April 2012**.

   This paper presents a case study describing how the ACAS tool was recently used for a safety risk assessment, by determining the probability of conflict, and the resulting implications for estimating separation assurance risk. Additionally to the case study, the paper discusses the current capacity of the ACAS framework as well as the integration of UAS into the NAS.

   Overall the safety risk assessment provides valuable insight into the risk of an ACAS system. Integration of UAS into the NAS is a critical factor in this project and as just the application of future research into integration is valuable.

9. **"Introduction to TCAS II Version 7.1." (n.d.): 1-50. FAA.gov. Federal Aviation Administration, 28 Feb. 2011. Web. 28 Feb. 2016.**

   This booklet describes different early avoidance systems, TCAS evolution, its components and functions. It also includes collision avoidance concepts, CAS logic functions, performance monitoring of the system.

TRAFFIC COLLISION AVOIDANCE SYSTEM (TCAS)

10. **Jeannin, Jean-Baptiste, et al. "A formally verified hybrid system for the next-generation airborne collision avoidance system."** ***Tools and Algorithms for the Construction and Analysis of Systems*****. Springer Berlin Heidelberg, 2015. 21-36.**

This paper discusses the development of a general strategy for analyzing the safety of real world collision avoidance systems as they apply to "TCAS X". This strategy identifies conditions on resolution advisories that have been proved to keep the aircraft clear of NMAC as well as identifying discrete states where TCAS X is probably safe.

This analysis of a next generation detect and avoid system provides insight into the future of TCAS equipage as well as understanding of intruder "safe region" formulations.

11. **Kochenderfer, Mykel J., James P. Chryssanthacopoulos, and Roland E. Weibel. "A new approach for designing safer collision avoidance systems."*****Air Traffic Control Quarterly*** **20.1 (2012): 27.**

This paper has summarized ongoing work exploring a new approach to derive airborne collision avoidance logic from new encounter models and performance metrics. Experiments demonstrated that the approach outlined in this paper have the potential to improve safety and reduce the rate of unnecessary alerts. The approach focuses on human effort in building models and deciding on performance metrics and using computers to optimize the logic.

This past detect and avoid analysis provides insight into how TCAS has been evaluated in the past as well as the standards and performance of TCAS architecture.

12. **Pritchett, A.; Haga, R.; Thakkar, D., "Pilot responses to traffic events during NextGen high traffic density terminal operations," in** ***Digital Avionics Systems Conference (DASC), 2014 IEEE/AIAA 33rd*** **, vol., no., pp.2C4-1-2C4-9, 5-9 Oct. 2014.**

This work evaluates pilot responses to TCAS Resolution Advisories (RA) during NextGen operations, such as Advanced Flightdeck Interval Management (AFIM), which couple an aircraft's autoflight system to the flight path of another aircraft via ADS-B In information. Additionally, this paper examines the pilot's ability to both maintain an interval and re-establish it after a TCAS resolution advisory (RA) involving either the pilot's own aircraft or the lead aircraft.

While this paper focuses primarily on high traffic terminal operations as well as pilot error in responding to resolution advisories, it gives insight into how a UAV pilot might need to react in order to achieve a similar level of assurance as a manned flight.

13. **Sahawneh, Laith R., et al. "Airborne Radar-Based Collision Detection and Risk Estimation for Small Unmanned Aircraft Systems."** ***Journal of Aerospace Information Systems*** **(2015): 1-11.** In this paper, an innovative approach is presented to quantify likely intruder trajectories and estimate the probability of collision risk for a pair of aircraft flying at the same altitude and in close proximity given the state estimates provided by an airborne radar sensor. The proposed approach is formulated in a probabilistic framework using the reachable set concept and the statistical data contained in the uncorrelated encounter model developed by Lincoln Laboratory, Massachusetts Institute of Technology. Monte-Carlo-based simulation is used to evaluate and compare the performance of the proposed approach with linearly extrapolated collision-detection logic.

14. **Smith, Kyle Alexander, et al.** ***Collision avoidance system optimization for closely spaced parallel operations through surrogate modeling*****. Diss. Massachusetts Institute of Technology, Department of Aeronautics and Astronautics, 2013.**

    This paper describes the application of surrogate modeling and automated search for the purpose of tuning ACAS X for parallel operations. The performance of the tuned system is assessed using an operational performance model. The tuning of ACAS X using surrogate modeling was an efficient way to tune the system in that the tuned logic outperforms TCAS in terms of both safety and operational suitability.

    The thesis written Kyle Smith provides insight into the optimization logic of the future of avoidance systems as well as a solid overview of the currently equipped TCAS platform.

15. **Smith, Nathan E., et al. "Optimal collision avoidance trajectories for unmanned/remotely piloted aircraft."** ***Proceedings of the AIAA Guidance, Navigation, and Control Conference (GNC'13)*****. 2013.**

This paper describes the optimal control problem associated with sense and avoid and uses a direct orthogonal colocation method to solve this problem and then analyzes these results in order to determine collision avoidance scenarios. The goal of this paper is twofold, determine the best technique for calculating the best avoidance trajectories and determine the best technique for estimating and intruder aircraft's trajectory.

16. **Volovoi, Vitali, Alexandra Balueva, and Rene Valenzuela Vega. "Analytical risk model for automated collision avoidance systems."** ***Journal of Guidance, Control, and Dynamics*** **37.1 (2013): 359-363.**

This method discusses an analytical procedure for evaluating the reliability of several layers of collision avoidance systems. Instead of using a Monte Carlo simulation and analytical approach is taken in order to increase computational efficiency and precision as well as increase transparency of the contributing risk factors.

This paper gives a past example of an avoidance system using an analytical model instead of a Monte Carlo model. This could provide insight into a possible alternative method of sense and avoid simulation and experimentation.

7 Miscellaneous

These are additional reports, presentations, and documents there were discovered during the literature review, referenced from A6 project participants, or shared from direct research partners.

7.1 WELL CLEAR DEFINITION

1. **Johnson, Marcus, Eric R. Mueller, and Confesor Santiago. "Characteristics of a Well Clear Definition and Alerting Criteria for Encounters between UAS and Manned Aircraft in Class E Airspace." (2015): 1-10. May 2015. Web. 25 Mar. 2016.**

   The study considers three well clear definitions and presents the relative state conditions of intruder aircraft as they encroach upon the well clear boundary in a particular airspace class E. It also shows the definition of the alerting criteria needed to inform the UAS operator of a potential loss of well clear in that airspace.

2. **Lee, Seung Man, Chunki Park, Marcus A. Johnson, and Eric R. Mueller. "Investigating Effects of Well Clear Definitions on UAS Sense-And-Avoid Operations in Enroute and Transition Airspace." 2013 Aviation Technology, Integration, and Operations Conference (2013): 1-15. Web. 28 Mar. 2016.**

   This paper investigates the effects that different well-clear metrics have on the rate of well-clear violations and evaluates the distribution of distances between aircraft at a well clear violation in high-altitude enroute airspace.

7.2 AIRSPACE SAFETY

1. **AEB Steering Group on Software Design Assurance Policy in the AMS. "Design Assurance Working Group (DAWG) Recommendations." 29 August 2011.**

   An FAA reference report that provides a structure for describing and comparing development assurance levels with associated safety analysis performance data. Not a UAS report, but this report provides recommendations for assessing software assurance against published standards and how to make recommendations for next steps and impacts of the research.

2. **NASA. "Unmanned Aerial System Traffic Management Concept of Operations (V0.4)." Dec. 2015.**

MISCELLANEOUS

The comprehensive guide to the UTM system design, testing plan, and overall objectives. This will be useful for presenting the expectations from A6 simulations based on the models developed during technology characterization.

3. **Cook, Stephen. "Transponder and Altitude Encoder System Issues for UAS: A Preliminary Hazard Analysis," Presentation to NATO Flight in Non-Segregated Airspace (FINAS) Working Group. 18 Sept. 2013.**

A thorough overview presentation on the MITRE Hazards Analysis process for evaluating specific UAS components. This presentation provides a format and framing structure for decomposing the A6 research.

4. **Weibel, Roland E. and R. John Hansman. "Assuring Safety through Operational Approval: Challenges in Assessing and Approving the Safety of Systems-Level Changes in Air Transportation." MIT International Center for Air Transportation (ICAT), Report No. ICAT-2009-04. Sept 2009.**

This report provides a review of methodologies for evaluating air transportation system safety using performance based assessment analysis techniques. Not a UAS report, but provides valuable recommendations for scoping system-level research and evaluating impacts of new technologies as airspace transitions into new capabilities and structures.